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Assessing airport ground access interventions: An integrated approach combining mode choice modeling and microscopic traffic simulation

Nicolò Avogadro [a,*], Sebastian Birolini [a], Renato Redondi [a], Paolo Deforza [b]

[a] *Department of Management, Information and Production Engineering, University of Bergamo, Italy*

[b] *SACBO S.p.A., Grassobbio, Bergamo, Italy*

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ABSTRACT

Airport ground accessibility is an important and integral part of airport planning, which significantly impacts airport attractiveness and its environmental sustainability. In this paper, we propose the combined use of road micro-simulation with meso-scope discrete choice modeling to support the evaluation of airport access interventions. The proposed integrated framework allows us to appraise mode choice and infrastructural interventions simultaneously to accurately assess the performance of airport access road networks in accommodating larger traffic. We validate and demonstrate the benefits of the proposed approach by applying it to a real-world case study based on the Milan–Bergamo Airport (BGY), in which (i) we conduct an *ex-post* counterfactual analysis to assess the impact of the interventions undertaken to mitigate the large growth (54.6%) in the years 2013–2019, and (ii) evaluate future scenarios up to 2030 considering the additional expected growth and introduction of direct rail services. Results indicate that BGY's ground access interventions have contributed to effectively accommodating traffic growth by significantly mitigating road congestion and associated pollutant emissions. Results also inform on the need and effectiveness of additional interventions to meet the substantial expected future growth.

1. Introduction

This paper investigates the planning and assessment of airport ground access interventions. Airport ground accessibility has recently received increasing attention in the literature owing to its strategic impact on airport attractiveness and overall environmental footprint of airport activities.

Airport accessibility is acknowledged as greatly impacting airport attractiveness, with ground access (and egress) being an integral and relevant portion of passengers' door-to-door travel experience (Belobaba et al., 2015). Ground accessibility significantly affects how an airport competes against neighboring airports (in multi-airport regions) in attracting operating airlines, and impacts its ability to extend the catchment area and stimulate air traffic (Bao et al., 2016; Gupta et al., 2008; Hess and Polak, 2005; Pels et al., 2003). Additionally, ground accessibility contributes to increasing the competitiveness of air transport, especially in short- and medium-haul markets, with respect to other transportation modes, such as high-speed rail (Avogadro et al., 2023; Avogadro and Redondi, 2023; Monteiro and Hansen, 1996; Mason and Gray, 1995).

The increasing pressure on landside facilities, particularly airport access road systems, generates negative externalities, most importantly road congestion and pollution from vehicle emissions. Airports are among a region's largest traffic generation and attraction centers, often being the origin of a significant amount of surface access trips (Mandle et al., 2000; Coogan, 2008). This, combined with airport operations being concentrated in peak hours (typically during early morning and evening) and synchronized with the typical commuters' traffic patterns, results in significant traffic congestion, in turn generating significant emissions from vehicles and affecting air quality in the neighborhoods of airports. Emissions from surface transport used by passengers and employees are the airport's second-largest emissions source after aircraft-related emissions. For instance, they accounted for approximately 33% of emissions at London Gatwick Airport (London Gatwick, 2021). Such negative externalities significantly harm the local community, urgently necessitating mitigation interventions. Accordingly, airport management companies and public administrations have increasingly considered airport access interventions, including upgrading the road networks surrounding airports and promoting intermodality.

* Corresponding author.
E-mail address: nicolo.avogadro@unibg.it (N. Avogadro).

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To assist the planning and evaluation of these types of interventions, developing comprehensive tools to assess the impacts and effectiveness of infrastructural investments on airport access systems is fundamental—both at strategic and operational levels. In this context, our paper seeks to accomplish the following objectives: (i) propose an integrated modeling framework combining road micro-simulation with meso-scope mode choice modeling of airport access to support evaluating airport ground access interventions; (ii) demonstrate the validity of the proposed approach in assessing the effectiveness of past interventions through tailored counterfactual analyses; and (iii) showcase the practical application of our approach in forecasting future scenarios, enabling the identification of potential bottlenecks and supporting strategies for future mitigation.

The proposed modeling approach leverages the granularity and sophistication of micro-simulation to appraise local interventions on the road network while accounting for variations of access trip generation (and mode choice) within the airport catchment area. Our approach relies on a highly granular database for the different flows using the access infrastructure, including passengers, employees, and suppliers. By micro-simulation, we carefully replicate these flows, taking into account the peculiarities of the airport context. We then evaluate the outputs based on multiple criteria such as passenger experience, in terms of travel time length and variability, as well as environmental dimensions (CO_2 and PM_x emissions).

