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Metro Network Expansion and Passenger Demand Dynamics: A Comparative Study of Two Urban Systems

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Abstract

This study investigates long term passenger demand responses following metro network expansion using empirical evidence from the West Midlands Metro and Sofia Metro. Using monthly ridership data and an interrupted time series framework, the analysis evaluates both immediate and longer term effects across six expansion events. Results show that demand responses are heterogeneous across systems and events. The Sofia Line 2 extension produced a large immediate increase in ridership, while the West Midlands Edgbaston Village extension exhibited gradual post opening growth with no significant initial jump. Comparative modelling indicates that proportional immediate effects are similar across systems when scale is controlled for, but post expansion growth is significantly stronger in the West Midlands Metro. Nonlinear modelling further suggests that demand does not stabilise quickly after expansion, instead evolving over time through a ramp up process. These findings challenge conventional assumptions of rapid equilibrium adjustment and highlight the importance of system context, network maturity, and temporal dynamics in shaping demand outcomes. The study provides important implications for transport forecasting, policy evaluation, and infrastructure investment appraisal.

Keywords: Urban transport, metro expansion, passenger demand, interrupted time series, ridership dynamics, network effects, transport modelling

1 Introduction

Urban rail systems are widely regarded as a central component of sustainable urban transport strategies, offering the potential to reduce congestion, lower emissions, and support compact urban development [1,2]. In this context, metro network expansion represents one of the most significant forms of long-term transport investment. A critical question for both planners and policymakers is how passenger demand evolves following such expansions, and whether expected ridership gains materialise in practice.

While conventional appraisal frameworks often assume that demand adjusts rapidly to a new equilibrium after infrastructure is introduced, emerging empirical evidence suggests that ridership responses may be more complex and temporally dynamic. Demand may increase immediately following an expansion, grow gradually over time, or in some cases fail to meet projected expectations. These differing trajectories have important implications for forecasting accuracy, investment appraisal, and the evaluation of transport policy.

Existing research has provided valuable insights into the relationship between metro expansion and ridership, but several limitations remain. Much of the literature focuses on single systems or individual expansion events, limiting the ability to generalise findings across contexts. In addition, relatively few studies explicitly distinguish between immediate level effects and longer-term growth dynamics within a unified analytical framework [3]. As a result, it remains unclear whether expansion-induced demand responses follow consistent patterns across systems with different characteristics.

This study addresses these gaps by examining passenger demand responses to metro network expansion in two contrasting urban contexts: the West Midlands Metro in the United Kingdom and the Sofia Metro in Bulgaria. Using monthly ridership data and a segmented regression interrupted time series approach, the analysis evaluates both immediate and longer-term demand effects across six expansion events. A pooled comparative model is further employed to assess whether demand responses differ systematically between systems once differences in scale are accounted for.

This study contributes to the literature in three key ways. First, it provides a comparative empirical analysis of multiple metro expansion events across two distinct urban systems using a consistent interrupted time series framework, addressing the predominance of single-case studies in existing research. Second, it explicitly decomposes ridership responses into immediate level effects and post-expansion growth dynamics, allowing for a more precise characterisation of demand evolution over time. Third, it extends conventional ITS analysis by incorporating nonlinear growth models to examine post-opening demand ramp-up, offering new empirical insight into the temporal adjustment process following infrastructure expansion. Together, these contributions provide a more nuanced understanding of how and when demand responds to network expansion, with direct implications for transport forecasting and appraisal.

The findings have implications for both transport modelling and policy, particularly in relation to forecasting assumptions and the evaluation of large-scale infrastructure investments.

2 Methods

2.1 Data and Use Cases

West Midlands metro

Prior to the first recorded expansion event, West Midlands metro (WMM) operated a stable network of 20.4 km between Birmingham Snow Hill and Wolverhampton St George's. Since its inception the network has undergone staged expansion, with the city centre extension in Birmingham completed progressively from 2015 onwards and new openings occurring between 2019 and 2024.

