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A retrospective TAG-informed conventional UK strategic variable-demand model to analyse Manchester Metrolink network expansion Phase 3

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Abstract
Urban rail demand forecasts are commonly evaluated using aggregate patronage, yet this can conceal whether demand is distributed correctly across the network and how passengers respond to expansion. A more disaggregated evaluation is therefore needed to distinguish overall demand scale from spatial allocation, behavioural response and network redistribution. This study addresses this issue using Manchester Metrolink Phase 3 and a retrospective TAG-informed conventional UK strategic variable-demand model. Controlled 2018 Do-Minimum and Do-Something scenarios are used to examine destination redistribution, mode switching and public transport network redistribution, while modelled corridor shares are compared with observed 2018/19 patronage and the original forecast. Observed patronage was 30.5% below the original forecast, but the retrospective model reproduced corridor shares more closely, reducing mean absolute share error from 3.64 to 2.28 percentage points. Total represented public transport demand increased by 1.35%, while tram-using journeys increased by 68.19%, demonstrating that aggregate forecast error can coexist with comparatively good spatial representation and substantial network redistribution.

Keywords: urban rail; passenger demand forecasting, network expansion, retrospective validation; variable demand modelling; spatial validation; network redistribution

1.Introduction

Background and Motivation

Strategic passenger-demand forecasting plays an important role in the planning and appraisal of urban rail investment. Forecast demand influences estimates of transport benefits, revenue, capacity requirements, operating needs and the wider justification for network expansion. As urban rail systems develop through new lines and extensions, planners need to estimate not only how many passengers may use the expanded system, but also where that demand will occur and how passengers may respond to changes in accessibility and network connectivity. Strategic transport models are widely used for this purpose because they provide a structured representation of trip distribution, mode choice and network use. [1,2]

Forecasting demand under network expansion is challenging because new infrastructure can influence several passenger decisions at the same time. Some passengers may switch from car or bus to tram or metro. Existing public transport users may change destinations, routes, services or interchange patterns. Improved accessibility may also redistribute demand across the wider network without producing an equivalent increase in total public transport travel. An increase in urban rail patronage can consequently contain several different behavioural and network effects.

Understanding these effects is important because strategic forecasting is used to support long-term investment decisions. If the expected passenger response to expansion is not represented accurately, this may affect estimates of benefits, capacity needs, operating requirements and investment performance. Evaluating forecasting performance after a network has expanded can consequently provide evidence about what conventional strategic models capture successfully and where weaknesses remain.

1.2 Problem formulation and Research Gap

Previous ex-post studies have shown that observed passenger demand can differ substantially from forecasts made before transport projects open. [3–6] However, comparing forecast and observed total patronage provides only a partial measure of forecasting performance.

A large aggregate difference does not establish whether the forecasting problem arose because the overall amount of demand was estimated incorrectly, demand was allocated to the wrong locations, behavioural responses were represented inadequately, or assumptions used during appraisal did not materialise. It is also possible for a forecast to reproduce total patronage reasonably well while allocating passengers incorrectly between corridors or services.

Forecasting performance under urban rail network expansion should consequently be examined across more than one dimension. In particular, it is useful to distinguish between:

- **aggregate demand scale**, which concerns the overall amount of passenger demand;
- **spatial allocation**, which concerns where that demand occurs;
- **behavioural response**, including changes in mode and destination choice; and
- **network redistribution**, which concerns how passengers use different public transport services and network paths following expansion.

Existing forecast-accuracy studies provide substantial evidence that differences between forecast and realised patronage occur. Transport-model validation guidance also emphasises the importance of geographic and network-level performance. However, there is less empirical evidence combining these perspectives after a completed urban rail expansion.

The research gap addressed in this study is not only whether a forecast was higher or lower than observed demand. The more detailed question is whether a TAG-informed conventional UK strategic variable-demand forecasting framework can reproduce the scale, spatial distribution and network response of passenger demand following urban rail expansion, and what the remaining differences reveal about forecasting performance.

1.3 Study Design and Scope

Manchester Metrolink Phase 3 provides the empirical case for examining strategic passenger-demand forecasting under urban rail network expansion. The programme expanded the light-rail network through four major corridors serving Ashton-under-Lyne, East Didsbury, Manchester Airport, and Oldham and Rochdale. Transport for Greater Manchester subsequently reported the original expected demand and observed 2018/19 patronage for these corridors, together with an evaluation of factors associated with differences between forecast and realised demand.[7] This provides a suitable basis for examining both historical forecast performance and the ability of conventional strategic modelling to reproduce the realised response to network expansion.

The empirical analysis uses three distinct representations of passenger demand:

1. **the original Phase 3 forecast,** representing the passenger demand expected during the planning and appraisal of the expansion;
2. **observed patronage 2018/19**, representing the realised passenger demand following he completion of the Phase 3 programme; and
3. **a retrospective TAG-informed conventional UK strategic variable demand model,** developed specifically for this study.

The third component is referred throughout the remainder of this paper as the **retrospective model.** This is not the reconstruction of TfGM's original forecasting model. Instead, it provides a standardised representation of conventional variable demand forecasting practice, informed by Department of Transport, Transport Analysis Guidance (TAG). Its purpose is to examine how well this type of forecasting framework represents the passenger demand response associated with a completed urban rail network expansion.

Within the retrospective model, two controlled 2018 network scenarios are constructed. The **Without-Phase-3 Scenario (Do-Minimum, DM)** represents the 2018 public transport network with the Phase 3 Metrolink extensions removed. **With-Phase-3 Scenario (Do-Something, DS)** represents the

corresponding 2018 network with the Phase 3 extensions included. The DM and DS scenarios were developed for this study and do not reproduce TfGM's original Phase 3 scenario design.

Comparing DS and DM scenarios provides a controlled means of examining the passenger demand response generated by the retrospective model when the Phase 3 network expansion is introduced. The background year and underlying socioeconomic conditions are held constant, while the principal network intervention is changed. This allows changes in represented public transport demand, destination, mode choice and public transport network, mode choice and public transport network use to be examined separately.

The empirical design consequently contains three related comparisons.

Original forecast versus observed patronage assesses historical forecast performance by identifying the difference between the passenger demand originally expected for Phase 3 and the demand subsequently observed.

Do-Minimum versus Do-Something identifies the passenger demand response generated by the retrospective model when Phase 3 network expansion is introduced.

Retrospective model versus observed spatial demand evaluates whether the model reproduces the geographical distribution of realised demand across the four Phase 3 corridors. This spatial performance can also be compared with the distribution implied by the original forecast.

The retrospective model represents home-based-work-travel (HBW-AM) during the morning peak. Its absolute demand totals are not treated as direct equivalent to TfGM's annual all purpose patronage figures. The model in this study is not used to produce an alternative annal patronage forecast. Spatial validation instead focuses on corridor demand shares and associated diagnostic measures allowing the geographical pattern generated by the model to be compared with observed outcomes without assuming direct relevance between the two demand scales.

1.4 Aim, Objectives and Research Questions

The overall aim of this study is:

To empirically evaluate strategic passenger-demand forecasting under urban rail network expansion by comparing the original Manchester Metrolink Phase 3 forecast, observed patronage and the outputs of a retrospective TAG-informed conventional UK strategic variable-demand model.

The study has three objectives.

Objective 1: To evaluate the accuracy of the original Phase 3 passenger-demand forecast against observed 2018/19 patronage and identify how forecast-outturn differences vary across the four expansion corridors.

Objective 2: To develop a retrospective TAG-informed conventional UK strategic variable-demand model and use a controlled 2018 Do-Minimum/Do-Something comparison to quantify the modelled passenger-demand response to Phase 3, including destination redistribution, mode switching and public transport network redistribution.

Objective 3: To compare the spatial distribution generated by the retrospective model with observed corridor patronage and the distribution implied by the original forecast, and to distinguish common demand-scale differences from corridor-specific residual model error.

These objectives are addressed through three research questions:

RQ1: How accurately did the original strategic passenger-demand forecast reproduce observed patronage following Manchester Metrolink Phase 3?

RQ2: What passenger-demand response to Phase 3 is generated by a retrospective TAG-informed conventional UK strategic variable-demand model when comparing Do-Minimum and Do-Something network conditions?

RQ3: How closely does the retrospective model reproduce the observed spatial distribution of demand compared with the original forecast, and what do the remaining differences reveal about aggregate demand scale and corridor-specific model error?

1.5 Study Outcomes and contribution

The study evaluates forecasting performance across four related dimensions: aggregate demand scale, spatial allocation, behavioural response and public transport network redistribution.

The first outcome is an empirical assessment of the performance of the original Phase 3 forecast. Comparing the original forecast with observed 2018/19 patronage establishes the overall forecast-outturn difference and identifies how this difference varies between the four expansion corridors. Evidence from TfGM's subsequent evaluation is then used to help interpret why realised demand differed from the original forecast, while recognising that the adjusted expected values are ex-post diagnostics and not independent forecasts.

The second outcome is an analysis of the demand response generated by the retrospective model. The DM–DS comparison identifies how the model responds to the introduction of Phase 3 and separates changes associated with mode choice, destination redistribution and public transport network use. This allows increases in tram use to be distinguished from changes in total represented public transport demand.

The third outcome is a spatial comparison between the original forecast, observed patronage and retrospective model. Corridor demand shares provide a common basis for assessing how closely each forecasting representation matches the realised geographical distribution of Phase 3 patronage. This makes it possible to examine whether substantial aggregate forecast error is accompanied by equally substantial spatial error.