To demonstrate the validity of the proposed approach, we consider a real-world case based on the Milan–Bergamo Airport (BGY). BGY constitutes an exceptional case study in light of its tremendous growth pattern over the last 20 years (compound annual growth rate [CAGR] of 12.5%)—boosted by the introduction of Ryanair in 2003—and its proximity to Bergamo city center (the third largest city in Lombardy), leading to serious access-related issues. Our study proposes an empirical evaluation leveraging counterfactual scenarios aimed at assessing the effectiveness of BGY infrastructural investments implemented between 2013 and 2019.[1] To this end, we employ the integrated model to build counterfactual scenarios, drawing from multiple data sources, including proprietary data from passengers' and employees' mobility surveys and publicly available data (e.g., public transport schedules). We also show how the proposed modeling approach can assess future scenarios characterized by introducing new access modes (i.e., rail) or modifications to current travel alternatives with a significant impact on the access mode choice.

In summary, the proposed approach strives to advance the current state-of-the-art methodologies for investigating airport accessibility and expand the toolkit currently utilized by airport management companies in practice, thereby enabling them to more effectively assess surface access trends and evaluate potential infrastructure investments.

The remainder of this paper is organized as follows. Section 2 reviews airport ground access studies. Section 3 describes the modeling framework and its peculiarities. Section 4 introduces the BGY case study and details the specific inputs and calibration process. Section 5 presents the results of the historical counterfactual analysis and the evidence from the future simulation scenarios. Section 6 discusses the findings of our work and identifies potential paths for future research.

2. Literature review

2.1. Modeling airport accessibility

With rapid air travel demand growth leading to increasing pressure on access networks, airport accessibility has attracted considerable attention among scholars. Most studies rely on revealed preference surveys to calibrate discrete choice models exploring the various factors contributing to access mode choice. Other researchers propose nested logit formulations to describe the combined access mode-airport-choice (Pels et al., 2003) or leverage stated preference surveys and hypothetical scenarios to evaluate the introduction of new transport mode alternatives (Jou et al., 2011; Birolini et al., 2019). Overall, the factors affecting access mode choice can be categorized into two main groups: (i) alternative-specific, and (ii) individual characteristics. The former includes the set of available travel alternatives and their specific features, such as frequency, travel time and cost, and comfort. The second refers to the decision maker's intrinsic preferences that typically depend on socioeconomic factors such as gender, age, education, car ownership, income, travel party size, and luggage size (Akar, 2013; Gupta et al., 2008; Budd et al., 2014; Gokasar and Gunay, 2017). To better analyze access mode preference, the nature and the composition of the different flows related to airport activities must be considered. These flows can generally be divided among four main airport user groups: passengers, employees, visitors, and commercial vehicles (Budd et al., 2016). Typically, each category accounts for at least 20% of the total trips to the airport (De Neufville et al., 2013).

Passengers are undoubtedly the most investigated airport-related flow. Regarding alternative-specific attributes, travel cost and time are the two most significant factors that negatively influence passenger choice of a specific access mode. Travel cost represents the total amount outlaid for the trip, including parking costs, toll charges, fuel costs, and public transport ticket costs, and is conventionally modeled through a unique coefficient (Jou et al., 2011; Evangelinos et al., 2021). Conversely, travel time is typically divided into different components to better evaluate the specific (dis)utility associated with the different portions of the overall travel. The main distinction adopted is between in-vehicle travel time (IVTT) and out-of-vehicle travel time (OVTT), including waiting and transfer time (Harvey, 1986; Jou et al., 2011; Bergantino et al., 2020). The value of time estimated for passengers traveling to airports is significantly higher than for commuters owing to the large penalty associated with being late and potentially missing a flight (Hess and Polak, 2005). Therefore, access time is important for air passengers, as well as its variability and reliability (Tam et al., 2011; Nam et al., 2005; Koster et al., 2011). Recently, researchers analyzed passengers' access preferences by further dividing this user group into smaller sub-groups characterized by specific preferences and requirements for access modes (De Neufville et al., 2013; Kazda and Caves, 2015). The most common market segmentation adopted is based on travel purpose. For instance, Harvey (1986) divided residents in the San Francisco Bay area into business and non-business travelers. Business passengers are more willing to pay, and sensitive to access time. Moreover, they are used to accessing the airport with their cars and parking there because companies generally reimburse their travel expenses. Conversely, non-business travelers are more sensitive to travel costs (Pels et al., 2003). Other studies extended this segmentation by considering a further distinction between residents and visitors (Gupta et al., 2008; Psaraki and Abacoumkin, 2002). For obvious reasons, residents are more likely to travel to the airport in private cars (leaving them in airport parking) or to be escorted by relatives and friends (drop-off). However, visitors tend to rent a car or use a taxi or public transport to access the airport.