Four completed expansion events fall within the study period. The Centenary Square extension, the first phase of the Birmingham Westside Project , opened in December 2019, extending the network from Grand central into Birmingham city center at a cost of £149 million. The second phase, Edgbaston village, opening on 17 July 2022 adding three further stops along Broad Street to Hagley Road in Edgbaston, coinciding with Birmingham 2022 commonwealth games. The Wolverhampton City Center extension opened in 17 September 2023, adding two stops at Pipers Row and Wolverhampton Railway station, creating integrated public transport interchange at a cost of £50 million. The Birmingham Eastside extension to Digbeth and the HS2 Curzon Street station opened in May 2024. A further major expansion, the Wednesbury to Brierley Hill extension, is currently under construction and is expected open in phases from 2026. This extension falls outside the study period and is therefore not included in the empirical analysis, though it represents the primary forward-looking application context for the forecasting work motivating this research.

Network length increased from 20.4km at the start of the study period (2013) to the 23.3 by 2025, with further growth anticipated as the Wednesbury to Brierley Hill extension is completed. This service area encompasses Birmingham, Wolverhampton, and surrounding urban districts, serving a combined population of approximately 1.8 million.

Metro Sofia

Metro Sofia is the underground rapid transit system serving Sofia, the capital city of Bulgaria. The system has undergone substantial network expansion during the study period, growing from 24.3km in 2011 to 52km by 2019. Two expansion events fall within the analysis window. The Line 2 extensions opened in September 2012, increasing network length from 24.3km to31km and extending the system's coverage of the city. Line 3 Phase 1 opened in September 2016, extending the network progressively from 31km through 36km and subsequently 40km by the end of 2016. Metro Sofia serves a metropolitan population of approximately 1.3million and carries higher monthly ridership than WMM, which reflects its population density and more extensive network coverage.

The Line 3 Phase 1 expansion in 2016 was implemented in multiple stages within a relatively short time period, resulting in successive increases in network length over the same calendar year. For the purposes of this analysis, these staged openings are treated as a single intervention. This approach is justified on the basis that the individual openings occurred in close temporal proximity and collectively represent a single functional expansion of the network. The intervention date is therefore defined as the initial opening point, with subsequent extensions captured within the post-intervention period.

Data

Monthly network-wide passenger journey data were obtained from the respective metro operators for both systems. For WMM the datasets covers January 2013 to May 2025, providing 149 monthly observations, For Metro Sofia, the datasets cover February 2011 to December 2024, providing 167 monthly observations. Both datasets record total monthly passenger journeys at the network level, along with independent variables including population, network length in kilometres, average fare, and GDP (used as a proxy for economic activity).

Two data quality issues were identified and addressed priori to analysis. For WMM, April and May 2022 recorded zero ridership due to full network closure following the discovery of structural cracks in the tram fleet, requiring withdrawal of vehicles for inspection and body panel replacement. These two months were treated as non-operational period and replaced using linear interpolation between March and June 2022 to preserve underlying demand trajectory without distortion from the construction related closure. For Metro Sofia, March 2015 recorded anomalously low numbers of passengers approximately 101,000 against a network mean of 6.8 million, coinciding with a period of active expansion construction and commissioning. This observation was treated as unreliable and replaced with a missing value. November 2024 also exhibited an anomalous value inconsistent with surrounding months and was similarly excluded.

2.2 Data preparation and anomaly treatment

The study adopts a quantitative research method to examine passenger demand responses to metro network expansion across two systems: West Midlands Metro and Metro Sofia. This analysis is conducted at a monthly temporal resolution and combines descriptive, quasi-experiental, and nonlinear modelling approaches to capture both immediate and dynamic demand effects. All empirical analysis was implemented in R using tidyverse, lubridate, zoo, sandwich,lmtest, and car packages.

Both datasets were standardised and cleaned prior to analysis. Monthly observations were constructed from raw year and month fields, converted into a continuous data index and ordered chronologically.