The fourth outcome is a set of scale and residual-error diagnostics used to distinguish a broadly common difference in demand scale from corridor-specific mismatch. These diagnostics provide further evidence on whether disagreement between modelled and observed demand is concentrated in particular corridors or reflects a more general difference in scale.

The contribution of the study lies in combining these different forms of evidence within a single empirical evaluation. The analysis does not seek to reproduce or reassess TfGM's original forecasting model directly. Instead, it uses the original forecast as a historical benchmark and then tests a separate TAG-informed retrospective model against realised post-expansion outcomes. This provides a clearer bias for assessing which aspects of conventional UK strategic variable-demand forecasting can reproduce the observed response to urban rail expansion and where limitations remain.

1.6 Paper Organisation

The remainder of this paper is organised as follows: Section 2 critically reviews conventional strategic passenger demand forecasting, with particular attention to UK variable demand modelling practice, passenger responses to urban rail network expansion, evidence on forecast accuracy and approaches to evaluating forecasting performance beyond aggregate patronage.
Section 3 introduces Manchester Metrolink Phase 3, the four expansion corridors and the historical forecast and observed patronage evidence used in the empirical analysis. Section 4 presents the empirical evaluation design, Section 5 presents the empirical results, Section 6 discusses the findings in relation to previous research on strategic demand forecasting and finally Section 7 concludes by

summarising the principal findings, limitation and implication for future passenger demand forecasting and empirical evaluation of urban rail network expansion.

2. Literature review

2.1 UK Strategic Variable Demand Forecasting under Network Change

Strategic transport-demand models are widely used to assess how travel may respond to changes in population, land use, transport supply and accessibility. The conventional four-stage framework has provided an important foundation for this practice, separating travel-demand estimation into trip generation, trip distribution, mode choice and network assignment. Bates traces the development of this approach to metropolitan transport studies undertaken from the 1950s, while McNally describes the four-stage model as the historically dominant framework for person-travel demand modelling.[8,9] Contemporary models may connect these stages differently, but the underlying structure remains influential in strategic forecasting.[10]

A major strength of the framework is its ability to represent complex transport systems through a structured sequence of travel decisions. Its sequential form, however, can also limit the interaction between those decisions. McNally notes that feedback between distribution, mode choice and assignment has varied considerably between applications, while McNally and Rindt argue that trip-based approaches simplify the behavioural processes that generate travel.[9,11] The issue is not that the conventional framework is unsuitable for strategic forecasting, but that its performance depends on how behavioural responses and feedback mechanisms are represented.

UK variable-demand modelling was developed partly to address this limitation. Department for Transport, Transport Analysis Guidance (TAG) recognises that changes in transport conditions can influence trip frequency, time period, destination choice and mode choice[2]. Frameworks such as DIADEM link changes in network conditions to these demand responses using an incremental modelling structure.[12] The demand matrix is consequently allowed to respond to changes in accessibility instead of remaining completely fixed.

This capability is particularly relevant to urban rail expansion. New infrastructure can reduce public transport travel times, create new connections and alter the accessibility of destinations. These changes may influence whether public transport is chosen, where passengers travel and which services they use once they enter the network. Public transport assignment then determines how this changing demand is distributed across routes and services.[2,13]

Greater behavioural responsiveness does not remove uncertainty from forecasting. Model outcomes remain sensitive to input assumptions, network representation and behavioural parameters. TAG consequently places considerable emphasis on calibration, validation, realism testing and fitness for purpose[2]. Parameters transferred from guidance or other models also require careful consideration because a model that represents existing travel patterns adequately may still respond incorrectly when network conditions change.

The literature consequently presents conventional UK strategic variable-demand modelling as an established and structured approach for representing demand response, while also showing that its behaviour under substantial network change cannot be assumed to be accurate simply because the model follows accepted practice. The relevant empirical question is how well such a framework reproduces the demand response that is subsequently observed.

2.2 Passenger demand response to urban rail network expansion

Urban rail expansion can influence passenger demand through several mechanisms. New lines and extensions may attract travellers from private cars, draw passengers from existing public transport

services, alter destination choices and change routes through the wider network. An increase in tram or metro patronage can consequently contain several different forms of behavioural response.

Evidence from Manchester demonstrates this complexity. Knowles found that Manchester Metrolink Phase 1 attracted more passengers than originally forecast and produced stronger switching from car than expected.[14] Senior's longer-term analysis also identified changes in both light-rail and bus use following Phase 1, with Metrolink attracting former car and bus users.[15] Taken together, these studies suggest that Metrolink growth can contain both mode shift from private transport and redistribution from existing public transport.

Studies in other cities show that the balance between these responses is highly context dependent. Sohoni, Thomas and Rao reported that approximately 80% of surveyed Mumbai Metro passengers had previously used public transport.[16] This indicates substantial redistribution within the public transport market. Liu and Li similarly found that subway openings across Chinese cities were associated with reductions in bus passenger demand as well as changes in other transport modes.[17] These findings differ from the stronger car-switching evidence reported for Manchester and demonstrate that there is no single composition of demand response that applies across urban rail systems.

Some schemes also show evidence of wider growth in public transport use. Werner et al. identified increased public transport use following a light-rail extension in Salt Lake City that could not be explained solely by displacement from nearby bus services[18]. However, the extension formed part of a wider complete-street redevelopment, making it difficult to isolate the effect of light rail alone. The study is useful because it shows that additional public transport demand is possible, while also demonstrating the difficulty of attributing observed change to one intervention.

The spatial response to expansion can also extend beyond the immediate area around new infrastructure. Yang et al. found that expansion of the Xi'an Metro produced different changes in metro use among residents at different distances from stations[19]. The authors linked these differences partly to employment accessibility and first- and last-mile connections. The result challenges a simple assumption that the strongest demand response must occur closest to new stations.

Network effects can be similarly widespread. Ye et al. modelled passenger-flow changes associated with new lines in Shanghai and showed redistribution across both new and existing sections of the urban rail network[20]. Although these estimates are model-based, they demonstrate that expansion can change the use of existing infrastructure as well as generate patronage on newly opened sections.

Passenger response may also develop over time. Shinn and Voulgaris found considerable variation in ridership development during the first years following the opening of US urban transit projects[21]. Sperry and Dye similarly identified a multi-year adjustment period for a new passenger rail station, although the intercity context limits direct transfer of the specific timescale to urban rail[22]. These studies indicate that the observed demand response depends partly on when post-opening performance is measured.

Across these studies, no single response dominates. Manchester provides evidence of both car and bus switching, Mumbai indicates strong transfer from existing public transport, Chinese evidence shows simultaneous effects across several modes, and other studies demonstrate spatial, network and temporal variation. Urban rail patronage growth should consequently not be treated as synonymous with equivalent growth in total public transport demand.

For the present analysis, the key implication is that expansion should be examined through separate measures of total public transport demand, destination redistribution, mode switching and network redistribution. This allows the analysis to distinguish growth in represented public transport demand from changes in how existing demand uses the expanded system.

2.3 Forecast Accuracy and Sources of Forecasting Error

A substantial body of ex-post research has examined differences between passenger-demand forecasts and observed outcomes. Pickrell's early assessment of US fixed-guideway projects identified large discrepancies between forecast and realised ridership and drew attention to the assumptions underlying project forecasts[3]. The study established the importance of testing forecasts against post-opening evidence, although its small and historically specific sample limits direct comparison with contemporary urban rail forecasting.

Flyvbjerg, Holm and Buhl later reported substantial passenger-demand overestimation across many rail projects in a larger international sample.[4] Their findings strengthened concerns about forecast optimism, but the sample combined different rail systems, countries, forecasting methods and institutional settings. The evidence demonstrates that large errors can occur; it does not establish that all urban rail forecasts fail systematically or to the same degree.

Nicolaisen and Driscoll provide an important qualification to these findings.[5] Their review shows substantial differences between ex-post studies in project selection, available data and error measurement. More importantly, they emphasise that an aggregate difference between forecast and observed demand does not reveal the cause of that difference. Forecast error may arise from inaccurate socioeconomic assumptions, service characteristics, behavioural representation, model specification, external events or combinations of these factors.

More recent evidence suggests that forecasting performance also varies over time. Hoque et al. examined 164 large public transport infrastructure projects in the United States and found observed ridership to be 24.6% below forecast on average.[6] Projects forecast from 2000 onwards performed better than earlier projects, while accuracy also varied with transport mode, service-area characteristics, ramp-up and forecast horizon. Their findings suggest that overestimation remains important but should not be treated as a fixed characteristic of public transport forecasting.

Project-level analysis provides further insight into the sources of error. Sanko, Morikawa and Nagamatsu examined an overestimate for the Tokadai Line in Japan and identified several contributing factors, including population assumptions, modal split, treatment of a competing railway, mode-choice specification and incomplete network representation[23]. The importance of this case lies in the interaction between these factors. The final patronage discrepancy could not be attributed solely to either the forecasting model or its inputs.

The literature also differs in how it interprets persistent forecast error. Some studies emphasise institutional or decision-making pressures surrounding major transport investment, while others focus more strongly on demographic, economic, behavioural and modelling uncertainty.[4,5] These explanations are not mutually exclusive, and the available ex-post evidence often cannot separate their individual contributions with confidence.