Unlike passenger access mode choice, airport employees' ground access has been much less investigated (Pasha and Hickman, 2016). This is mainly owing to these airport users' relatively lower strategic relevance to the airport business and their commuting nature. However, the high dependency of these flows on airport operation scheduling—operating 24/7 and involving shifts outside usual commuting hours and regular workdays in the week, ultimately resulting in incompatibility with public transportation services—and the higher incidence of travel by car among employees compared to passengers necessitates the proper analysis of employees' access mode choice (Miyoshi and Mason,

[1] 2019 represents the last year before the outbreak of the COVID-19 pandemic, which, due to tight travel restrictions, severely affected the air transport industry.

2013; Miyoshi and Rietveld, 2015). Some scholars have focused on employees' access and discussed policy instruments for airport employees' trips (Ricard, 2012; Tsamboulas et al., 2012; Kisia, 2012). Nevertheless, these studies do not consider any explicit mode choice modeling nor do they consider employees' segmentation. Recently, Risby et al. (2022) demonstrated that the primary common factors influencing passenger and employee modal choices are convenience and reliability, while secondary factors, such as cost and family commitments, play a significant role in differentiating the choices of these two user groups. Other studies have focused on evaluating employees' surface access policies, such as incentives for the use of public transportation services or the shared use of cars (Humphreys and Ison, 2005; Ison et al., 2014) and disincentives to car use such as parking lot charges and restrictions (Ison et al., 2007), while also considering the challenges and vulnerability related to the recent COVID-19 pandemic (Warnock-Smith et al., 2023; Yilmaz et al., 2023).

In addition to passengers and employees, visitors and commercial vehicles constitute a significant, yet largely under-researched portion of airport surface access trips (Budd et al., 2016). Airport visitors primarily include individuals dropping off or picking up relatives and friends (the so-called "meeters and greeters") who travel to airports to wave off or welcome passengers (Budd, 2016). Visitors also cover people using the airport's retail or dining facilities or visiting on-site tenant companies. Commercial vehicle trips consist of suppliers delivering food and beverages for airport retail facilities, in-flight catering, and heavy goods vehicles delivering air cargo, typically accessing the airport 24 h per day.

Discrete choice models not only represent the current state-of-the-art in airport accessibility studies but also constitute the main tool utilized by airport management companies, as well as local and regional planning authorities, to evaluate airport access interventions and support their strategic infrastructural planning (Gosling, 2008).

In summary, the existing literature has predominantly addressed airport accessibility concerning passenger access, with limited attention given to research on airport employees and other airport-specific flows (e.g., visitors and commercial vehicles). Additionally, none of the previous studies jointly consider these user groups within a single framework. However, an integrated appraisal is desirable to accurately evaluate the performance of airport ground access systems and plan their upgrading accordingly. Ultimately, existing works mainly leverage discrete choice models, which typically consider aggregate parameters of the overall travel path (e.g., travel time and cost), failing to fully exploit the sophistication and granularity of information that can be obtained through integration with micro-simulation modeling. This paper addresses these two aspects by simultaneously considering all airport user flows and jointly leveraging meso-scope mode choice with detailed micro-simulation to evaluate airport ground access interventions.

2.2. Airport ground access externalities

Access to airports is commonly dominated by private transportation modes, both at major international airports and smaller regional ones (Coogan, 2008). At major European airports, it is estimated that 65% of all surface access journeys are undertaken by private car, and this percentage can be even more pronounced at smaller regional or secondary airports (Humphreys and Ison, 2005; Budd et al., 2014). Coogan (2008) estimated that an airport handling 45 million passengers per year can generate up to 8 million vehicle km of surface access per day, while a 5 million passenger per year airport can generate over 800,000 daily vehicle km. These values make airports among the largest traffic generation and attraction centers in many regions (Mandle et al., 2000). Major airports offer a wide range of flight options and destinations, extending their catchment area to regional or national levels. This is especially true for long-haul destinations, typically served from a restricted set of airports in a country.

