

IMPACT ASSESSMENT OF TROLLEYBUS LINE EXTENSION ON URBAN PUBLIC TRANSPORT

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Abstract

This paper analyzes the impact of extending a trolleybus line on urban public transport performance, using an integrated methodological framework that combines gravity-based accessibility modeling with before/after analysis of generalized travel cost. The proposed approach enables the simultaneous evaluation of both territorial and operational effects generated by infrastructure interventions.

The developed model establishes a direct relationship between generalized cost and accessibility and introduces an additional component that captures the influence of peri-urban areas on transport demand. This methodological extension is particularly relevant for medium-sized cities, where urban–peri-urban connections play an important role in shaping mobility flows.

The case study highlights the strategic role of interface nodes in increasing the attractiveness of the public transport network. The results indicate a reduction in generalized cost, an increase in accessibility for the served areas, and an estimated growth in transport demand.

The analysis shows that the impact of infrastructure interventions is not determined solely by their physical size, but by their position within the network and their ability to reduce critical components such as transfers and access time. The proposed model provides a consistent tool for evaluating public transport modernization and can be applied in strategic urban mobility planning processes.

Keywords: accessibility, generalized travel cost, urban public transport, trolleybus line extension, gravity model

1. INTRODUCTION

Urban public transport systems constitute one of the basic components in organizing the mobility, economic exchange, and space in modern cities. Efficient transport networks, by providing access to employment, education, health care, and public services as well as social cohesion and environmental protection by decreasing private vehicle use [1] to [3]. In medium-sized urban agglomerations, such systems are even more important due to the simultaneous presence of multiple mobility requirements, infrastructure restrictions, and the increasing interdependence between the urban core and the peri-urban space [4]. Increasing

population size and urban mobility complexity and urbanization are the reasons that public transport modernization has become a necessity in sustainable transport [1], [5].

In recent years, electric public transport (tramways, metros, trolleybuses), which reduce emissions, increase energy efficiency, and meet carbon neutrality goals [6], are being increasingly used. Among public transport systems, the trolleybus system is unique because it has a number of advantages of both bus and metro vehicles [7]. It has the flexibility of bus transport but, unlike diesel buses, uses zero-emission energy. This is why it is often chosen when cities are looking for solutions in terms of transport modernization without incurring high costs to install infrastructure [8]. The modernization strategies adopted by public transport providers often include electric vehicles as well as improvements to the public transport corridors and network extensions aimed to improve the coverage and service quality [6], [7].

The provision of public transport extensions is one of the more common interventions aimed to provide more efficient and attractive urban mobility. The interventions affect the accessibility conditions within the study area in the sense that the links between residential areas, workplaces, places of education, commercial centers, and the nodes that connect different modes of transport are reinforced [9]. The extension of public transport network can generate a series of operational results even if the lengths of the extended corridors are relatively short, such as by providing a continuous route, reducing the number of transfers, or integrating the network in a certain way [10]. Such effects do not only affect travel times but can also change the whole travel experience and the perceived attractiveness of public transport compared to the private automobile use [3].

The actual influence of the interventions on the public transport network is difficult to estimate. There are several approaches to the evaluation of this impact, but these usually involve the measurement of certain operational indicators (infrastructure length, commercial speed, passenger growth, or travel time reduction) [1]. Although these indicators can help understand the network development to a certain extent, they can only partially reflect the territorial and behavioral effects of changes to the transport network [4]. For example, these indicators cannot reflect redistribution effects across space, or even behavioral changes caused by changes in accessibility or passenger experience resulting from changes in transfer arrangements, waiting conditions, or network structure [5].

Consequently, a new approach that combines territorial with operational indicators is needed [4], [11]. The accessibility indicators of public transport are used to this end; they measure the ability of individuals in a specific urban area to reach their target destinations (employment, health services, education, and other

public and commercial services) using the public transport network [9]. In contrast to indicators that focus exclusively on mobility, accessibility measures evaluate how transport infrastructure relates to the location of spatial opportunities in the urban area [5].

At the same time, operational assessment is required because travel behavior is shaped by the passenger's experience of service performance including waiting, transfer, reliability and continuity of service [3]. The operational effects in transport engineering and transport economics are typically captured in the concept of generalized travel cost, which represents the different costs of travel as one variable [3], [10]. The generalized travel cost captures the total travel time as well as the additional disutility of transfer operations, waiting time, reliability, etc [7]. Empirical analysis shows that passengers perceive transfer penalty and waiting time more negatively than travel time inside a vehicle [10].