This distinction is particularly relevant to Manchester Phase 3. TfGM's later evaluation adjusted expected patronage using realised information on factors including service characteristics, economic conditions and development assumptions[7]. These adjustments brought expected demand closer to observed patronage on several corridors, indicating that differences between forecast assumptions and realised conditions were important. The adjustment does not establish that assumptions explain the entire forecast error, since remaining discrepancies may still reflect local behavioural conditions, network representation or model limitations.

The conclusion is that forecast error and model error are not equivalent concepts. Forecast outcomes reflect both the forecasting framework and the assumptions applied to it. An observed forecast outturn difference establishes that expected demand did not materialise, but additional analysis is required before conclusions can be drawn about why the discrepancy occurred.

2.4 Evaluating forecast error beyond aggregate patronage

Accurately forecasting the overall level of passenger demand remains important because it affects expected benefits, revenues, operating requirements and the wider investment case. However, comparing total forecast and observed patronage captures only one aspect of forecasting performance.

A model may overestimate total demand while reproducing the relative geographical distribution of passengers reasonably well. Another model may produce an aggregate total close to the observed value while allocating demand incorrectly between corridors or services. These errors have different implications. Errors in overall demand affect expected system use and benefits, while spatial errors can influence station demand, corridor loading, interchange requirements and capacity planning.

Transport-model validation guidance reflects this distinction. UK TAG requires models to be calibrated and validated for their intended purpose and treats demand modelling and public transport assignment as separate but connected components[2,13]. Public transport assignment validation can use station entries and exits, boardings, alightings and passenger counts to examine how passengers are distributed through the network. These measures provide information that cannot be obtained from an aggregate demand total alone.

There is also an important difference between reproducing existing travel conditions and reproducing change. Rodier argues that stronger validation requires comparison with observations that were not used during model development.[24] A model may fit its base year closely without responding correctly when socioeconomic or network conditions change. For network-expansion analysis, the model's response to change is consequently at least as important as its ability to reproduce an existing state.

Related studies have extended post-opening evaluation beyond aggregate demand. Cartenì et al. assessed the forecasting performance of transport models following rail network changes in the Campania region[25], while more recent work in Amsterdam has examined both observed passenger redistribution after a new metro line and the external validation of public transport route-choice models under changed network conditions[26]. These studies demonstrate the value of evaluating models against spatial and network outcomes after infrastructure change. However, they focus on particular components of forecasting performance, such as route choice, observed redistribution or forecast-outturn differences, leaving limited evidence on how an integrated conventional variable-demand framework performs across demand scale, spatial allocation and network redistribution simultaneously.

This distinction leads to two separate dimensions of performance. Demand scale concerns the overall amount of passenger demand, while spatial structure concerns where that demand is distributed across the network. The two need not perform equally well.

For urban rail expansion, this separation is especially important because the evidence reviewed in Section 2.2 shows that substantial changes in tram or metro use can occur through redistribution within the public transport system. A model can consequently reproduce important spatial or network responses even when its absolute demand scale differs from observed annual patronage.

The implication for empirical evaluation is that aggregate forecast-outturn comparison should be complemented by measures of spatial and network performance. Corridor shares, network-use indicators and residual spatial diagnostics can reveal whether a forecasting framework reproduces the geography and distribution of passenger response once differences in overall scale are recognised.

2.5 Literature Synthesis and Research Gap

The literature reviewed above has four findings that shape the empirical analysis of this study recorded in **Table 1** below.

Literature theme	What is established	What remains unresolved	Response in this study

UK strategic variable-demand forecasting	Conventional and TAG-informed frameworks can represent changes in destination choice, mode choice and network use following changes in accessibility.	Following recognised modelling practice does not demonstrate that the resulting response matches realised behaviour after major network expansion.	A retrospective TAG-informed conventional UK strategic variable-demand model is tested against post-expansion evidence.
Passenger response to urban rail expansion	Expansion can produce mode switching, public transport redistribution, spatial change and network-wide effects. The balance differs between systems.	Urban rail patronage alone does not reveal how much change reflects additional PT demand and how much reflects redistribution of existing demand.	The DM–DS analysis separates total represented PT demand, destination redistribution, mode switching and network redistribution.
Forecast accuracy and sources of error	Forecast-outturn discrepancies can be substantial and can arise from assumptions, external conditions and model structure.	Aggregate error cannot identify which source produced the discrepancy.	Original Phase 3 forecasts are compared with observed patronage, while TfGM's adjusted evidence is used cautiously to interpret possible sources of difference.
Forecast validation	Model validation can be conducted at aggregate, spatial and network levels, and performance at one level does not guarantee performance at another.	There is limited ex-post evidence combining historical forecast accuracy with spatial and network validation following completed urban rail expansion.	Observed corridor shares are compared with both the original forecast and the retrospective model, followed by scale and residual-error diagnostics.

Table 1 Summary of Reviewed literature and gaps

The literature consequently identifies a specific gap. Existing studies have examined forecast-outturn error, transport-model validation and the spatial and network effects of urban rail expansion, but these strands have largely been considered separately. Limited empirical evidence evaluates a completed urban rail expansion using a conventional strategic variable-demand framework while distinguishing aggregate demand scale from spatial allocation and examining destination, mode and public transport network redistribution within the same analysis. This study addresses this gap through the retrospective evaluation of Manchester Metrolink Phase 3.

Manchester Metrolink Phase 3 provides an opportunity to examine this issue using three complementary forms of evidence: the original passenger-demand forecast, observed post-expansion patronage and a retrospective model developed for this study. This allows forecasting performance to be examined across aggregate demand scale, spatial allocation, behavioural response and public transport network redistribution.

3. Manchester Metrolink Phase 3 Case Study

3.1 Phase 3 Network Expansion and Corridor Characteristics

Manchester Metrolink is the light-rail system serving Greater Manchester. The network has expanded incrementally since its initial opening, with the Phase 3 programme representing a major stage in its development. Phase 3 extended the network to Ashton-under-Lyne, East Didsbury, Manchester Airport, and Oldham and Rochdale[7] as shown in figure 1.

The four corridors differed in both infrastructure type and network context. The Ashton extension completed the East Manchester corridor from Droylsden to Ashton-under-Lyne in October 2013.[27] The East Didsbury extension continued the South Manchester line from St Werburgh's Road through Didsbury and opened fully on 23 May 2013.[28] The Airport line created a new branch through Wythenshawe to Manchester Airport and opened in November 2014.[27]
The Oldham and Rochdale corridor differed from the other Phase 3 extensions because it involved conversion of the former heavy-rail Oldham Loop as well as new street-running sections through Oldham and Rochdale town centres. Services were introduced progressively, with the final town-centre sections completed in 2014[7,27]. This previous heavy-rail provision makes the corridor analytically different from extensions that introduced Metrolink into areas without an equivalent predecessor service.

The corridors also occupy different positions within the wider Metrolink network. East Didsbury and the Airport line share part of the southern network before separating, Ashton extends eastwards from the established network, and Oldham and Rochdale combine conversion and extension within the north-eastern part of the system. These differences provide variation in network context within a single metropolitan transport system.

For consistency with TfGM's Phase 3 monitoring and evaluation, the present study uses these four extensions as the units of corridor-level analysis.[25] Other infrastructure delivered as part of the wider development of Metrolink, including the Second City Crossing, is not treated as a separate patronage corridor in the empirical comparison.

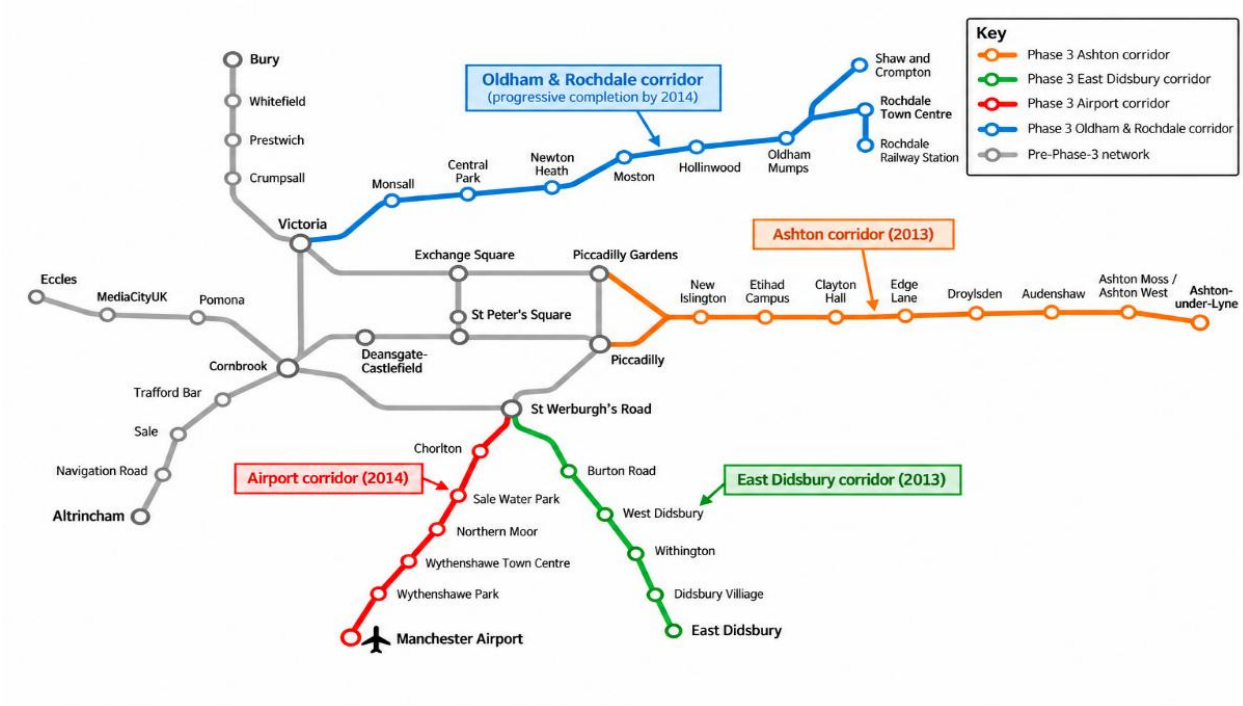


Figure 1. Manchester Metrolink network and Phase 3 corridors used in this study[7,29].