Several data anomalies were identified and addressed to ensure analytical validity and flow. For West Midlands Metro, April and May 2022 recorded zero demand due to complete system shutdown following structural defects in the Urbos 3 tram fleet. As these observations reflect a temporary cessation of service as opposed to an underlying demand condition, they were treated as missing and replaced via linear interpolation between March and June 2022 using zoo::na.appox function. This approach preserves continuity in the demand trajectory while avoiding distortion from non-operational periods.

For Metro Sofia, two anomalous observations were identified: March 2015, coinciding with network expansion works, and November 2024, likely reflecting a ticketing or reporting irregularity. Both values were excluded from analysis.

Multicollinearity was assessed using variance inflation factors (VIF). Initial model specifications including population and GDP exhibited substantial collinearity with the time trend, with VIF values exceeding conventional thresholds (VIF> 10). Given the deterministic upward trajectory of these variables, their inclusion does not provide independent explanatory power within a segmented time series framework. Consequently, they were excluded in favour of a more parsimonious specification focused on temporal structure. Final VIF values for retained predictors remained within acceptable bounds.

The decision to exclude population and GDP from the final specification is based on both statistical and conceptual considerations. In a segmented time series framework, these variables exhibit strong correlation with the underlying time trend, reflecting long term growth patterns rather than independent short term variation. Their inclusion introduces multicollinearity without contributing additional explanatory power to the estimation of intervention effects.

Given that the primary objective of the model is to estimate changes in level and trend associated with expansion events, the inclusion of highly collinear macroeconomic variables may obscure the interpretation of these parameters. The final specification therefore prioritises a parsimonious model structure focused on temporal dynamics, which is consistent with standard practice in interrupted time series analysis. As a robustness consideration, the stability of results under alternative specifications is acknowledged, though detailed sensitivity analysis is beyond the scope of this study.

As an initial step, a descriptive before and after analysis was conducted for each expansion event. Mean monthly passenger demand was calculated over 12 months preceding and the 12 months following each opening date. Percentage change between these periods provides an intuitive measure of immediate demand response.

A 12-month window is used for the before and after comparison to provide a balanced measure of demand that captures both short term fluctuations and seasonal variation. This period is sufficiently long to smooth out monthly irregularities while remaining short enough to reflect conditions reasonably close to the intervention date.

Using symmetric pre and post periods also improves comparability by ensuring that observed differences are not driven by unequal time horizons. This approach is consistent with common practice in transport evaluation studies, where 12-month windows are frequently used to account for seasonality in ridership data.

While this approach does not control for underlying trends or external shocks, it is useful for transparent benchmark against which more formal model-based estimates can be compared. Results associated with periods overlapping the COVID-19 pandemic are retained for completeness but interrupted with caution.

2.3 Interrupted time series (ITS) modelling

To estimate demand responses while controlling for pre-existing trends, a segmented regression interrupted time series model was employed. ITS is widely used in the evaluation of transport and policy interventions where experimental designs are not feasible [5,6]. The identification strategy relies on the assumption that, conditional on pre-existing trends, the timing of network expansion is exogenous to short-term fluctuations in demand. Under this assumption, the pre-intervention trajectory provides a valid counterfactual for post-intervention outcomes.
The baseline specification is:

$$\text{Demand}_{\_t} = \beta_0 + \beta_1\,\text{time}_{\_t} + \beta_2\,\text{post}_{\_t} + \beta_3\,\text{time\_post}_{\_t} + \varepsilon_{\_t}$$

Where time_t is a continuous monthly index. The time variable is defined as a sequential monthly index beginning at the first observation for each system. post_t is a binary indicator equal to one from the intervention date onwards, and time_post_t is a post intervention time counter that increments from zero to the intervention point, i.e., measuring every month that has passed since the expansion opened. The post-intervention time variable is defined as zero prior to the intervention and increases linearly from one in the first post-intervention month.