In recent years, the continuous growth in demand for air travel has led to increased road trips to and from airports, putting pressure on ground access networks. This trend is even more pronounced at secondary airports—not designed to manage large numbers of passengers—which have suffered a significant increase in pressure on both airport facilities and the surrounding access networks. This increase in traffic volumes has generated negative externalities, such as road congestion, overcrowded parking facilities, decreased quality of local air, noise, and greater pollution from vehicle emissions (Akar, 2013; Tam et al., 2011). Access-related emissions play a substantial role in an airport's overall carbon footprint. For instance, at Glasgow airport, which handles approximately 9 million passengers in 2019, surface access contributed 56,946 tons of CO_{2eq}—constituting 41.4% of the total airport emissions (Ricardo, 2022). Similarly, handling 46.6 million passengers, London Gatwick airport reported 241,174 tons of CO_{2eq} (32.8% of total airport emissions) from passenger and employee access (London Gatwick, 2021). Consequently, scholars have devoted increasing attention to negative externalities generated by airport access trips (Budd et al., 2011a,b; Neufville, 2006).

Simultaneously, the environmental impacts of aviation have come under increased scrutiny, and accommodating aviation growth while mitigating its environmental burden has become one of the most critical and challenging goals on policymakers' agendas at both European and global levels. In this regard, although for the scope of airport carbon accreditation surface accessibility lies with on-ground and low-altitude emissions from aircraft within Scope 3 emissions, namely those not directly under the airport's control, these emissions can be influenced by airport management companies. Furthermore, because surface transport used by airport users significantly impacts the overall airport environmental performance (second-largest source of emissions after aircraft), ground access is an important area that managers are looking at to curb emissions and improve their carbon footprint in collaboration with other stakeholders. The main strategy to pursue this reduction concerns encouraging a modal shift from private vehicles to public transportation for accessing airports, which is the primary solution for reducing access network congestion (Coogan, 2008; De Neufville et al., 2013). Moreover, assessing access traffic implications has become a critical component of the airport expansion plan approval process (Coogan, 2008; Kazda and Caves, 2015). Thus, airport managers are increasingly challenged to develop surface access policies that trade off the effective use of surface access capacity and implement effective access infrastructure investments aligned with airport environmental and business objectives (Coogan, 2002). This leads to long evaluations and complex multi-objective decisions, calling for decision support methods.

In this context, the combined use of road micro-simulation with meso-scope discrete choice modeling appears to be an effective tool for modeling airport access systems and supporting airport management companies to evaluate a variety of (interrelated) airport access interventions from a multi-stakeholder perspective.

3. Modeling framework

Fig. 1 represents the modeling architecture, detailing the various data sources, data pre-processing procedures, intermediate inputs of the meso-scope discrete choice modeling and micro-simulation, and different outputs.

The modeling architecture consists of two main modules: a meso-scope discrete choice model and micro-simulation model. While the micro-simulation model captures the last-mile ground access to the airport in a detailed fashion, the meso-scope discrete choice model accounts for the geographical distribution of airport users and the respective availability of alternative transport modes. The integration between the two modules allows us to relate semi-aggregate origin–destination (O–D) access trip data to disaggregate flow data in the airport's neighborhood.