3.2 Original Forecast and Observed Patronage Evidence
Transport for Greater Manchester's Phase 3 monitoring and evaluation report provides both the original expected 2018 passenger demand and observed 2018/19 patronage for the four Phase 3 corridors[7]. These values form the historical evidence used to evaluate the original forecast in this study.

Corridor	Principal Phase 3 intervention	Opening/Completion used in this study	Original expected 2018 demand(million journeys)	Observed 2018/19 patronage (million journeys)
Ashton	Extension of East Manchester line to Ashton-under-Lyne	2013	5.52	3.10
Airport	New branch through Wythenshawe to Manchester Airport	2014	5.73	3.44
East Didsbury	Extension of South Manchester line to East Didsbury	2013	6.47	5.90
Oldham and Rochdale	Conversion/extension of former heavy-rail corridor with town-centre sections	2014*	10.05	6.85
Total			**27.77**	**19.29**

Table 2. Characteristics of the Phase 3 corridors used in this study

**The Oldham and Rochdale corridor opened progressively, with the final town centre sections completed in 2014.*

The figures in Table 2 are retained here as the empirical evidence base. The magnitude and spatial distribution of the forecast-outturn differences are analysed in Section 5.1, where the original forecast is evaluated against observed patronage.

TfGM's later evaluation also produced adjusted expected demand values using information that became available after the original forecast, including realised service, economic and development conditions[7]. These adjusted values are not independent forecasts and are not used as an alternative predictive benchmark in this study. They are used later as diagnostic evidence when interpreting possible reasons for the difference between original expected and observed patronage.

3.3 Empirical Suitability of the Phase 3 Case

Manchester Metrolink Phase 3 provides a useful empirical setting for evaluating strategic passenger-demand forecasting for several reasons.

First, the programme contains four expansion corridors within the same metropolitan transport system. This provides variation in realised passenger outcomes while limiting differences in the wider regional context that would arise from comparing unrelated urban rail systems.

Second, the four corridors represent different forms of network expansion. They include conventional extensions, a new branch and the conversion of a former heavy-rail corridor. The case consequently allows forecasting performance to be examined across different network contexts within the same system.

Third, TfGM provides a relatively detailed combination of original forecast information, observed post-opening patronage and subsequent monitoring evidence[7]. This enables the historical forecast to be evaluated against realised demand and provides additional evidence for interpreting the observed differences.

Fourth, 2018/19 provides a well-established post-opening observation period for all four corridors and precedes the major disruption to public transport demand associated with the COVID-19 pandemic. By this stage, each Phase 3 corridor had been operational for approximately four to six years, reducing the likelihood that the comparison reflects only the initial months of passenger adjustment.

Finally, the availability of corridor-specific patronage allows forecasting performance to be examined at both the overall and spatial levels. The four-corridor structure provides the basis for comparing the

geographical distribution implied by the original forecast with observed demand and, later, with the spatial distribution generated by the retrospective TAG-informed model.

4. Methods

4.1 Empirical evaluation and Modelling framework

The empirical analysis uses a retrospective TAG-informed conventional UK strategic variable-demand model to examine the passenger-demand response associated with Manchester Metrolink Phase 3. The model follows the conventional four-stage structure of trip generation, trip distribution, mode choice and public transport assignment, with accessibility-responsive destination-choice feedback incorporated into the trip-distribution process. The framework is informed by UK Department for Transport, Transport Analysis Guidance (TAG), particularly guidance on variable-demand modelling, public transport assignment and strategic model development[2,13,30].

Figure 2 presents the modelling sequence. Stage 1 establishes 2018 home-based-work morning-peak trip ends. Stage 2 establishes the base origin-destination demand matrix. Two alternative 2018 public transport networks are then constructed: a **Without-Phase-3 Scenario (DM)** and a **With-Phase-3 Scenario (DS)**. Public transport impedance is calculated separately for the two networks, and the resulting accessibility change feeds into Stage 3 mode choice and destination-choice feedback. Updated public transport demand is subsequently assigned to the respective networks in Stage 4.

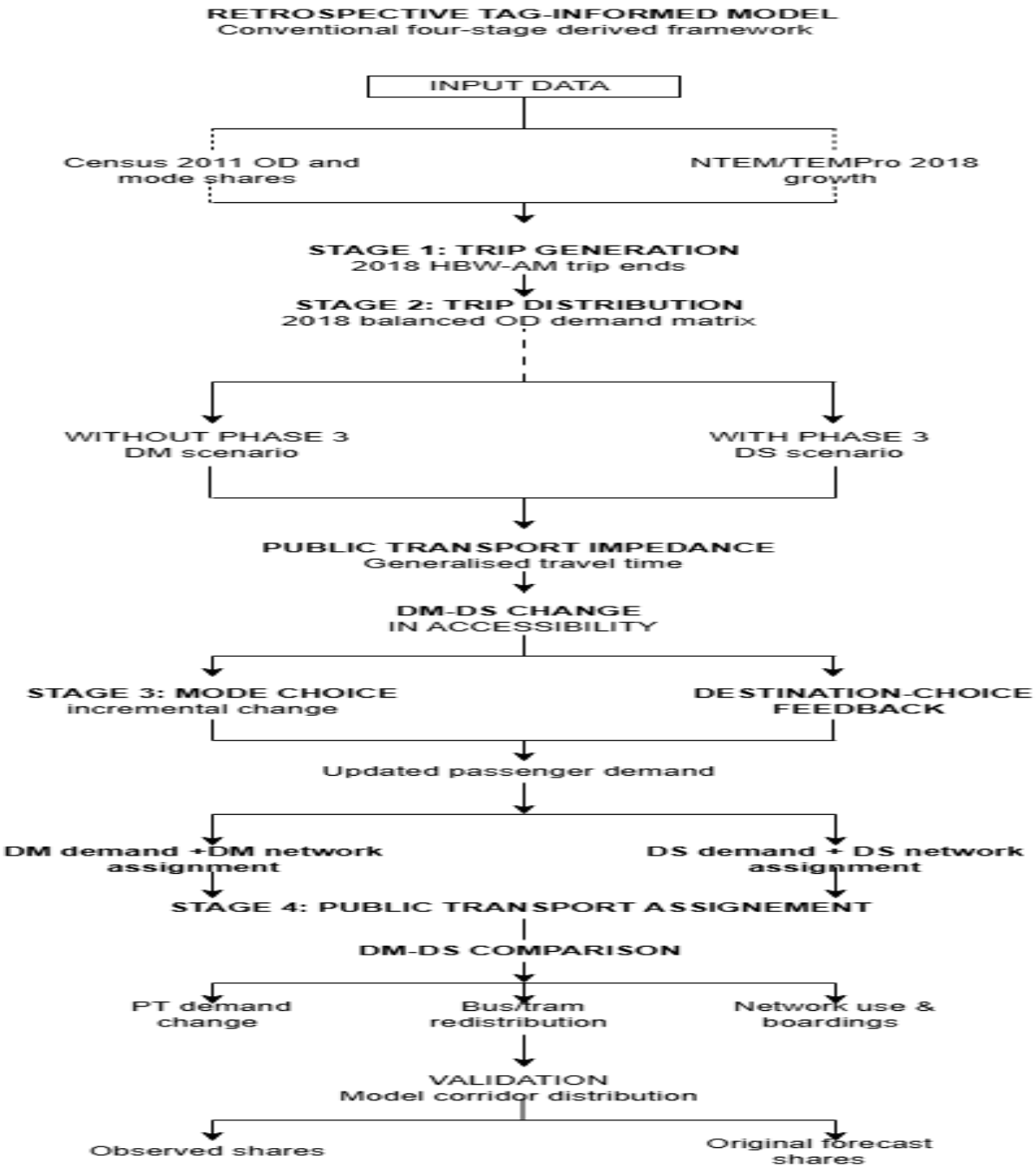


Figure 2. Retrospective TAG- informed strategic variable demand modelling framework

Stage 1 establishes 2018 HBW-AM trip ends and Stage 2 establishes the balanced OD demand matrix. The Without-Phase-3 and With-Phase-3 networks are used to calculate changes in public transport impedance and accessibility. These changes feed into Stage 3 incremental mode choice and destination-choice feedback to Stage 2. Updated demand is then assigned to the networks in Stage 4 before demand and network responses are evaluated.

The principal model inputs are summarised in Table 3. The detailed analysis focuses on home-based work travel during the morning peak (HBW-AM).

Model component	**Data/source**	**Role**
Base commuting demand	2011 Census WU03EW	Base OD commuting pattern and observed travel-to-work mode information

Future trip-end growth	NTEM Version 8.0 / TEMPro	Growth of productions and attractions from 2011 to 2018
Public transport network	Historical TfGM GTFS	Representation of bus and Metrolink services
Walking network	OpenStreetMap	Pedestrian access and transfer routing
Public transport routing	OpenTripPlanner 1.5	Journey times, walking, waiting, transfers and itineraries
Behavioural parameters	DfT TAG Unit M2.1	Mode- and destination-choice sensitivities
Public transport impedance assumptions	DfT TAG Unit M3.2	Generalised-time weights and interchange penalties

Table 3. Principal inputs to the retrospective model.