Hence, interventions in the transport infrastructure that minimize transfer demands and improve interchange service may increase the attractiveness of public transport significantly, while the growth of the public transport system in terms of coverage of the urban territory is relatively modest [8]. Consequently, the analysis of the transfer structures and redistribution of accessibility is becoming more relevant in public transport analysis [4]. New direct connections might be provided, additional transfers eliminated, and better integration between urban and peri-urban public transport could be established [4]. This is the case for medium-sized cities where mobility from the suburbs depends on few transfers between the commuter flows and the urban transport network [5].

However, many traditional approaches in transport analysis evaluate operational aspects in isolation, and they do not take into account how different territorial accessibility and travel conditions are interlinked [11]. Therefore, this study presents a framework for assessing the impact of trolleybus infrastructure expansion on public transport performance in terms of territorial accessibility, as well as on the travel conditions and the transfer structure.

The aim of this paper is not to elaborate a new transport theory but to combine the perspectives of different transport analysis methods for a coherent approach to the modern evaluation of urban transport performance in the current context of public transport modernization in medium-sized urban areas. It should be noted that a limitation in the proposed methodological approach is that, although formulated at the level of the origin to destination relationship, the method might be used for analysis of aggregate-level corridor indicators if there is insufficient information on passenger flows. Another limitation is the estimation of many of the parameters related to travellers perception and behaviour. These will be determined as ranges of values for literature-based

parameterization and tested with sensitivity analysis because empirical data is not available. Therefore, the resulting estimates are intended as a planning tool that allows strategic decision-making rather than precise travel demand forecasting. In addition, this study aims to add to the knowledge in the field of how to evaluate the impact of modernizing a public transport system in the current context, and what the contribution of different infrastructure improvements is in that evaluation.

2. INFRASTRUCTURE INTERVENTIONS AND PUBLIC TRANSPORT PERFORMANCE

It is common to view infrastructure interventions in urban public transport networks as key tools for achieving a better accessibility level of cities, a reduction of traffic congestion, and a more sustainable urban development. Interventions such as extension of the networks, modernization of transit corridors, electrification of fleets and improvement of interchanges are likely to have impacts on the spatial structure and operational efficiency of urban mobility [12]. Nowadays, such interventions are evaluated not only in terms of their physical characteristics or implementation costs, but in terms of the increase in accessibility, the improvement in connectivity, and the enhancement of competitiveness of public transport relative to cars [13].

Two main types of effects can be associated with public transport infrastructure projects: territorial effects and operational effects. Territorial

effects refer to the evolution of the accessibility of urban areas in relation to employment opportunities, education, health services and other urban attractions offered by the transport network. Operational effects, on the other hand, are related to the performance of the network, referring to changes in terms of travel time, waiting conditions, reliability, service continuity and requirements for transfers [14]. These two effects are conceptually different, but they are strongly interrelated in

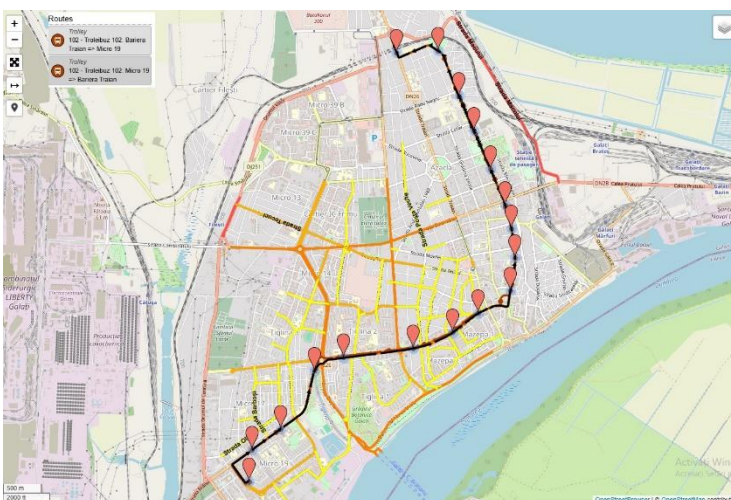


Figure 1 - Trolley line no 102 after extension
(source - OSM)

the sense that changes in network performance lead to changes in accessibility, and accessibility changes lead to changes in travel behaviour and in travel demand [15].

For this reason, recent studies of transport planning have highlighted the relevance of an evaluation approach able to combine both territorial accessibility and the operational characteristics of travel in terms of time and travel conditions [13], [15]. The evaluation of accessibility allows the analysis of the evolution of territorial accessibility with reference to the opportunity space made available to citizens by transport interventions, while indicators of operational performance reflect changes in network structure and service performance from the user's perspective [14].