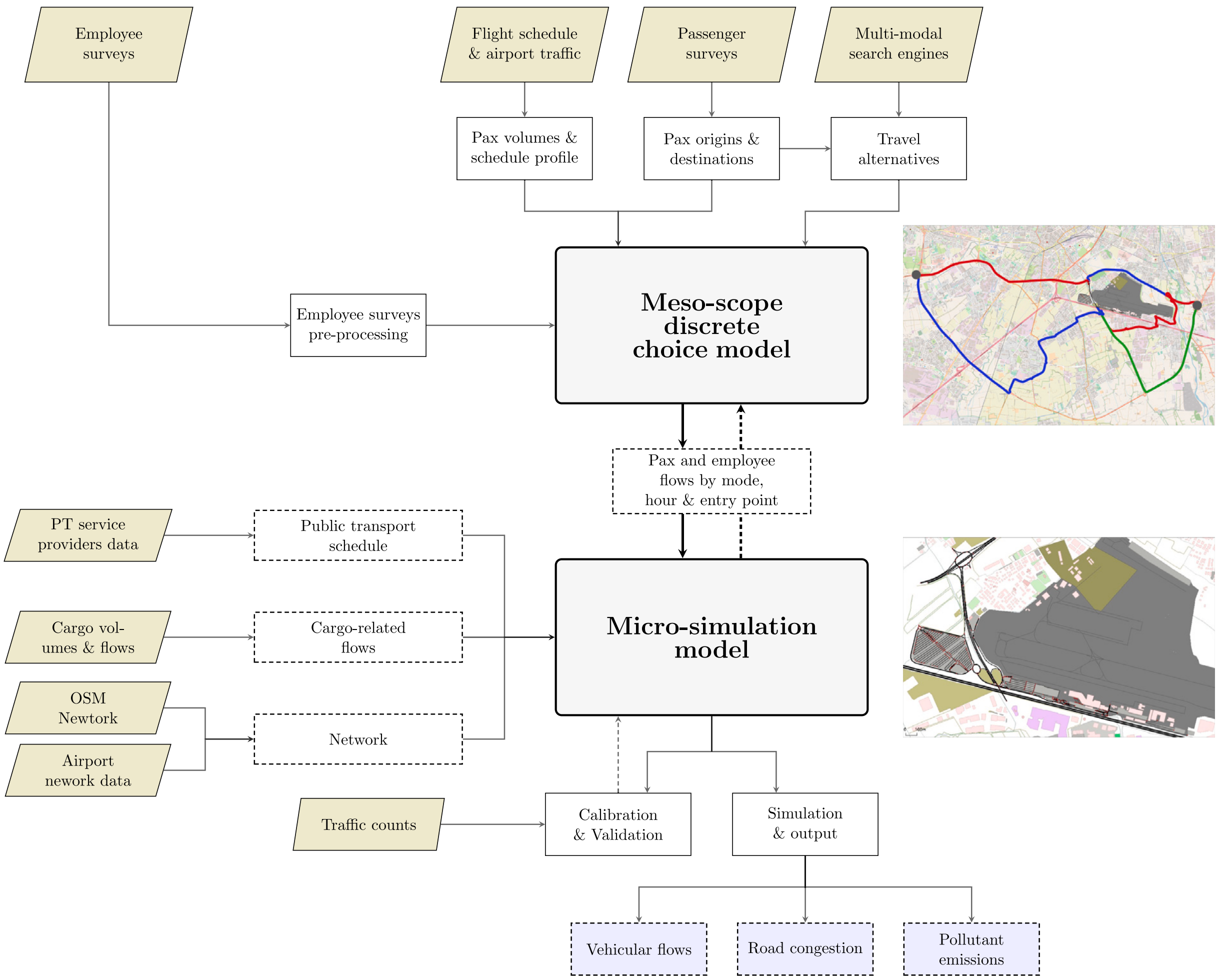


Fig. 1. Modeling architecture.

Specifically, the meso-scope discrete choice model consists of evaluating the airport's catchment area, passenger and employee flows, and airport access mode choice to estimate the flows by hour, mode, user category, and entry point in the last-mile road network in the airport's neighborhood (the area modeled within the micro-simulation model). To conduct the meso-scope analysis, various data sources are used, including employee and passenger surveys, flight schedules, airport traffic data, and characteristics of available travel alternatives to access the airport. Data regarding flight schedules and traffic volumes are used to estimate passenger volumes and their schedule patterns throughout the day. By combining this information with passenger surveys that define the airport catchment area and the passenger municipality of origin/destination, we estimate passenger flows for each hour and municipality. Given the set of municipalities, it is then possible to collect, using multimodal search engines (e.g., Rome2Rio and Google Maps), data on the characteristics of different travel alternatives to access the airport, such as time and cost. This information is then used within the discrete choice model for characterizing passenger mode choices and further stratyfing the flows by mode. Similar to passengers, we use specific surveys conducted by the airport management company to estimate the hourly flow of airport employees by access mode and entry point in the micro-simulation area.

By combining all these data sources, the meso-scope discrete choice model provides a comprehensive representation of the mobility demand to and from the airport, ultimately internalizing considerations at the regional level that may impact the vehicle flow in the area surrounding the airport modeled within the micro-simulation. Additionally, the feedback loop from the micro-simulation to the meso-scope discrete choice model captures the possibility that substantial intervention in the last-mile access network may impact passenger and employee mode choice.

The micro-simulation model relies on two primary inputs: mobility demand and road network. Mobility demand refers to the transportation demand between different parts of the network (in the form of an O–D matrix) and is specified in a dis-aggregate fashion (hourly flows per vehicle type). Besides mobility demand from the main airport users (passengers and employees from the meso-scope model), the micro-simulation model also considers cargo activities and volumes at the airport level to estimate the cargo-related and supplier vehicle flows (from counts or modeled otherwise). The public transportation services near the airport are specified in the micro-simulation model using the timetable provided by the public transport service providers. In cases where the last-mile access network modeled via micro-simulation is not exclusively used by airport users but also by commuting traffic, mobility demand for that component is also required. The second input into the micro-simulation model is the access road network in the neighborhood of the airport, which is reconstructed from publicly available map data (e.g., Open Street Map) and further refined through pre-processing and fine-tuning using airport-specific information.