Stage 1: Trip generation and Base Demand

Stage 1 establishes the 2018 level of HBW-AM travel before the Phase 3 network intervention is introduced. The observed base travel pattern was obtained from the 2011 Census WU03EW origin-destination dataset, which records commuting movements between usual residence and workplace at Middle Layer Super Output Area level and distinguishes method of travel to work.[31] The initial processing covered 346 MSOAs within Greater Manchester.

Growth from 2011 to 2018 was derived from the Department for Transport's National Trip End Model Version 8.0 Core Scenario, accessed through TEMPro[32]. Initial processing covered 15 journey purposes and four time periods before the detailed empirical analysis was restricted to HBW travel during the morning peak.

The NTEM growth represents background demographic and socioeconomic change. The outputs from Stage 1 are the 2018 origin productions and destination attractions used in the trip-distribution stage.

Stage 2: Trip distribution

Stage 2 establishes the spatial distribution of the HBW-AM trips generated in Stage 1. The 2011 Census commuting matrix provides the initial origin-destination structure. This matrix was adjusted to the 2018 NTEM production and attraction totals using iterative proportional fitting. This retains the observed commuting structure as far as possible while ensuring consistency with the 2018 trip ends.

A gravity-model specification was calibrated against the observed commuting matrix as an additional diagnostic of spatial interaction:

$$f(c_{ij}) = \exp(-\beta c_{ij})$$

Where: c_{ij} is travel impedance between origin i and destination j, β is impedance parameter, and $f(c_{ij})$ the impedance-decay function used in the gravity model.

The calibrated value was: $\beta = 0.254$. The corresponding Common Part of Commuters statistic (CPC) was: $CPC = 0.7612$.

The gravity model was used to assess the representation of spatial interaction. The expansion experiment retained the observed and 2018-balanced OD structure as the starting demand matrix. Destination-choice feedback is introduced later, after the accessibility difference between the two network scenarios has been calculated.

Without-Phase 3 and With-Phase 3 Network Scenarios

Two controlled 2018 public transport network networks were constructed (Table 4).

The **Without-Phase-3 Scenario (Do-Minimum, DM)** represents the 2018 public transport network with the Phase 3 Metrolink infrastructure and services removed.
The **With-Phase-3 Scenario (Do-Something, DS)** represents the corresponding 2018 public transport network with the Phase 3 extensions included.

Scenario	Network representation	Function
Without Phase 3 (DM)	2018 background bus and established Metrolink network with Phase 3 removed	Counterfactual network
With Phase 3 (DS)	Corresponding 2018 bus and Metrolink network with Phase 3 included	Expansion network

Table 4. Network scenarios used in the retrospective modelling experiment.

The DM and DS scenarios use the same 2018 trip ends and socioeconomic conditions. Their principal difference is the absence or presence of the Phase 3 infrastructure and services.
Public transport supply was represented using historical TfGM General Transit Feed Specification data obtained from the Transitland archive[33]. The feed used in the analysis was valid between 19 July and 19 September 2018.
The DS network contains the represented 2018 bus and Metrolink system, including the Ashton, Airport, East Didsbury, and Oldham and Rochdale Phase 3 corridors. The DM network retains the same background bus network and established Metrolink services but removes the Phase 3 stops and services.

Oldham and Rochdale counterfactual
Oldham and Rochdale requires special counterfactual treatment because it is the only Phase 3 corridor in the study where Metrolink directly replaced an operational heavy-rail service that should, in principle, form part of the Without-Phase-3 alternative. The GTFS dataset used in this study does not include National Rail services, so the former heavy-rail service cannot be restored in the DM network.
Removing Phase 3 without restoring the previous rail service would exaggerate the accessibility improvement attributed to the Metrolink conversion. The primary specification consequently suppresses Oldham and Rochdale-related accessibility effects within the destination-choice feedback mechanism.
A second specification permits accessibility changes from all four Phase 3 corridors and is used as a sensitivity test. The conservative specification is used for the headline analysis.

Public Transport Impedance and Accessibility Change
Public transport routing was undertaken separately for the Without-Phase-3 (DM) and With-Phase-3 (DS) networks using OpenTripPlanner version 1.5[34], combining the historical GTFS services with an OpenStreetMap pedestrian network[35].

Six departure times were sampled during the morning peak:

07:00, 07:30, 08:00, 08:30, 09:00 and 09:30.

Sampling multiple departure times allows variation in scheduled public transport services across the morning peak to be represented without requiring every possible departure time to be modelled.

For each OD pair and network scenario, public transport impedance was expressed as generalised time:

$$GT_{ij} = T_{ij}^{transit} + 1.75T_{ij}^{walk} + 2.0\left(T_{ij}^{initial\,wait} + T_{ij}^{transfer\,wait}\right) + 6N_{ij}^{transfers} \quad (1)$$

Where i is the origin zone and j is the destination zone, $T^{transit}$ represents in-vehicle time, T^{walk} represents walking time, $T^{initial\,wait}$ and $T^{transfer\,wait}$ represent waiting times and $N^{transfers}$

represents the number of transfers. The walking-time multiplier of 1.75, waiting-time multiplier of 2.0 and six-minute transfer penalty were selected within the indicative ranges reported in TAG Unit M3.2[13]. Generalised time representations that assign additional disutility to walking, waiting and interchange are consistent with conventional public transport assignment practice. The formulation recognises that passengers typically perceive time spent walking, waiting or transferring as more burdensome than the same amount of time spent travelling on board a service.

For the purposes of this study, the improvement in public transport impedance associated with Phase 3 was defined for each OD pair as:

$$s_{ij} = GT_{ij}^{DM} - GT_{ij}^{DS}. \qquad (2)$$

Where GT_{ij}^{DM} is the generalised time for OD pair ij in the Without-Phase-3 network (DM), and GT_{ij}^{DS} is the generalised time for the same OD pair in the With-Phase-3 network (DS).

A positive value of s_{ij} indicated that Phase 3 reduced the generalised public transport time between that origin and destination. A value close to zero indicates little change in represented public transport accessibility between the two scenarios.

Fare differences were not included in the DM-DS impedance change, and car impedance was held constant. A specific counterfactual issue arose for the Oldham and Rochdale corridor. The available GTFS datasets did not contain National Rail services, so the former Oldham Loop heavy-rail service could not be restored in the DM scenario. Removing Phase 3 without restoring its predecessor would overstate the accessibility improvement associated with the Metrolink intervention. The primary specification suppresses Oldham and Rochdale-related accessibility effects within the destination-choice feedback mechanism. A full-accessibility specification allows changes from all four corridors to influence destination choice. The primary specification is used for the headline results because it provides the more conservative counterfactual.

Stage 3: Incremental mode choice and Destination-Choice Feedback

The third conventional modelling stage estimated whether the improvement in public transport accessibility changed the probability that a journey would use represented public transport. An incremental pivot formulation was used in this stage, instead of estimating absolute future mode shares from a newly calibrated mode-choice model. This preserves the observed base mode share, and models only the change resulting from the difference between DM and DS public transport conditions, consistent with incremental approaches used in variable demand forecasting[2].

For OD pair ij, the post intervention represented- PT share was calculated as:

$$p_{1,ij} = \frac{p_{0,ij}\exp(\beta s_{ij})}{(1 - p_{0,ij}) + p_{0,ij}\exp(\beta s_{ij})}, \qquad (3)$$

Where $p_{0,ij}$ is the base represented public transport share, s_{ij} is the improvement in the public transport generalised time and β is the mode choice sensitivity parameter. The central specification was

$$\beta_m = 0.0231 \text{ min}^{-1}$$

with lower and higher sensitivity specifications used to examine parameter uncertainty.

The coefficient was derived from: $\beta_m = \lambda\theta$

Where λ is the destination-choice sensitivity parameter and θ is the main-mode scaling parameter.

For the central specification: $\lambda = 0.033$ and $\theta = 0.70$

Giving: $\beta_m = 0.033 \times 0.70 = 0.0231 \text{ min}^{-1}$

Lower and upper sensitivity specifications were also used to examine parameter uncertainty.

Parameter	Lower	Central	Upper
Destination-choice sensitivity, λ	0.023	0.033	0.043
Main-mode scaling parameter, θ	0.51	0.70	0.83

Table 5. TAG-informed behavioural parameters used in the retrospective model.

These values shown in Table 5 are benchmark parameters informed by TAG Unit M2.1. Their use allows the study to evaluate the behaviour of a conventional TAG-informed specification without retrospectively recalibrating the parameters to improve agreement with observed Phase 3 demand.
The represented public transport market comprises bus and Metrolink. National Rail is not included within the network assignment and is treated as background. Car impedance remains fixed between the DM and DS scenarios.

The strict pivot formulation creates an important structural limitation. If the observed represented-public-transport share for an OD pair is zero, Equation (3) necessarily produces a With-Phase-3 represented-public-transport share of zero. The model cannot create represented-public-transport demand in OD markets where the base represented-public-transport share is zero, regardless of the size of the accessibility improvement.

This limitation is retained explicitly because identifying the strengths and weaknesses of the conventional modelling framework is part of the retrospective evaluation.