Figure 2. Focused corridor extension
(source OSM)

Interventions on the infrastructure network, like a corridor extension or an improvement of the interchanges, might reduce the travel burden experienced by passengers, by shortening in this way, not only travel times, but also transfers time, route discontinuity or lack of connectivity [12]. Finally, the relationship between territorial accessibility of urban areas and operational travel time and conditions is more critical in the case of the extension or modification of public transport corridors, that involve, in fact, not only a change in terms of the spatial structure of the network, but also a change in the operational conditions experienced by passengers in their movement in the network [15].

Therefore, to evaluate the infrastructure interventions more widely and holistically, it becomes necessary to develop an evaluation perspective that can integrate both territorial accessibility effects and operational travel conditions and to analyse them in order to better comprehend the impact on urban mobility performance.

2.1 Gravity-based accessibility models

2.1.1 Concept of accessibility in transport systems

Accessibility represents one of the central concepts in transport planning because it reflects the relationship between transport systems and the spatial distribution of opportunities within urban territory [16]. Unlike mobility indicators, which primarily describe the physical movement of individuals or vehicles, accessibility evaluates the ability of people to reach desired destinations

such as workplaces, educational institutions, healthcare services, commercial areas, and social activities through the transport network [17]. Consequently, accessibility is increasingly regarded as a more comprehensive indicator of transport system performance because it captures not only movement itself, but also the effectiveness with which transport networks connect populations to urban opportunities [18].

The concept of accessibility has evolved significantly within transport research over recent decades. Early accessibility approaches were generally based on simple cumulative opportunity models or threshold-based measures that quantified the number of destinations reachable within a predefined travel time or distance [19]. Although such methods remain useful because of their simplicity and intuitive interpretation, they also present important limitations. In particular, threshold-based approaches tend to treat all destinations located within the selected threshold equally while ignoring the progressive influence of travel impedance on travel behavior [20]. As a result, they may oversimplify the relationship between spatial separation and passenger decision-making.

To overcome these limitations, transport researchers increasingly adopted gravity-based accessibility formulations inspired by spatial interaction theory [21]. These models are conceptually derived from Newtonian gravity principles, according to which the interaction between two locations increases with the attractiveness of destinations and decreases with increasing travel impedance [22]. Within transport analysis, destination attractiveness is commonly associated with the concentration of opportunities such as employment, services, or commercial activities, while impedance generally reflects the generalized travel burden associated with movement through the transport system [17].

Unlike binary threshold-based accessibility measures, gravity-based approaches represent accessibility as a continuous function in which interaction gradually decreases as generalized travel cost increases [18], [21]. This characteristic allows gravity-based models to provide a more realistic representation of passenger behavior because they acknowledge that the probability of interaction between locations declines progressively rather than abruptly [23]. Consequently, these models are widely used in transport planning and accessibility evaluation studies because they are capable of simultaneously representing territorial structure, travel impedance, and destination attractiveness within a unified analytical framework [24].

Recent transport research further emphasizes that gravity-based accessibility models are particularly useful for evaluating infrastructure interventions within public transport systems because they capture not only operational travel conditions, but also the spatial redistribution of opportunities

generated by network modifications [25]. Improvements in route continuity, reductions in transfer requirements, or changes in generalized travel conditions may therefore influence accessibility patterns across urban areas even when the physical scale of the intervention remains relatively limited [18]. For this reason, gravity-based accessibility analysis has become increasingly important in studies concerning public transport modernization, sustainable mobility planning, and transport equity evaluation [24], [25].

2.1.2 Gravity accessibility formulation

As one of the most commonly employed types of access measures in transport planning literature [26], gravity accessibility models offer a continuous function to describe the association of opportunities to travel impedances in space [26]. Gravity accessibility models originate from early spatial interaction theory, which evolved in the middle of the twentieth century, starting with the use of spatial interaction concepts that have their root in physics gravity [27]. The work of Hansen [17] was especially important in the fields of transport geography and regional science when he defined accessibility as the link between land use opportunities and travel impedances. These concepts were further developed by spatial interaction theory and accessibility measures [20], [22].

Gravity models became more important in transport engineering over time as a realistic measure of accessibility, replacing binary measures based on travel time thresholds [21]. Binary accessibility assumes that any place within a travel threshold time is accessible, and any place outside a travel threshold is inaccessible. Gravity accessibility models use generalized travel impedance as a measure to describe an alternative to binary measures [18]. They offer a progressive function to describe accessibility according to travel impedance [24].