The coefficient β_2 captures the immediate level shift in demand associated with the expansion, while β_3 captures any change in the post-intervention growth trajectory relative to the pre-existing trend. Distinguishing between these two is very important, as infrastructure expansions may induce either short-term demand shocks or longer-term behavioural adjustments.

Models were estimated separately using the full time series for the relevant system. Residual diagnostics were conducted to assess autocorrelation, heteroskedasticity, and model fit. Autocorrelation was addressed using Newey-West standard errors, while visual inspection of residual plots confirmed no systematic violations of linear model assumptions.

Results are interpreted as evidence of expansion-associated demand change. While the ITS framework controls for pre-existing demand trends, it cannot fully isolate expansion effects from concurrent contextual factors notably the Birmingham 2022 Commonwealth Games coinciding with the Edgbaston Village opening and results are interpreted accordingly.

The identification strategy relies on the assumption that the timing of network expansion is exogenous to short-term fluctuations in passenger demand. While infrastructure investments are planned over long time horizons and are therefore unlikely to respond to short-term demand shocks, it is acknowledged that this assumption may not hold perfectly in all cases. In particular, expansion timing may coincide with broader economic conditions, policy initiatives, or major events that also influence travel behaviour.

To mitigate this limitation, the analysis explicitly controls for pre-intervention demand trends and interprets estimated effects as expansion-associated changes rather than strictly causal impacts. Events that coincide with major external disruptions, such as the COVID-19 pandemic, are identified and interpreted with caution in the results.

2.4 Comparative analysis of two models

To assess whether demand responses differ by systems, a combined segmented regression model was estimated using pooled data from Metro Sofia and West Midlands Metro. To avoid duplication issues associated with multiple events per system, a single representative expansion event was chosen for each case: Edgbaston Village (July 2022) expansion event for West Midlands Mero and the Line 2 extension event (September 2012) for Metro Sofia. These events were chosen due to relatively clean post-trajectories, free from major external disruptions.

The combined model equation is specified as:

$$\begin{aligned} \text{Demand}_{\_t} = {} & \beta_0 + \beta_1 \text{time}_{\_t} + \beta_2 \text{post}_{\_t} + \beta_3 \text{time\_post}_{\_t} \\ & + \beta_4 \text{system}_{\_t} + \beta_5 (\text{post} \times \text{system})_{\_t} \\ & + \beta_6 \left(\text{time\_post} \times \text{system}\right)_{\_t} + \varepsilon_{\_t} \end{aligned}$$

Where $\text{system}_{\_t}$ is a binary indicator distinguishing the two networks. Interaction terms allow for both immediate level shift and the post-intervention slope change to vary across systems.

The time_post variable was constructed separately within each system to ensure correct alignment with system-specific intervention dates. Newey–West standard errors were applied to account for serial correlation.

2.5 Demand ramp-up dynamics

To further examine the temporal dynamics of post-expansion demand, nonlinear growth models were estimated over a 24-month post-intervention period for selected events unaffected by major external disruptions. Specifically, the Edgbaston Village extension (West Midlands Metro) and the Line 2 extension (Metro Sofia) were analysed.

Two functional forms were considered: an exponential growth model and a logistic growth model. The exponential specification captures continuous but decelerating growth towards an upper bound, while the logistic model allows for an initial acceleration phase followed by gradual saturation, which is consistent with behavioural adoption processes.

The exponential model is defined as:

$$\mathrm{Demand}_{\_t} = \mathrm{A}_0 + \mathrm{A}(1 - \exp(-\mathrm{kt}))$$

where A_0represents demand at the point of opening, A is the long-run demand increment, and k is the rate of adjustment.

The logistic model is defined as:

$$\mathrm{Demand}_{\_t} = \mathrm{A}_0 + \mathrm{L}/(1 + \exp(-\mathrm{k}(\mathrm{t} - \mathrm{t}_0)))$$

where L represents the total long-run increase in demand, k is the growth rate, and t_0 is the inflection point at which growth transitions from acceleration to deceleration.