Variable-demand destination-choice feedback
Although destination choice corresponds conceptually to the trip-distribution stage, it is presented here because it operates as a feedback mechanism after the difference between DM and DS accessibility has been calculated. The change in composite public transport accessibility generated by the DM-DS comparison was calculated from the incremental mode-choice logsum as described in TAG unit M2.1: For each OD-pair:

$$\Delta LS_{ij} = \frac{\ln\left[\left(1 - p_{0,ij}\right) + p_{0,ij}\exp\left(\beta s_{ij}\right)\right]}{\beta}. \qquad (4)$$

Where ΔLS_{ij} represents the change in composite accessibility for OD pair ij, expressed in minutes.

The logsum captures more than the change in public transport travel time alone. It combines the accessibility improvement with the existing probability of using represented public transport. An OD pair with both a meaningful public transport base share and a substantial improvement in public transport conditions consequently produces a larger composite accessibility response than an OD pair in which public transport has little existing presence.

The accessibility change was incorporated into destination choice using the incremental logit formulation set out in TAG Unit M2.1. Expressing the change in destination utility as the product of the destination-choice sensitivity parameter λ and the accessibility change in equivalent generalised minutes ΔLSij gives the following multiplicative adjustment to each origin-destination movement:

$$M_{ij} = \exp\left(\lambda \Delta LS_{ij}\right), \qquad (5)$$

Where M_{ij} is the destination attractiveness multiplier. A central value of λ = 0.033 was adopted for public transport home-based-work trips, with 0.023 and 0.043 used for lower and upper sensitivity testing respectively, corresponding to the minimum, median and maximum illustrative values reported in TAG Unit M2.1.

Because the implemented accessibility signal is non-negative, the unconstrained destination -choice multiplier satisfies: $M_{ij} \geq 1$

For the represented OD pairs. A value of: $M_{ij} = 1$, indicates no accessibility driven adjustment to that OD movement, while: $M_{ij} > 1$ indicates that the OD movement receives an upward accessibility adjustment before the matrix is rebalanced.

The multiplier was applied to the 2018 balanced OD matrix. Iterative proportional fitting was then used to restore the fixed 2018 production and attraction totals. This step allows the accessibility improvement produced by the network expansion to alter where existing HBW trips are distributed, while maintaining the overall number of trip origins and destinations established in Stage 1.

The destination-choice component does not generate new trip ends. Any resulting change in represented public transport demand arises from the interaction between the redistributed OD pattern and the mode-choice response.

Stage 4: Public transport assignment

The fourth stage assigned represented public transport demand to the DM and DS networks. For each OD pair, OpenTripPlanner identifies usable public transport itineraries across the six sampled morning-peak departure times. Demand is divided equally across the selected feasible itineraries. The assignment provides a deterministic schedule-based representation of route choice. It does not represent a fully stochastic route-choice model in which passengers select between alternatives according to estimated route-choice probabilities.

The DM demand matrix is assigned to the Without-Phase-3 network, while the updated DS demand matrix is assigned to the With-Phase-3 network. Comparing the two assignments allows the analysis to identify changes in the amount and distribution of represented public transport demand after Phase 3 is introduced.

Intrazonal movements and external-zone journeys are retained in the wider demand matrices but are excluded from detailed public transport network loading where a meaningful network path cannot be represented. One small unrouteable OD residual is also excluded from the final assignment totals.

Three separate measures of passenger movement are retained because they represent different aspects of network use (Table 6).

Measure	**Definition**
Person journey	A complete public transport journey from origin to destination
Boarding	One passenger boarding one public transport service or vehicle leg
Passenger segment	One passenger travelling across one stop-to-stop network section

Table 6. Passenger-movement measures retained from public transport assignment.

A single person journey may generate more than one boarding where a passenger transfers between services. The same journey may also generate several passenger segments as the passenger travels across successive stop-to-stop sections.

These distinctions are important when interpreting the effects of network expansion. An increase in tram boardings does not necessarily represent an equivalent increase in the number of public transport journeys. A passenger who previously travelled entirely by bus may use a combination of bus and tram after Phase 3 while still making only one complete person journey.

The assignment results are consequently examined at both the person-journey and network-use levels.

4.2 Demand- Response Decomposition

The difference between the DM and DS model outputs is decomposed into three forms of passenger-demand response: destination redistribution, mode switching and public transport network redistribution.

Destination redistribution

Destination redistribution represents changes in the allocation of existing HBW trips between destinations following changes in relative accessibility.
Because productions and attractions remain constrained, this component should not be interpreted as newly generated travel. It represents changes in where existing trips are allocated within the model.

Mode switching
Mode switching represents changes in the proportion of the relevant travel market using the represented bus and Metrolink public transport system.
The direct mode-choice response is obtained through Equation (3), while the destination redistribution generated through Equations (4) and (5) can subsequently alter the amount of represented public transport demand because trips are redistributed between OD markets with different public transport shares and accessibility conditions.

The resulting change in total represented public transport demand is consequently a combined mode-choice and destination-choice response.

Public transport network redistribution
Public transport network redistribution represents changes in the services, modes and paths used once journeys enter the represented public transport system.
The analysis in this study reports:

- total represented public transport person journeys;
- destination-redistributed HBW trips;
- bus-only journeys;
- tram-using journeys;
- tram boardings; and
- tram passenger-segment loads.

This distinction makes it possible to determine whether Phase 3 primarily changes the overall amount of represented public transport demand or changes how existing public transport demand is distributed across destinations, modes and network paths.

4.3 Validation framework and Evaluation Metrics
The empirical evaluation distinguishes between the historical performance of the original Phase 3 forecast and the performance of the retrospective model.
This distinction is necessary because the two demand representations are different. The original TfGM forecast and observed patronage represent annual all-purpose passenger journeys. The retrospective model represents HBW travel during the morning peak. Absolute retrospective-model demand is consequently not treated as an alternative annual patronage forecast.

Historical forecast accuracy
The original Phase 3 forecast and observed 2018/19 patronage can be compared directly because both are expressed as annual passenger journeys.

For corridor i, the percentage forecast-outturn difference is calculated as:

$$E_i = \frac{O_i - F_i}{F_i} \times 100 \qquad (6)$$

Where F_i is the original forecast patronage and O_i is the observed patronage. A negative value indicates that observed patronage was below original forecast, while a positive value indicates observed patronage above forecast. The same calculation is applied to all four individual Phase 3 corridors and to total patronage.

Spatial validation of the retrospective model

Because the retrospective model and the observed patronage data differ in temporal and journey-purpose coverage, validation of the retrospective model focuses on the relative spatial distribution of demand across the four Phase 3 corridors.

For corridor i, the corridor demand share is calculated as:

$$S_i = \frac{Q_i}{\sum_{j=1}^{4} Q_j} \quad (7)$$

Where Q_i is demand associated with corridor i. This converts each demand representation into a common four corridor spatial distribution. Three sets of shares are compared:

1. observed 2018/19 patronage shares;
2. corridor shares implied by the original Phase 3 forecast; and
3. corridor shares generated by retrospective model

Spatial performance is summarised using mean absolute error:

$$MAE = \frac{1}{n}\sum_{i=1}^{n}\left|S_i^{model} - S_i^{obs}\right| \quad (8)$$

And root mean squared error:

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(S_i^{model} - S_i^{obs}\right)^2} \quad (9)$$

Where $n = 4$ for the four Phase 3 corridors.

Both MAE and RMSE are reported in percentage points. MAE provides the average absolute difference between modelled and observed corridor shares, while RMSE gives greater weight to larger corridor-level discrepancies. Corridor ranking is also examined as an additional indication of whether the model reproduces the relative spatial ordering of demand.

Modelled tram-containing person journeys are associated with the individual Phase 3 corridors using their assigned network paths. Shared interface stops such as Firswood, Chorlton, St Werburgh's Road and Queens Road are not sufficient on their own to classify a journey because they serve multiple parts of the network.

Corridor classification therefore uses corridor-specific sections of the assigned journey path. Where a journey uses more than one Phase 3 corridor, its contribution is allocated fractionally between the relevant corridors to avoid double counting.

Scale and residual error diagnostics

A further diagnostic examines whether the difference between retrospective-model HBW-AM demand and observed annual patronage follows a broadly common proportional relationship across the four corridors.

For corridor i, the implied scale factor is:

$$k_i = \frac{O_i}{M_i} \quad (10)$$

Where O_i is the observed annual patronage and M_i is the corresponding retrospective model corridor demand.

If the k_i values are similar across corridors, this indicates that much of the difference between modelled and observed volumes may reflect a common difference in demand scale. Large variation between corridor specific scale factors would instead indicate stronger spatial disagreement.

A common total-preserving scale factor is calculated as:

$$k = \frac{\sum_i O_i}{\sum_i M_i} \quad (11)$$

The common factor preserves the observed total when applied to the modelled corridor volumes. This exercise does not convert the retrospective model into an annual passenger-demand forecast. Observed patronage is used to derive the scale factor, so the resulting scale-normalised comparison is an ex-post diagnostic of residual spatial mismatch.

A leave-one-corridor-out (LOO) diagnostic is also used to test whether each corridor follows the proportional relationship observed across the other three corridors.

For corridor i, the scale factor estimated from the remaining corridors is:

$$k_{-i} = \frac{\sum_{j \neq i} O_j}{\sum_{j \neq i} M_j} \qquad (12)$$

The excluded corridor is then predicted as:

$$\hat{O}_i = k_{-i} M_i \qquad (13)$$

Where $\hat{O}_i$ is the scale-predicted patronage for the excluded corridor. Comparing $\hat{O}_i$ and O_i identifies whether the excluded corridor behaves similarly to the relationship observed across the other three corridors. A large residual indicates a corridor-specific difference that cannot be explained by the common scale relationship alone.