The general form of a gravity accessibility model is:

$$A_i = \sum_j O_j f(c_{ij}) \quad (1)$$

where:

- A_i = accessibility index associated with origin zone i ;
- O_j = quantity of opportunities located in destination zone j ;
- c_{ij} = generalized travel cost between zones i and j ;
- $f(c_{ij})$ = impedance decay function expressing the influence of travel cost on interaction probability.

The impedance function can be described as either an exponential or power decay function [21], [26]. The exponential formulation may be expressed as:

$$f(c_{ij}) = e^{-\beta c_{ij}} \quad (2)$$

while the power formulation may be represented as:

$$f(c_{ij}) = c_{ij}^{-\gamma} \quad (3)$$

where:

- β = exponential impedance decay coefficient;
- γ = power-decay impedance coefficient.

These parameters show the degree to which travelers are sensitive to generalized travel cost. A higher value of the impedance function indicates more sensitivity to travel burden, meaning that the interaction declines more quickly with increasing travel impedance [18]. Thus, a higher degree of sensitivity indicates that a traveler may select a closer destination or a transportation route with a lower generalized travel cost.

In transport accessibility studies, the generalized travel cost is not restricted to the actual travel time, it is a measure for travel cost that includes in-vehicle travel time, waiting time, transfer penalties, reliability, walking effort, and monetary cost transformed to a generalized time [3], [10]. Consequently, gravity accessibility measures are a measure of both the distance between places and the quality of the transport system itself.

Another attribute of the gravity model is that it is nonlinear, meaning that the accessibility level is not simply reduced by a constant with higher travel cost but declines gradually with generalized travel cost [21]. Thus, small decreases in generalized travel time may result in relatively large changes in accessibility in areas that are currently not well connected or have many transfers [24]. This makes the gravity model more useful for measuring accessibility improvements due to public transport service.

This explains why gravity accessibility measures have been extensively used in public transport modernization, rail transit network development, new transport corridor development, accessibility inequality, and public transport planning for sustainability [25], [28]. In transport planning, gravity accessibility measures are particularly appropriate to measure accessibility and travel time at destinations as it captures all factors that may affect the quality of transport network service and territorial connectivity in an integrated manner.

2.1.3 Application in Public Transport Studies

Due to their capacity to allow infrastructure interventions to be examined via operational indicators but also through how they alter the spatial distribution of opportunities within an urban territory, gravity-based models have been widely

adopted in public transport literature [18]. In real life, changes made in the transport network modify the generalized cost between origin-destination zones and thus influence the accessibility conditions in the system. This means that accessibility analysis makes it possible to assess the impacts that interventions made to transport infrastructure may generate not only in terms of the system's operational conditions, but also concerning its mobility in the territory. Accessibility indicators have thus been very often used in public transport studies to investigate the effects of corridor extensions, reorganization of the network, modernization of interchanges, or integration of the public transport supply [21].

Improvements in accessibility are often perceived as increases in public transport attractiveness, given that a decrease in the generalized cost contributes to facilitating the access of residents to the employment, educational, health and commercial opportunities of the region [24]. Moreover, accessibility analysis makes it possible to identify territorial imbalances in the transport system, revealing the areas that are more favored or the more disadvantaged zones in the light of the transport infrastructure interventions [25]. Gravity-based accessibility models are a widely employed instrument in public transport studies precisely because they make it possible to consider the territorial dimension and the travel conditions of the system together within a same perspective. Unlike other indicators that only consider the system's performance conditions, an accessibility measure combines in itself the evaluation of the transport system in both its operational and its territorial conditions. Consequently, these models are suitable for studying the impacts that transport infrastructure interventions may generate in terms of connectivity in the routes, in the conditions for transfers or even in terms of the access to the opportunities within the territory. These are thus reasons why gravity-based accessibility measures are becoming more common in research concerning public transport in the fields of sustainable mobility, transport equity and public transport modernization [24].

2.2 Generalized Travel Time and Transfer Analysis

2.2.1 Generalized Travel Cost Concept

In order to better understand the territorial implications of transport systems, accessibility analysis makes it possible to consider a set of different indicators able to measure the impact of transport infrastructure interventions on their mobility in the territory. On the other hand, the system's operational performance must also be considered through indicators that represent the travel experience of passengers. One of the most employed indicators is that of generalized travel cost, which gathers a series of aspects into a single indicator

[3]. Unlike conventional measures of travel time, the generalized cost combines the duration of the movement with other aspects of the travel burden related to the waiting time and the time involved in transfers. These indicators may be perceived as inconvenience and include also aspects such as reliability, walking distance or monetary cost [10].