Models were estimated using nonlinear least squares, with starting values informed by observed data ranges. Model performance was assessed using residual standard error and visual fit to observed trajectories. In cases where convergence was weak or fit was poor, results were interpreted qualitatively rather than relying on parameter estimates.

Across both case studies, the estimated trajectories suggest that demand does not stabilise rapidly following expansion but instead evolves gradually over time. This supports the interpretation of post-expansion demand as a dynamic adjustment process rather than an immediate equilibrium shift.

3 Results

3.1 Descriptive demand patterns

Figures 1 and 2 present monthly passenger demand trajectories for both systems over the study period with expansion events marked by vertical indicators. Both systems exhibit net upward trends over the observation period, though the trajectory of growth differs substantially across phases and between systems. Metro Sofia carries consistently higher absolute ridership than West Midlands Metro, with mean monthly demand of approximately 6.8 million journeys compared to 506,000, reflecting structural differences in network scale, urban density, and catchment population between the two systems.

Pre-expansion demand in WMM grew steadily from 4.6 million annual journeys in 2013 to 7.9 million by 2019, representing organic growth of 73% before the first extension opened. This pre-existing upward trend is important context for interpreting subsequent expansion effects and motivates the use of a controlled ITS specification rather than simple before/after comparison. Metro Sofia's pre-expansion window is shorter, 19 months prior to the Line 2 opening, but similarly shows an upward trajectory from approximately 4.5 million monthly journeys.

The COVID-19 pandemic represents a major external disruption visible in both series from March 2020, with demand collapsing to below 200,000 monthly journeys in WMM and approximately 1.1 million in Sofia at the trough. Both systems recovered strongly, with WMM reaching record annual totals of 8.37 million journeys in both 2023 and 2024, and Sofia reaching 113 million in 2024, it’s highest on record.