The micro-simulation model can be executed based on the mobility demand and network specifications. To ensure that the simulation accurately replicates the functioning and performance of the considered road network, the micro-simulation model undergoes a calibration and validation process using traffic counts collected on-site by the airport management company. Once calibrated, the micro-simulation model can be used to test various scenarios and derive insights, including vehicular flows in each portion of the network, as well as congestion and pollution levels, which can be used to identify and address potential traffic bottlenecks and environmental impacts, and to evaluate the effectiveness of both historical and prospective interventions on the airport access system.

4. Empirical setting

4.1. BGY case

The BGY airport constitutes an exceptional case study for investigating the impacts of airport expansion and access infrastructure interventions for two main reasons. First, it has experienced significant growth rates in passenger traffic over the last few decades, a trend that is likely to continue, resulting in further congestion on the road access system and polluting emissions. Second, the BGY management company has implemented and planned a extensive range of infrastructure investments to mitigate these criticalities.

Located in one of Europe's most densely populated and industrialized areas, BGY is approximately 4 km southeast of Bergamo city center and roughly 46 km northeast of Milan. Since the introduction of Ryanair in 2003, the airport has experienced continuous and impressive growth in passenger traffic, with a CAGR of 10.4% in the period 2003–2019, reaching a record 13,857,257 passengers in 2019. Further, aircraft movements have more than doubled over the past two decades, and freight traffic has increased considerably (+18.4%). The airport is now the third busiest in Italy and the largest mainland base for the Irish carrier. The recent COVID-19 pandemic severely affected the European and global aviation industries, considerably reducing traffic at BGY. In 2020, airport traffic was 72% lower than in 2019. However, in 2022, the airport's traffic almost recovered to pre-pandemic levels, with only a slight decline of 5.1% compared to 2019. In the first eight months of 2023, it surpassed the pre-pandemic threshold, with traffic growth of about 16.4% compared with the same period of 2019. The prospects for exceeding pre-pandemic traffic levels have been confirmed by the Italian Airports System Masterplan, recently approved by the Italian Civil Aviation Authority,[2] which forecasts steady traffic growth for the airport over the next few years. Specifically, BGY is expected to reach approximately 17 million passengers in 2025 (+23% compared to 2019) and 19.8 million in 2030 (+43.1%).

Owing to its strong growth, BGY airport has long faced (and will most likely continue to face) increasing pressure on its airside facilities and access road network. The airport is situated on a narrow strip of land between a major motorway and local highway, with the terminal confined between the motorway and airport runway. Currently, the airport terminal is not directly connected to Bergamo city center by rail, and travelers arriving at Bergamo railway station need to transfer via a public bus service or taxis to reach the airport terminal. Similar to other low-cost airports, BGY is connected to the main cities of Northern Italy by an express coach service. Nevertheless, the dominant access modes are private car and drop-off, thus necessitating a series of parking lots in the airport neighborhood. The strong growth in access- and egress-related flows has led to heavy congestion on the surrounding access road system.

The BGY management company has implemented significant investments in the access road network to reduce car dependency for ground access trips and better accommodate the increasing passenger demand. Moreover, BGY has promoted the construction of a direct railway link between the airport terminal and Bergamo station (expected to be completed by 2026), which can potentially boost access to the airport via public transport by directly connecting the airport with the Milan metropolitan area (Birolini et al., 2019).

Ultimately, the position of the airport (4 km from the city center with limited expansion capabilities), strong car dependency (due to the lack of suitable transit alternatives), and its remarkable growth have brought great focus on the BGY ground access system as a key requirement for attractive, smooth, and sustainable airport operations.

4.2. Specific inputs and model tuning

The practical implementation of the proposed framework in the BGY case study requires various inputs, their pre-processing, and the formulation of specific assumptions.

4.2.1. Meso-scope discrete choice modeling

To conduct the meso-scope discrete choice modeling—aimed at estimating the flows by hour, mode, user category, and entry point in the network in the neighborhood of BGY—we leveraged the OAG database, the multimodal search engine Rome2Rio, and passenger and employee surveys collected by the BGY management company.

Regarding passenger flows, we followed a four-step procedure estimating daily passenger volumes at BGY based on annual traffic figures, and then progressively stratifying by hour, origin, mode, and entry point.