The generalized travel cost between two zones may be expressed as:

$$GC_{ij} = \alpha T_{ij} + \beta W_{ij} + \gamma TR_{ij} + \delta F_{ij} \quad (4)$$

where:

- GC_{ij} = generalized travel cost between origin zone i and destination zone j ;
- T_{ij} = in-vehicle travel time;
- W_{ij} = waiting time;
- TR_{ij} = transfer burden;
- F_{ij} = monetary fare component;
- $\alpha, \beta, \gamma, \delta$ = weighting coefficients associated with each component.

In this formulation, the generalized cost is obtained in terms of general time units and the coefficients represent the weight that passengers usually assign to each aspect within the transport cost. It has been proven in multiple studies that the inconvenience caused by waiting time and transfers may be considered worse than the in-vehicle travel time [10]. This means that the coefficients for these factors are usually higher than the coefficient associated with in-vehicle travel time. The generalized travel cost concept is useful in the evaluation of public transport infrastructure interventions as it allows to observe the changes that may occur in the system in terms of the passengers experience of public transport travel. This measure may therefore include modifications in terms of service connectivity or improvement of the reliability, which are elements usually not considered by other transport system performance indicators and yet capable of improving significantly the general travel conditions.

2.2.2 Transfer Analysis in Public Transport Networks

The condition for transfers represents one of the most significant aspects that passengers perceive in terms of quality within a public transport service. A transfer condition may be defined as the set of circumstances that require the passenger to change the vehicle or the route while the travel to arrive at the destination [3]. Transfers boost the network's spatial reach and connectivity, but at the cost of an extra layer of discomfort from walking, waiting, waiting times, and coordination [3].

The transfer burden may be represented as:

$$TR_{ij} = n_{ij}\theta \quad (5)$$

where:

- TR_{ij} = transfer burden associated with movement between zones i and j ;
- n_{ij} = number of transfers required for the journey;
- θ = transfer penalty coefficient.

The transfer penalty coefficient is intended to quantify the degree of discomfort that a passenger associates with an additional transfer. Many empirical studies in transportation demonstrate that people often interpret transfers as an extra amount of in-vehicle travel time, in terms of some additional waiting time, because transfer operations entail both walking and a lack of certainty, as well as a disruption in continuity of the trip [10]. Hence, actions such as reducing the number of transfers or improving transfers can substantially affect a passenger's satisfaction. In many public transport systems, line extensions and network redesigns may generate new transfers between urban regions. Changes may reduce travel burdens in terms of generalized costs, although actual travel times do not significantly change. Therefore, transfer analysis is increasingly used in public transport evaluation studies nowadays.

2.2.3 Before–After Analysis in Transport Evaluation

Before–after analysis is one of the most widely used approaches to quantify the transport performance effects of interventions in the transport system. The method measures the before and after changes of a specific performance indicator to estimate the variation of the indicators observed [12].

In the case of generalized travel cost, the variation generated by an intervention in the infrastructure network can be expressed as follows:

$$\Delta GC_{ij} = GC_{ij}^{after} - GC_{ij}^{before} \quad (6)$$

where:

- GC_{ij}^{before} = generalized travel cost before the intervention;
- GC_{ij}^{after} = generalized travel cost after the intervention;
- ΔGC_{ij} = operational change associated with the intervention.

A negative value of ΔGC_{ij} is negative, it implies that the situation for travelers has improved because the generalized cost has fallen. In the field of public transport, the before and after method has been employed to evaluate the performance effects of such projects as corridor modernization, expansion of the rail networks, redesign of networks, and improvement of transfer opportunities [12].

This method is particularly suited to public transport infrastructure because such types of interventions may influence not only the characteristics of the transportation supply but also the characteristics of waiting time and transfer

opportunities. Thus, by using this method, one can assess the transport performance from the passengers' perspective.

2.4 Integration of Accessibility and Generalized Travel Analysis

In transport evaluation research, accessibility analysis and generalized travel analysis are usually carried out separately. However, the integrated approach would give a deeper insight into how transport interventions affect both access opportunities on the territory and travel conditions on the public transport system [18]. Access analysis measures how the availability of opportunities in an area changes, while generalized travel analysis measures how passengers perceive changes in their travel experiences in terms of waiting time, travel costs and transfer burden.

Therefore, the joint analysis of accessibility and generalized travel cost analysis is appropriate in public transport modernization research, in which infrastructure projects tend to produce both territorial and transportation supply effects at the same time [24]. This is especially the case for extensions of public transport corridors, upgrading transfer locations, and redesigning public transport networks, as they affect both accessibility and public transport travel performance.