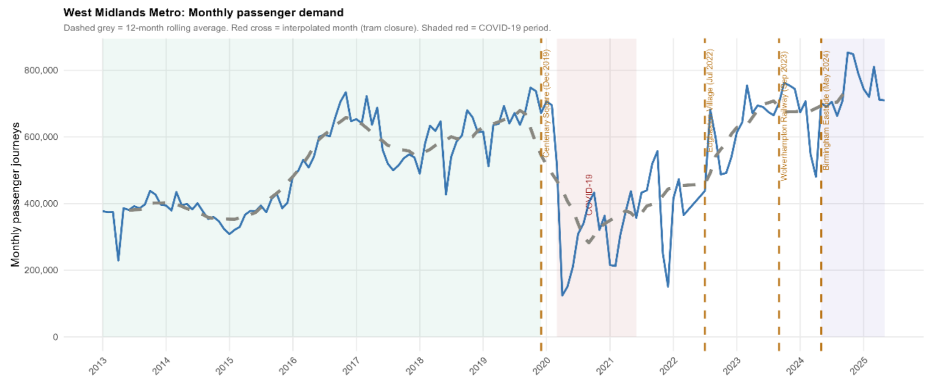

Figure 1 WMM monthly demand trajectory

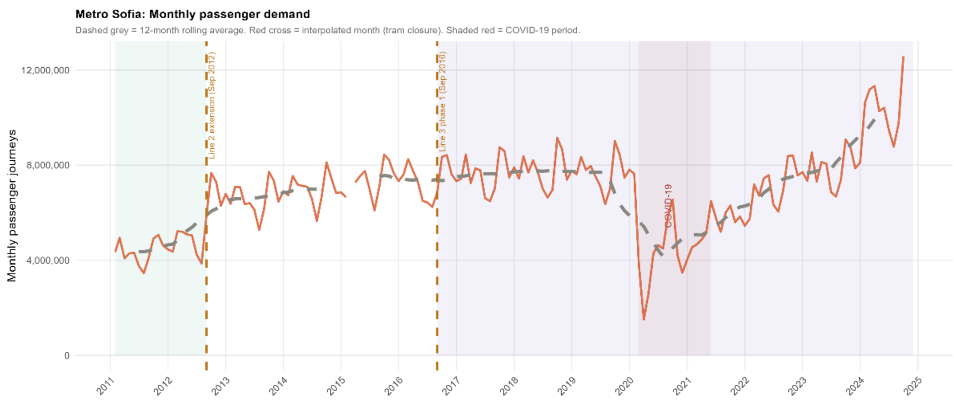

Figure 2 Sofia monthly demand trajectory

3.2 ITS results – level shifts and slope changes

Table 1 reports level shift (β_2) and slope change (β_3) coefficients with Newey-West robust standard errors for all six expansion events. Results are discussed jointly for each event.

System	Event	level shift (β_2)	Level shift SE	Level shift P-value	slope change (β_3)	Slope change SE	Slope change P-value
WMM	Centenary square (Dec2019)	-380,235	72,262	<0.001***	3,200	1,775	0.074
WMM	Edgbaston Village (Jul 2022)	71,459	66,901	0.287	5,304	1,632	0.001**
WMM	Wolverhampton Railway (Sep 2023)	116,905	67,858	0.087	2,890	3,083	0.350
WMM	Birmingham Eastside (May 2024)	125,668	57,017	0.029*	2,806	3,787	0.460
Sofia	Line 2 extension (Sep 2012)	1,897,069	382,993	<0.001***	−18,994	23,032	0.411
Sofia	Line 3 phase 1 (Sep 2016)	−1,432,270	635,381	0.026*	−40,220	13,185	0.003**

Table 1: Interrupted time series – level shift and slope change for all expansion

*Note: Newey-West robust standard errors. β_2 = immediate level shift at opening; β_3 = change in monthly growth rate after opening. Centenary Square result reflects COVID-19 suppression and is not interpreted as a causal expansion effect. *p < 0.05, **p < 0.01, ***p < 0.001.*

The Sofia Line 2 extension (September 2012) produces the largest and most statistically robust demand response in the dataset. The ITS model identifies an immediate level shift of 1,897,069 additional monthly journeys (SE = 382,993, $p < 0.001$), confirming that the expansion produced a large discrete demand increase beyond what the pre-existing trend would predict. The post-opening slope change is not significant (-18,994, $p = 0.411$), indicating that while demand jumped substantially at opening, the monthly growth rate did not accelerate further. The Sofia Line 3 Phase 1 opening (September 2016) produced a significant negative level shift of -1,432,270 journeys (SE = 635,381, $p = 0.026$) and a significant negative slope change of -40,220 journeys per month (SE = 13,185, $p = 0.003$). Both effects are statistically significant, suggesting the 2016 expansion was associated with disruption to existing demand patterns during the preceding construction and commissioning period rather than generating new ridership in the short to medium term.

For West Midlands Metro, The Centenary Square opening (December 2019) shows a statistically significant negative level shift of −380,235 journeys (SE = 72,262, $p < 0.001$). However, this effect coincides with the onset of the COVID-19 pandemic and therefore cannot be interpreted as a causal effect of the expansion. The estimate reflects pandemic-related demand suppression rather than infrastructure impact. The Edgbaston Village extension (July 2022) produces the most analytically important WMM result: the level shift is not significant (71,459, SE = 66,901, $p = 0.287$) but the slope change is highly significant at +5,304 additional journeys per month (SE = 1,632, $p = 0.001$). This characterises a gradual ramp-up response, no discrete demand jump at opening but a sustained post-opening acceleration in monthly growth that compounds to approximately 127,000 additional journeys over a 24-month horizon. The Wolverhampton Railway Station extension (September 2023) shows a positive but non-significant level shift of +116,905 (SE = 67,858, $p = 0.087$). The Birmingham Eastside extension (May 2024) produces a statistically significant positive level shift of +125,668 (SE = 57,017, $p = 0.029$), providing early evidence of a demand response over its 13-month observable window.