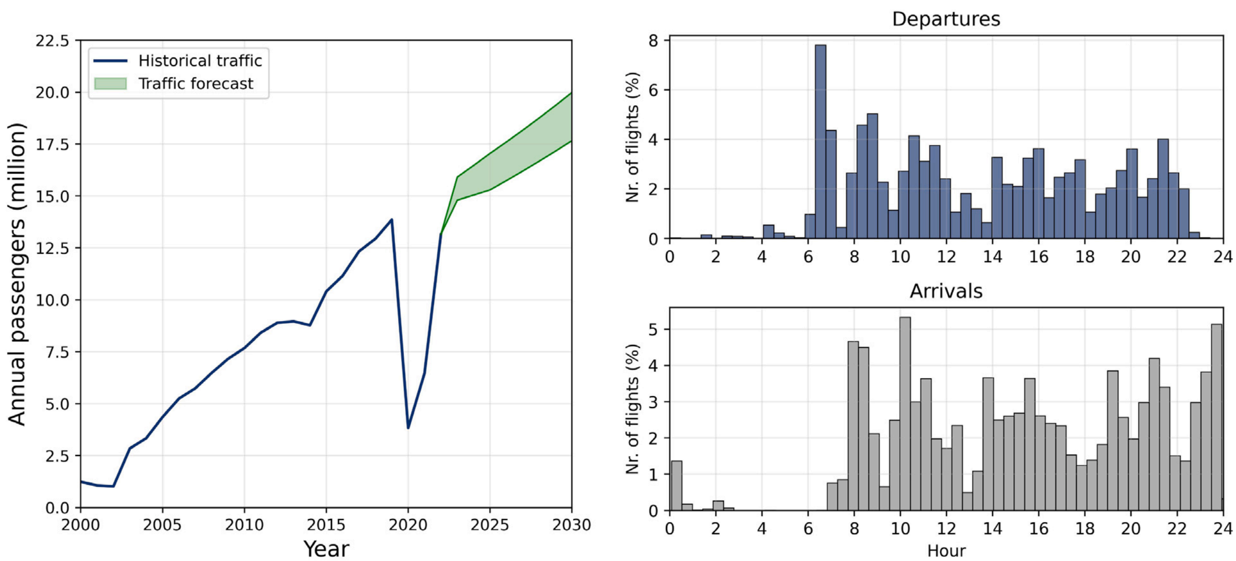
We first used the OAG Traffic Analyzer database to estimate the historical passenger volume of BGY. In addition to historical data, we considered the passenger traffic forecast from the Italian Airports System Masterplan recently approved by the Italian Civil Aviation Authority to ensure the possibility of simulating future scenarios. As mentioned, BGY traffic grew steadily over the period 2013–2019, and, according to the National Airports System Masterplan, it will continue to grow with a CAGR of 3.51% and 3.31% in 2025 and 2030, respectively. Fig. 2(a) depicts the historical and expected passenger trend at BGY.

Second, based on the annual passenger traffic figures, we estimated the number of passengers per day and time by using flight schedules obtained from the OAG Schedule Analyzer and assuming a seat-proportional redistribution. In our analysis, we focused on a prototypical weekend day in July, the month with the most congested days at BGY. Fig. 2(b) represents the distribution throughout the day of flights departing from and arriving at BGY. Consistent with the usual scheduling patterns observed at low-cost airports, flights are distributed almost evenly during daylight hours, with a slight peak in the early morning. The schedule pattern was then translated into the number of passengers accessing/egressing the airport—leveraging information on arrival patterns provided by the airport.

The next steps involved disaggregating these figures by origin, mode, and entry point.

To do so, we first inferred the geographical distribution of passenger flows from surveys. The surveys were conducted through on-site interviews at BGY airport between 2013 and 2019, with three 7 day sessions each year. The Computer-Aided Personal Interview technique was used for the interviews. The resulting sample consisted of 13,415 observations. The data collected from the surveys allowed us to identify passengers' municipalities of origin or destination, thus providing insights into the BGY catchment area. Table 1 reports the province of origin/destination for BGY passengers interviewed in the period 2013–2019. BGY's catchment area extends throughout Northern Italy with markedly higher concentration in the Bergamo province (21.5% of overall passengers), the Milan metropolitan area (29.6%), and Brescia (9.1%). Approximately 21.9% of passengers originate from outside the Lombardy region, mainly from the North-west (Aosta Valley, Piedmont, and Liguria) and North-east (Veneto, Trentino, and Friuli Venezia Giulia) of Italy.

[2] Italian Airports System Masterplan 2022 — www.enac.gov.it/documenti/piano-nazionale-degli-aeroporti.



(a) Annual number of passengers. **(b)** Schedule pattern.

Fig. 2. Historical and forecast of passenger traffic and flight schedule pattern at BGY.

Table 1
Origin/destination of BGY passengers interviewed in 2013–2019 and estimated market share by car.