Thus, the integrated assessment of the two dimensions helps provide a better understanding of the relationship between infrastructure change and urban mobility performance. Rather than measuring accessibility and transport performance as independent measures, the joint analysis assumes that changes in the network affect both accessibility and public transport performance. This assumption becomes particularly important in the study of medium-sized city systems in which relatively local infrastructure projects may have a widespread influence on both accessibility and connectivity of the network as a whole.

3. METHODOLOGICAL FRAMEWORK

3.1 Objectives and Analytical Structure

The main purpose of this research is to analyze the impacts on territorial accessibility and travel conditions within an urban public transport network brought about by an intervention in transport infrastructure. The framework adopted here does not assess infrastructure performance only in terms of purely physical metrics, such as the length of the corridor or operations of the vehicles, so as to provide an integrated view of both the impacts on generalized travel

burden, and on accessibility and on transfer structure induced by a modification to the transport network.

The premise that underlies the present approach is that the impact of an infrastructure intervention may be relatively more important than its purely physical length when it is positioned along strategic links in the transport network, namely at strategic transfer interfaces. Therefore, an integration of both territorial accessibility and operational travel conditions is used to interpret infrastructure performance within a wider perspective.

The study case used for its application is a corridor extension featuring a rather small physical extension length, and which involves the provision of new stations, a change to the transfer structure, and operational integration with an existing trunk corridor, and which also allows for a comparison of conditions before and after the intervention.

Therefore, the study does not look only at the impact of infrastructure on the geometry of the network, but also the transport capacity of the existing network to absorb more demand and the potential connectivity improvements provided by the infrastructure intervention.

From an operational perspective, this case is characterized by an essentially stable corridor configuration where the infrastructure intervention does not require a change in fleet provision or headway, i.e. infrastructure impact is not related to the provision of additional supply. This is important since the impact of infrastructure provision on performance can be expected to vary depending on the extent to which the network possesses available supply capacity to absorb the potential change in demand induced by the infrastructure provision.

Table 1. Main Operational Characteristics of the Evaluated Corridor

Indicator	Symbol	Value
Total corridor length (one way)	L	18 km
Extension length	L_e	1.9 km
Extension share	L_e/L	10.6%
One-way travel time	T	40 min
Round-trip cycle time	C	80 min
Added stations	–	2
Representative headway	H	9 min
Mean waiting time	$W = H/2$	4.5 min
Estimated operating vehicles	$N = C/H \approx$	9

From the demographic and demand perspectives, it can be assumed that demand trends are not fully explained by simple population dynamics, therefore it can also be expected that improvements in operational accessibility and in network configuration may contribute to the explanation of transport usage.

Table 2. Demographic Structure Used in the Evaluation Process

Year	Total population	0–18	18–25	25–65	65+
2021	217,851	37,035	19,607	115,461	45,748
2022	214,693	36,497	19,323	113,787	45,086
2023	211,535	35,961	19,038	112,113	44,423
2024	208,377	35,424	18,754	110,439	43,760

Table 3. Public Transport Demand Indicators

Year	Passes / facilities	Sold tickets	Total validated journeys
2021	17,527,077	11,601,519	29,127,596
2022	18,108,572	11,933,301	30,008,873
2023	18,676,370	12,311,778	30,977,148
2024	19,079,809	12,676,455	31,680,264

3.2 Integrated Evaluation Framework

As discussed in Section 2.1, interventions to public transport infrastructure impact the system at two main levels: territorial, in terms of accessibility redistribution; and operational, in terms of generalized cost and transfer conditions. An additional level is introduced in this framework, which considers the impact related to transfer-interface integration to the transport network.

This is especially relevant to urban systems as the transfer nodes constitute an important component in the structure of the network where demand is highly dependent on the interconnection of the various layers. The integrated territorial–operational evaluation framework therefore does not attempt to offer a completely new theory but rather seeks to combine two existing approaches and apply them to an integrated evaluation of both accessibility and travel conditions.

The values of the parameters used within the framework, the impedance decay values, the transfer penalties, and the peri-urban demand shares, are used as planning parameters for evaluating the impact of infrastructure alternatives. They are assumed to lie in the ranges typically reported in the transport planning literature, and tested by sensitivity analysis. Due to lack of detailed origin and

destination and revealed preference data for the corridor under analysis, the framework was not behaviourally calibrated in this paper. Thus the framework should be considered as a strategic framework for infrastructure evaluation, and not as a fully calibrated passenger demand forecasting tool.