3.3 Cross -case comparative model

Table 2 presents the combined pooled segmented regression model estimated on log-transformed demand, which accounts for the substantial difference in absolute ridership scale between the two systems. The model explains 88.4% of variance in monthly log-demand across both systems ($R^2 = 0.884$).

Term	Estimate	Standard Error (SE)	p-value
Intercept	15.308	0.038	<0.001***
Time	0.000	0.002	0.897
Post	0.401	0.073	<0.001***
Time_post	0.000	0.003	0.930
System (WMM)	−2.310	0.118	<0.001***
Post× system (WMM)	−0.178	0.190	0.348
Time_post × system (WMM)	0.009	0.002	<0.001***

Table 2: Combined segmented regression model, pooled WMM and Metro Sofia

Note: Dependent variable is log-transformed monthly demand. Reference category = Metro Sofia (Line 2 extension, Sep 2012). WMM primary event = Edgbaston Village (Jul 2022). Newey-West robust standard errors applied. $R^2 = 0.884$, Adjusted $R^2 = 0.881$. Coefficients are in log units - exp(0.401) = 1.493 implies a 49% demand increase for Sofia at opening. *$p < 0.05$, **$p < 0.01$, ***$p < 0.001$.

The post coefficient is positive and highly significant (β = 0.401, $p < 0.001$), indicating that the Line 2 expansion in Sofia was associated with an approximate 49% increase in demand at opening. The system coefficient is large and significant (β = -2.310, $p < 0.001$), reflecting that WMM's baseline demand is approximately 10% of Sofia's in absolute scale - exp(-2.310) = 0.099, consistent with the structural differences in network coverage and catchment population.

The post:systemWMM interaction is not significant (β = -0.178, $p = 0.348$), indicating that in proportional terms the immediate demand response at opening did not differ significantly between the two systems once demand scale is accounted for through log transformation. This is an important qualification of the absolute-scale comparison: the apparent disparity in immediate responses largely reflects scale differences rather than fundamentally different demand mechanisms operating across the two contexts.

The time_post:systemWMM interaction is highly significant (β = 0.009, $p < 0.001$), indicating that WMM's post-opening monthly growth rate was significantly more accelerated than Sofia's following their respective primary expansion events. This finding directly corroborates the individual event results -WMM's Edgbaston Village opening generated a sustained post-opening growth trajectory that was proportionally stronger than Sofia's post-Line 2 response and constitutes the principal cross-case finding of the combined model.

3.4 Post expansion demand evolution dynamics

Figures 3 and 4 present indexed post-opening demand trajectories for the Edgbaston Village and Sofia Line 2 events respectively, with fitted exponential and logistic growth curves where convergence was achieved.