Because observed patronage is used in deriving the scale factors in Equations (10)– (13), these measures are ex-post diagnostics only. They are not interpreted as ex-ante forecast-accuracy measures.

The complete evaluation framework is summarised in Table 7 below:

Evaluation question	Measure	Interpretation
How accurate was the original forecast?	Forecast-outturn difference (%)	Historical aggregate and corridor-specific forecast performance
What overall demand response does the retrospective model generate?	DM-DS change in represented PT demand	Change in total represented public transport demand
How much destination response occurs?	Redistributed HBW trips	Change in the spatial allocation of existing trips
How does mode use change?	Change in represented PT and bus/tram journey composition	Mode-choice response
How does network use change?	Tram-using journeys, boardings and passenger segments	Public transport network redistribution
Does the model reproduce observed spatial demand?	Corridor shares, MAE, RMSE and ranking	Spatial performance
Are remaining differences common or corridor-specific?	Scale factors and leave-one-corridor-out residuals	Residual scale and spatial mismatch

Table 7. Evaluation measures used in the empirical analysis

5. Results

5.1 Origin Phase 3 forecast performance

Observed 2018/19 patronage across the four Phase 3 corridors was 19.29 million passenger journeys, compared with the original forecast of 27.77 million. The outturn was therefore 8.48 million journeys below forecast, equivalent to a forecast-outturn difference of −30.54%.

The size of the difference varied considerably between corridors. East Didsbury was closest to its original forecast, with observed patronage 8.81% below forecast. The corresponding differences were 31.84% below forecast for Oldham and Rochdale, 39.97% for Airport and 43.84% for Ashton as shown in Table 8.

Corridor	Forecast-outturn difference (%)	Adjusted expected demand (million)	Actual minus adjusted expected (million)
Ashton	−43.84	2.89	+0.21
Airport	−39.97	3.04	+0.40
East Didsbury	−8.81	5.66	+0.24
Oldham and Rochdale	−31.84	8.46	−1.61
Total	**−30.54**	**20.05**	**−0.76**

Table 8. Original Phase 3 forecast performance and TfGM adjusted expected demand.

TfGM's adjusted expected values were closer to observed patronage on Ashton, Airport and East Didsbury. Actual patronage exceeded the adjusted values by 0.21 million, 0.40 million and 0.24 million journeys, respectively. Oldham and Rochdale remained the main exception, with observed patronage 1.61 million below the adjusted expected value.

These adjusted values are used only as diagnostic evidence because they incorporate factors identified after the scheme had opened. They are not treated as an alternative independent forecast.

5.2 Destination and mode choice response

The retrospective model generated a comparatively small increase in aggregate represented public transport demand (Metrolink + bus) between the DM and DS scenarios. DM represented public transport demand was 54,342.37 trips. The direct mode choice response added 457.63 trips, while destination-choice feedback contributed a further 275.55 trips. Combined DS demand was therefore 55,075.55 trips. Table 9gives the breakdown of the demand response.

Demand-response component	Change in represented PT trips
Direct mode-choice response	+457.63
Additional response following destination redistribution	+275.55
Combined response	**+733.18**
Combined change relative to DM	**+1.35%**

Table 9. Retrospective DM-DS represented public transport demand response.

The direct mode choice component accounted for approximately 62.4% of the combined increase, while the additional response following destination redistribution accounted for 37.6%.
Destination choice feedback redistributed approximately1646 HBW trips between OD movements in the primary specification, equivalent to around 0.42% of internal HBW trips. Because overall production and attraction totals remained fixed, these movements represent redistribution of existing trips rather than newly generated travel.
The full accessibility sensitivity specification produced larger redistribution approximately 2,460 HBW trips, or 0.63% of internal trips, compared with 1646 trips in the conservative primary specification. This indicated that allowing the compete Oldham accessibility effect to enter the destination-choice response increases the magnitude of redistribution.

5.3 Public transport network redistribution
Although total represented public transport demand increased by only 1.35%, the way passengers used the public transport network changed much more substantially (Table 10).

Assignment indicator	Short description	DM–DS change
Total represented PT demand	Total HBW-AM person journeys using bus and/or Metrolink	+1.35%
Tram-using journeys	Person journeys containing at least one tram leg	+68.19%
Bus-only journeys	Person journeys made entirely by bus	−7.43%

Tram boardings	Number of times passengers board a tram service	+4,795
Tram passenger segments	Passenger movements across individual tram stop-to-stop sections	+92.73%

Table 10. Changes in represented public transport demand and network use

Tram-using journeys increased by 68.19%, while bus-only journeys declined by 7.43%. Tram boardings increased by 4,795 and tram passenger-segment movements increased by 92.73%.

The results consequently show a much larger change in the composition and network allocation of represented public transport journeys than in overall number. The expansion produced a relatively small net change in represented public transport demand alongside substantial movement towards tram and different paths through the public transport network.

5.4 Corridor spatial validation

The spatial comparison using corridor shares because the retrospective model retrospective model represents HBW-AM demand, whereas observed patronage and the original forecast represent annul passenger journeys.

Observed demand was concentrated most strongly on Oldham and Rochdale corridor, and the East Didsbury corridor as shown in Table 11. Together these two corridors accounted for approximately two-third of observed Phase 3 patronage.

Corridor	**Observed share (%)**	**Original forecast share (%)**	**Retrospective model share (%)**	**Original absolute error (pp)**	**Retrospective absolute error (pp)**
Ashton	16.07	19.88	20.64	3.81	4.57
Airport	17.83	20.63	17.04	2.80	0.79
East Didsbury	30.59	23.30	28.14	7.29	2.45
Oldham and Rochdale	35.51	36.19	34.18	0.68	1.33
MAE				**3.64**	**2.28**
RMSE				**4.36**	**2.70**

Table 11. Corridor-share comparison between observed patronage, the original forecast and the retrospective model

Across the four corridors, the original forecast produced a mean absolute share error of 3.64 percentage points and an RMSE of 4.36 percentage points. The retrospective model produced2.28 and 2.70 percentage points receptively.

The largest improvement occurred on East Didsbury. Its original forecast share was 7.29 percentage points below the observed share, whereas the retrospective model difference was 2.45 percentage points. Airport also improved substantially, from an absolute share error of 2.80 to 0.79 percentage points.

The improvement was not uniform across all corridors. Ashton had an absolute error of 4.57 percentage points in the retrospective model compared with 3.81 percentage points in the original forecast. Oldham and Rochdale also increased slightly from 0.68 to 1.33 percentage points.

The retrospective model nevertheless reproduced the broad ranking of demand across the four corridors, with Oldham and Rochdale, and East Didsbury remaining the two largest markets.

The retrospective model reproduced the broad ordering of corridor demand, with a rank correlation of 0.80 relative to observed patronage. The principal ranking difference occurred between Ashton and Airport: observed patronage placed Airport slightly above Ashton, while the retrospective model placed Ashton above Airport.

5.5 Scale and residual error diagnostics

The corridor-specific scale factors showed a closely grouped relationship for Airport, East Didsbury and Oldham and Rochdale, while Ashton differed substantially shown in Table 12.

Corridor	Implied scale factor
Ashton	3,407.61
Airport	4,579.17
East Didsbury	4,756.24
Oldham and Rochdale	4,545.62
Mean: Airport, East Didsbury and Oldham/Rochdale	**4,627.01**
Coefficient of variation: same three corridors	**2.45%**

Table 12. Corridor-specific model-to-observed scale relationships

The three corridors excluding Ashton corridor had a mean scale factor of 4,627.01 and a coefficient of variation of only 2.45%. Ashton had a substantially lower implied factor of 3,407.61.
Applying a single total-preserving scale factor across all four corridors produced a factor of 4,375.76. After this common scaling was applied, the scale-normalised mean absolute percentage error was 11.15%. This value is used only as a diagnostic of residual spatial mismatch after aggregate scale has been removed; it is not an ex-ante forecast-error measure.

A leave-one-corridor-out (LOO) test provided a further assessment of the stability of the scaling relationship. For each corridor, the common scale was estimated from the remaining three corridors and then applied to the excluded corridor. The largest residual occurred for Ashton, where the model implied 4.21 million annual-equivalent journeys compared with 3.10 million observed, an overprediction of 35.80%. The corresponding errors were −5.35% for Airport, −11.13% for East Didsbury and −5.68% for Oldham and Rochdale (Table 13).

Excluded corridor	Scale-implied patronage (million)	Observed patronage (million)	Residual (%)
Ashton	4.21	3.10	+35.80
Airport	3.26	3.44	−5.35
East Didsbury	5.24	5.90	−11.13
Oldham and Rochdale	6.46	6.85	−5.68
LOO MAPE			**14.49**

Table 13. Leave-one-corridor-out scale diagnostics for retrospective model demand

The leave-one-out MAPE across the four corridors was 14.49%. Ashton was the clear residual, with its scale-implied value 35.80% above observed patronage. The other three corridors remained within approximately 5–11% of their observed values.
The share and scale diagnostics identify Ashton as the main remaining corridor-specific mismatch. Airport, East Didsbury and Oldham and Rochdale show more consistent proportional relationship between retrospective-model demand and observed patronage.