3.2.1 Operational Component

For each origin–destination pair i, j , the generalized travel cost associated with scenario s may be expressed as:

$$GC_{ij}^s = \alpha T_{ij}^s + \beta W_{ij}^s + \gamma TR_{ij}^s + \delta F_{ij}^s + \mu R_{ij}^s \quad (7)$$

where:

- GC_{ij}^s = generalized travel cost in scenario s ;
- T_{ij}^s = in-vehicle travel time;
- W_{ij}^s = waiting time;
- TR_{ij}^s = transfer burden;
- F_{ij}^s = fare component;
- R_{ij}^s = reliability component;
- $\alpha, \beta, \gamma, \delta, \mu$ = weighting coefficients.

The generalized cost is expressed in generalized time. As such, the value of the weighting factors can be seen as a relative weight that expresses the relative importance of the various components of the generalized cost in a transport user's behavior.

The transfer burden component may further be represented as:

$$TR_{ij}^s = n_{ij}^s \theta + \omega d_{ij}^{tr,s} \quad (8)$$

where:

- n_{ij}^s = number of transfers;
- θ = transfer penalty coefficient;
- $d_{ij}^{tr,s}$ = transfer walking or circulation effort;
- ω = conversion factor associated with transfer movement.

The operational improvement generated by the intervention may then be represented as:

$$\Delta GC_{ij} = GC_{ij}^0 - GC_{ij}^1 \quad (8)$$

where positive values of ΔGC_{ij} indicate an improvement in generalized travel conditions.

Analysis of the intervention's operational impact shows that the most pronounced effects stem mainly from the decreased burden of transfers and conditions for access, instead of the reduced on-board travel time. This matters a

lot because users seem to consider transfers and waiting times more negatively than the traveling time itself [10].

Table 4. Representative Generalized Travel Cost Components

Component	Before	After
Access time	12 min	4 min
Waiting time	4.5 min	4.5 min
Transfers	1	0
Transfer penalty	8 min	0
Total generalized cost	52 min	36 min
Absolute variation	–	16 min
Relative variation	–	30.8%

As shown by Table 4, the operational change indicates that relatively minor infrastructure interventions can lead to huge decreases in the generalized travel burden, if they simultaneously improve transfer and access conditions.

3.2.2 Territorial Component

Accessibility associated with origin zone i in scenario s may be represented using a gravity-based formulation dependent on generalized travel cost:

$$A_i^s = \sum_j O_j e^{-\lambda G C_{ij}^s} \quad (9)$$

where:

- A_i^s = accessibility index of origin zone i ;
- O_j = opportunities located at destination zone j ;
- λ = impedance decay parameter.

The accessibility variation generated by the intervention may then be represented as:

$$\Delta A_i = A_i^1 - A_i^0 \quad (10)$$

This formulation is advantageous because it includes in the accessibility evaluation the operational travel conditions, via the generalized travel cost rather

than via the mere physical distance. As a result, improvements in waiting time conditions or transfer burden can yield to accessibility enhancements, even if the overall magnitude of the infrastructural expansion is relatively small.

**Table 5. Accessibility Ratio
Under Alternative Impedance Parameters**

λ	ΔGC	A_i^1/A_i^0
0.04	16	1.90
0.05	16	2.23
0.06	16	2.61

The stability of accessibility variation under different impedance coefficients suggests that the observed accessibility gains are not exclusively dependent on a single parameter assumption. Nevertheless, the results should be interpreted as strategic planning estimates rather than exact forecasts because accessibility variation remains sensitive to behavioral parameter calibration.

3.2.3 Interface Integration Component

The approach also considers the interface-integration dimension of the transport network in addition to territorial accessibility and operational travel conditions. This component represents the influence on passengers' attraction to the service and network connectivity exerted by the nodes of the interchange strategically located within the network.

The peri-urban demand for the sm scenario may be described by the following expression:

$$Q_{peri}^s = \rho Q_{sys}^s \quad (11)$$

where:

- Q_{peri}^s = demand associated with peri-urban interaction;
- Q_{sys}^s = total system demand;
- ρ = estimated peri-urban demand share.

Given that it lacks data from detailed origin-destination surveys, the value of the peri-urban share coefficient is used as a planning parameter estimated from ranges based on the literature and observations from the system operation, rather than a measurement based on specific observations of passenger demand.