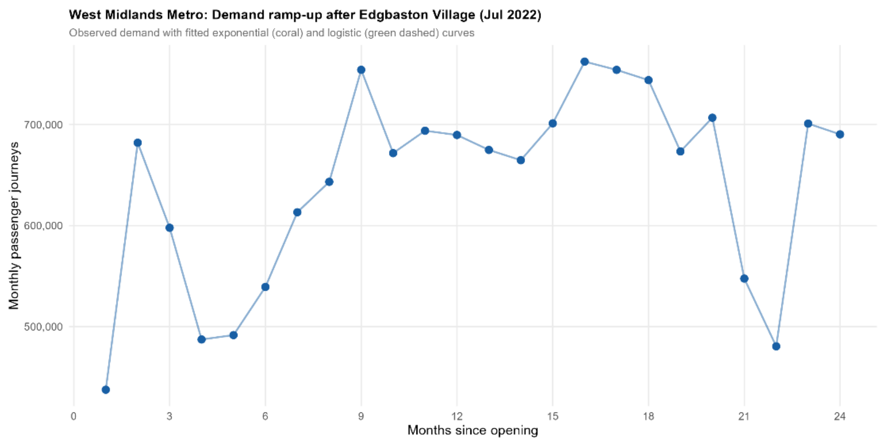

Figure 3 WMM Edgbaston village post expansion demand evolution

Figure 4: Sofia Line 2 post expansion demand evolution

Neither system exhibits rapid demand stabilisation within the 24-month observation window. The Edgbaston Village trajectory oscillates between 110% and 180% of the opening-month level throughout the window, stabilising in the 155–165% range by months 18–24 with no downward trend. The Sofia Line 2 trajectory maintains a consistent 110–130% range with seasonal oscillation, remaining above the opening-month baseline at month 24. These patterns are consistent with the significant post-opening slope change identified for Edgbaston Village and support the broader finding that expansion-induced demand growth accumulates gradually rather than stabilising quickly following opening [7].

3.5 Model diagnostics

Variance inflation factors for the combined model ranged from 3.1 (post) to 6.3 (time_post). The modest elevation in time_post reflects the structural dependence between the three ITS terms and is expected in segmented regression designs. No predictor exceeded a VIF of 10. Newey-West robust standard errors were applied throughout, and the combined model was estimated on log-transformed demand to address the large difference in absolute demand scale between the two systems.

3.6 Summary of findings

First, expansion events are associated with statistically significant demand responses, but the nature of response varies substantially across events and between systems. Sofia's Line 2 extension produced a large immediate step-change of approximately 1.9 million monthly journeys while WMM's Edgbaston Village produced no significant immediate level shift but a highly significant post-opening growth acceleration of +5,304 journeys per month, two qualitatively distinct response types with different implications for forecasting.

Second, the cross-case comparison on log-transformed demand shows that immediate proportional demand responses did not differ significantly between systems (post:systemWMM, p = 0.348), suggesting broadly comparable proportional effects once scale is accounted for. However, WMM's post-opening monthly growth trajectory was significantly more accelerated than Sofia's (time_post:systemWMM, p < 0.001), consistent with the sustained ramp-up pattern visible in the indexed trajectory analysis..

4 Conclusions and Contributions

This study demonstrates that passenger demand responses to metro network expansion are heterogeneous and strongly dependent on system context, timing, and network maturity. While expansions are generally associated with positive demand effects, these effects are neither uniform nor guaranteed.

Empirical results show two distinct response patterns. In the Sofia Metro, expansions such as the Line 2 extension generated large and immediate increases in ridership, reflecting strong network effects and existing latent demand. In contrast, the West Midlands Metro exhibits more gradual demand responses, most notably in the Edgbaston Village extension, where no significant immediate increase was observed but a sustained post opening growth trend emerged. Other expansion events in the West Midlands show weaker or statistically insignificant effects, suggesting that impacts may take longer to materialise or depend on complementary conditions.

Comparative analysis indicates that once differences in system scale are accounted for, immediate proportional demand responses are not significantly different between the two systems. However, post expansion growth is significantly stronger in the West Midlands Metro, supporting the interpretation that developing systems experience slower but sustained demand build up, whereas more mature systems realise benefits more immediately.

Across both case studies, no expansion event resulted in rapid demand stabilisation within two years of opening. Instead, demand evolves progressively over time, indicating that behavioural adjustment, network integration, and external factors play a key role in shaping ridership outcomes.

The study makes three main contributions. First, it provides a comparative empirical analysis across multiple expansion events using a consistent interrupted time series framework. Second, it distinguishes clearly between immediate and longer term demand effects. Third, it demonstrates that post expansion demand follows a dynamic adjustment process rather than an immediate equilibrium shift.

These findings have important implications for transport planning and policy [3,4]. Forecasting approaches that assume rapid post opening stabilisation may misrepresent actual demand trajectories. In developing systems, infrastructure expansion alone may be insufficient to generate strong ridership growth without supporting measures such as improved connectivity, service integration, and land use coordination. In more mature systems, while immediate gains are more likely, demand still requires time to fully adjust.

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