6. Discussion

The findings demonstrate why forecast performance under urban rail network expansion should not be evaluated from aggregate patronage alone. The original Phase 3 forecast greatly exceeded realised 2018/19 patronage, consistent with wider evidence that rail and public transport forecasts can differ materially from post-opening outcomes[4-6]. However, the retrospective model reproduced the spatial distribution of demand across the fur Phase 3 corridors more closely than the original forecast, reducing the mean absolute corridor-share error from 3.64 to 2.28 percentage points. This distinction is important because an error in the overall level of demand does not necessarily imply an equally large error in its spatial distribution. Previous ex-post studies have similarly cautioned that an observed forecast error

does not, by itself, identify whether the source lies in model structure, forecasting assumptions, external conditions or a combination of these factors[3-6].

The evidence from TfGM's post-opening review reinforces this distinction. When the original Phase 3 forecasts were adjusted to reflect conditions that differed from those assumed during the appraisal, including service frequencies, journey times, economic conditions, development demand and Airport-related assumptions, the resulting expected patronage moved closer to observed demand on Ashton, Airport and East Didsbury[7]. This is consistent with the important role for forecasting assumptions in explaining the original forecast outturn gap. It does not establish that input assumptions were the sole or dominant cause of the error, because the adjusted values were produced after the realised conditions were known. The remaining discrepancy on Oldham and Rochdale also shows that revising the identified assumptions did not remove all corridor-level differences. Forecast error should consequently be understood as potentially combining assumption error, implementation and external-condition differences, and limitations in the representation of travel behaviour.

The retrospective modelling results provide a complementary perspective by showing the response that the response to network expansion is not captured adequately by changes in total public transport demand alone. The increase in represented HBW-AM public transport demand was comparatively small, while the increase in tram-using journeys was much larger. This indicates that a substantial part of the modelled response to Phase 3 involved passengers changing the public transport services and paths they used rather than a corresponding increase in the total number of public transport journeys. This pattern is consistent with earlier evidence from Manchester and other urban rail systems showing that new rail demand can include transfers from existing bus and other public transport services as well as shifts from private modes[14-18]. It also supports more recent work showing that network expansion can redistribute passenger flows across existing stations, corridors and network sections[19,20].

This difference has practical implications for the appraisal of urban rail expansion. A relatively small change in aggregate transport demand can coexist with great changes in tram use, boardings and passenger movements across network sections. Such redistribution can affect vehicle loading, interchange activity, capacity requirements and the use of existing infrastructure even where the total number of represented public transport journeys changes only modestly. Evaluating expansion primarily through net patronage growth may consequently understate important operational and network effects. For strategic planning, demand forecasts should be examined not only in terms of how many passengers are expected, but also where those passengers travel, which modes they use and how they are redistributed across the network.

The corridor-level validation provides further evidence for separating aggregate demand scale from spatial model performance. Airport, East Didsbury and Oldham and Rochdale exhibited a relatively consistent proportional relationship between retrospective-model demand and observed patronage, whereas Ashton remained a clear residual. This suggests that the difference between the HBW-AM model and annual patronage cannot be characterised solely as one common scaling issue across the entire network. At the same time, the Ashton residual should not be attributed to a specific behavioural or modelling cause from the available evidence. Possible influences include corridor-specific travel behaviour, accessibility, trip-purpose composition, access and egress conditions and simplifications in the assignment process, but the analysis cannot distinguish between these explanations.

The Ashton result also differs from TfGM's adjusted forecast analysis, in which Oldham and Rochdale corridor retained the largest unexplained difference after identified forecast assumptions were revised[7]. These findings address different questions and are not contradictory. TfGM's analysis examined why realised patronage differed from the assumptions embedded in the original Phase 3 forecasts. The present retrospective analysis instead examines whether a standardised TAG-informed variable-demand

framework reproduces the spatial and network pattern associated with the expansion under reconstructed 2018 conditions. The two residuals should consequently not be interpreted as competing estimates of the same modelling error.
Several limitations constrain the interpretation of the retrospective results. The framework is a standardised representation of conventional strategic variable -demand forecasting practice, and not a reconstruction of TfGM's historical forecasting model. The destination and mode choice parameters were transferred from TAG-informed benchmark values. The analysis is restricted to HBW travel during the morning peak, while the observed patronage data include annual travel across all purposes and time periods. Overall trip productions and attractions are fixed, meaning that the model represents destination redistribution and mode switching but does not generate an endogenous trip-frequency response. The public transport assignment is also simplified through sampled morning-peak departures, and the former Oldham Loop heavy-rail service could not be fully restored in the DM network. The conservative treatment adopted for Oldham and Rochdale reduces this counterfactual problem but cannot remove it completely.

The temporal dimension of demand response is outside the scope of the present modelling framework. The analysis provides a controlled comparison of 2018 network conditions and does not trace how passenger demand evolved from the opening of each Phase 3 extension to the validation year. This distinction is important because post-opening demand may develop gradually as passengers adapt to new services and the expanded network becomes integrated into established travel patterns. The present analysis therefore focuses on the spatial and network response represented under the 2018 conditions, while temporal demand evolution and post-opening ramp-up require a longitudinal modelling approach using repeated observations over time[21,22].

The scale-normalisation diagnostics should also be interpreted within these limitations. The common scaling factor was derived using observed patronage and was applied only to examine the residual spatial pattern after the aggregate scale difference was removed. The resulting 11.15% scale-normalised MAPE is consequently an ex-post diagnostic and not evidence that the retrospective model could have forecast annual patronage with an error of 11.15%. Similarly, the close scale relationships observed for three of the four corridors do not demonstrate that one unobserved factor explains their demand levels. They show only that these corridors exhibit a similar proportional relationship between modelled HBW-AM demand and observed annual patronage.

Overall, the findings support a broader approach t evaluating passenger demand forecasting under urban rail expansion. Aggregate forecast-outturn comparisons remain important because the overall level of demand affects expected benefits, revenues, operations and the investment case. However, aggregate performance should be considered alongside spatial allocation, destination response, mode switching and network redistribution. The Manchester case shows that a large patronage forecast shortfall can coexist with a comparatively reasonable representation of the geography of demand and substantial redistribution through the public transport network. Future forecasting frameworks should therefore be evaluated on multiple dimensions and tested across additional urban rail systems, trip purposes and expansion types. Incorporating locally estimated behavioural parameters, broader trip-purpose coverage, endogenous trip-frequency response and dynamic post-opening demand adjustment would provide a stronger basis for assessing where conventional strategic models remain adequate and where improved forecasting approaches are required.

7. Conclusions

This study evaluated how well a conventional strategic variable-demand forecasting framework can reproduce passenger demand responses to urban rail network expansion using Manchester Metrolink Phase 3 as a retrospective case study. The analysis distinguished aggregate demand scale, spatial

demand allocation, mode switching, destination redistribution and public transport network redistribution, enabling different dimensions of forecast performance to be assessed separately.

For the first research question, the findings show that a large aggregate forecast-outturn difference does not necessarily imply equally poor representation of the spatial distribution of demand. Although observed Phase 3 patronage was significantly below the original forecast, the retrospective model reproduced the corridor distribution more closely, with a mean absolute share error of 2.28 percentage points compared with 3.64 percentage points for the original forecast. This indicates that the overall scale of demand and its spatial allocation should be treated as distinct dimensions of forecast performance.

For the second research question, the modelled response to Phase 3 shows that network expansion can substantially alter how passengers use the public transport system without producing an equivalent increase in total represented public transport demand. The relatively small change in overall represented demand occurred alongside much larger changes in tram use, reflecting a combination of destination response, mode switching and redistribution through the public transport network. This highlights the importance of examining passenger movement across modes and services when evaluating the effects of network expansion.

For the third research question, the corridor-level diagnostics show that aggregate scale differences do not explain all remaining spatial mismatch. Airport, East Didsbury and Oldham and Rochdale exhibited relatively similar proportional relationships between modelled and observed demand, while Ashton remained the clearest corridor-specific residual. Together with TfGM's post-opening evidence on differences between forecast assumptions and realised conditions, this suggests that forecast-outturn discrepancies may reflect several sources, including assumptions, local demand characteristics and limitations in model representation. The present analysis does not identify the individual contribution of each source.

In summary, the study demonstrates the value of evaluating passenger-demand forecasting beyond aggregate patronage totals. Assessing demand scale alongside spatial allocation, behavioural response and network redistribution provides a more informative account of what conventional strategic forecasting captures and where limitations remain. Applying this approach across additional urban rail systems, trip purposes and expansion contexts would help establish how consistently conventional variable-demand models reproduce passenger responses to network expansion and where further methodological development is needed.

Data availability

The datasets used in this study were obtained from publicly available sources, including Transport for Greater Manchester, the UK Census, NTEM/TEMPro and historical public transport timetable data. The processed datasets used to produce the reported results will be made available through the accompanying research repository, subject to the redistribution conditions of the original data providers.

Code availability

The code used for data processing, variable-demand modelling, network analysis and validation will be made available through a public research repository following preparation of a reproducible version of the analysis.

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Author contributions

The lead author conceived the study, developed the methodology, conducted the data preparation, modelling and analysis, interpreted the results, and drafted the manuscript. The co-authors contributed to study design, methodological development, interpretation of the findings and critical revision of the manuscript. All authors reviewed and approved the final manuscript.

Competing interests
The authors declare no competing interests.

Use of generative artificial intelligence
A large language model (ChatGPT, OpenAI) was used during manuscript preparation to support language editing, structural refinement, and clarification of statistical and modelling outputs.

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