Consequently, the transfer-interface demand linked with the corridor could be formulated as follows:

$$Q_{BT}^s = Q_{peri}^s \sigma \kappa^s \quad (12)$$

where:

- σ = share of peri-urban demand using the interface node;
- κ^s = corridor capture coefficient in scenario s .

The resulting variation may be represented as:

$$\Delta Q_{BT} = Q_{BT}^1 - Q_{BT}^0 \quad (13)$$

The proposed indicator does not reflect the precise modelling of passenger demand. It is a rough approximation devised to show how transfer-interface integration shapes the demand within a corridor.

3.2.4 Composite Infrastructure Impact Indicator

Finally, the integrated impact indicator may be expressed by the following:

$$I^* = \eta_1 \left(\sum_i q_i \frac{\Delta A_i}{A_i^0} \right) + \eta_2 \left(\sum_i \sum_j p_{ij} \frac{\Delta G C_{ij}}{G C_{ij}^0} \right) + \eta_3 \left(\frac{\Delta Q_{BT}}{Q_{BT}^0} \right) \quad (14)$$

subject to:

$$\eta_1 + \eta_2 + \eta_3 = 1$$

where:

- q_i = territorial weighting coefficient;
- p_{ij} = OD demand weighting coefficient;
- η_1, η_2, η_3 = policy weighting coefficients associated with territorial, operational, and interface dimensions.

This composite structure permits infrastructure interventions to be assessed simultaneously from the territorial perspective, the operational perspective and the interface-integration perspective.

It implies that, instead of evaluating the different dimensions separately, the framework takes into account how public transport infrastructure interventions often have simultaneous impact on accessibility structure, the perception of the passenger, and network integration..

4. CONCLUSIONS

This work has developed and applied an integrated framework for evaluating public transport infrastructure interventions that combines three separate elements of analysis, namely gravity-based accessibility, generalized travel costs and peri-urban interface effects. The methodology was used to evaluate the spatial and service characteristics of the intervention, and to assess how these affect transferability and travel burden.

Results showed that the effect of PT infrastructure extensions cannot be determined by the length of the extension in the urban area alone. Other important characteristics, such as position in the network, line continuity and interactions between urban and peri-urban areas, play a major role in explaining effects of such infrastructure investments. In this case, effects of the extension are primarily driven by changes in access times and travel burden, rather than in reduction of in-vehicle travel time. Hence, a distinction needs to be made between travel time and generalized travel cost expressed in time. Furthermore, an additional benefit was obtained from the spatial evaluation, showing that generalized travel cost reductions imply improved territorial accessibility according to the gravity-based impedance function. In other words, operational gains are evaluated using their effect on spatial accessibility, which improves when the perceived travel burden to access network services decreases.

A further aspect is the calibration of parameters. The behavioural and interface parameters used in this paper have been taken from previous transport studies and tested for sensitivity, but they are not calibrated for any location in terms of local behavioural patterns. As a result, the impacts reported should not be taken as predictions, but instead as strategic planning estimates. Future studies should estimate empirically these values using origin and destination survey data, smart-card data, passenger counts, and revealed preference data, for improved predictive and transferable powers.

Overall results must be seen as useful for strategic planning purposes, but need to be carefully interpreted according to the assumptions of impedance function decay, transfer penalty, peri-urban share of demand served and corridor capture rate. The framework was tested on the peri-urban interface in a case where no other demand estimation models were available. The proposed approach does not aim to substitute other demand modelling methods for passenger flows or OD matrix estimations. Instead, it provides a method to estimate urban demand using transfer gateway trips, which can be useful in cities with medium urban and peri-urban mobility where no OD information exists. Results show generalized travel cost reductions and improved accessibility, estimated to result in an additional

0.31M annual journeys. As such, the results represent an estimation of the magnitude of the effects, resulting from the set assumptions and explored sensitivities.

In conclusion, while the framework provides a useful way to differentiate between alternative interventions, these results should not be used as ridership predictions. Limitations of the analysis include the use of a corridor rather than an OD matrix estimation, use of assumed or referenced parameters and a simplified characterization of demand and its flows in the peri-urban area, issues that can be improved in further studies by collecting data via smart-card, survey and count data, and calibrating impedance function parameters. Furthermore, additional data and information need to be obtained to support reproduction of this analysis. Future work is recommended to provide a more accurate and operational planning and investment prioritization tool. Ultimately, the research demonstrates that PT infrastructure interventions should be evaluated using an approach that combines the impact of operational accessibility and generalized travel burden, as well as interactions between urban and non-urban areas. Such a method is useful for planning in medium sized urban areas, provided that limitations and simplifications are well-defined and understood prior to application of the necessary assumptions.

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