Province/Area	Obs.	%	TT by car (min)	TT by public transport (min)	MS_{car}
Bergamo	2882	21.5%	24	86	54.7%
Brescia	1220	9.1%	51	143	66.8%
Como	329	2.5%	68	171	72.1%
Cremona	223	1.7%	64	155	68.9%
Lecco	394	2.9%	55	146	64.7%
Lodi	109	0.8%	58	172	68.9%
Mantua	156	1.2%	94	214	78.7%
Milan	3968	29.6%	47	115	61.3%
Monza-Brianza	633	4.7%	40	129	63.7%
Pavia	266	2.0%	80	170	70.3%
Sondrio	97	0.7%	137	260	77.2%
Varese	197	1.5%	70	175	69.8%
North-west Italy	1016	7.6%	133	235	72.3%
North-east Italy	1856	13.8%	145	263	75.5%
Other	69	0.5%			

The last step involved the dis-aggregation of the hourly O–D passenger flows by mode. The available travel alternatives to BGY are private car (both left in airport facilities or external parking lots), drop-off, rental car, taxi, bus, and rail. As the airport is not directly connected by rail to Bergamo city center, passengers arriving by train need to continue their journey to the airport using taxis or public transport services. Overall, BGY access relies heavily on private vehicles, used by approximately 56.6% of passengers in 2019. The use of public transport increased from 34% to 36.5% between 2013 and 2019. Additionally, the share of passengers at BGY for interconnecting flights nearly doubled during this period (from about 3% to 7%), with rapid growth in 2017–2018, when Ryanair introduced some interconnecting flights at the airport (Morlotti et al., 2020). Considering the specific ground access transport modes, the most popular public option in 2019 was the bus (28.3%). Among private transport modes, private vehicle drop-off was most common, representing 28% of passengers using ground access. Access by car left in the airport's parking facilities or external parking areas accounted for approximately 25.2%. Between 2013 and 2019, the increase in nearby facilities offering parking services stimulated growth in the number of cars not parked in BGY's internal parking lot—accounting for 45% of passengers parking their cars in 2013 to 53% in 2019. Around 7.5% of the passengers used a rented car, while approximately 11% used taxis.

To estimate the share of passengers in each O–D using any given mode, we deployed a multinomial choice model (MNL) and utilized granular O–D information on the different transport alternatives obtained from the multimodal search engine Rome2Rio. The MNL model was estimated using the same kind of dataset as Birolini et al. (2019), which refers to the same study context. We considered as passenger mode choice determinants alternative-specific attributes such as total outlay cost per person (TC), IVTT, and OVTT, along with individual characteristics such as age, gender, and the size of the ground access travel party. Regrettably, the lack of pertinent and reliable data in the survey conducted by the airport management company prevented us from including other factors impacting passenger mode choices, such as travel purpose, passenger destination, and number of luggage items. However, we would like to note that the proposed approach is flexible and can accommodate more detailed access mode choice model specifications. Table 2 presents the model estimation results, with driving a car as the baseline alternative. All the coefficients are correct in sign and statistically significant, except for the effects of gender and travel party size on the choice of taxi alternatives. The

Table 2
MNL model estimation results.

Parameters	Estimate	Std. Error	*t*-statistic
Alternative specific constants			
Bus	−1.7838	0.2059	−8.6644***
Drop-off	−1.1104	0.1603	−6.9257***
Taxi	−2.2312	0.3852	−5.7916***
Train	−3.4057	0.3018	−11.2832***
Alternative specific variables			
TC	−0.0257	0.0028	−9.2054***
IVTT	−0.0091	0.0020	−4.5384***
OVTT	−0.0105	0.0036	−2.8791***
Individual characteristics			
Bus: Age (< 35)	0.7266	0.1174	6.1903***
Drop-off: Age (< 35)	0.5181	0.1010	5.1305***
Taxi: Age (< 35)	−2.4468	0.7294	−3.3545***
Train: Age (< 35)	0.8122	0.1773	4.5802***
Bus: Gender (male)	−0.5396	0.1162	−4.6422***
Drop-off: Gender (male)	−0.3365	0.0989	−3.4012***
Taxi: Gender (male)	−0.0453	0.3186	−0.1422
Train: Gender (male)	−0.4412	0.1768	−2.4954**
Bus: Travel party	0.3381	0.0570	5.9325***
Drop-off: Travel party	0.2091	0.0463	4.5215***
Taxi: Travel party	0.1338	0.1235	1.083
Train: Travel party	0.3116	0.0807	3.8626***

*** 99% level of confidence, ** 95% level of confidence, * 90% level of confidence.

estimated value of IVTT is €21.30/h. Consistent with previous studies, the average value of OVTT is higher and equal to €24.54/h. Table 1 also reports the average travel time by car and public transport by province and the estimated market share by car, considering the MNL model outcomes. Across all provinces, private car usage emerged as the predominant access mode to BGY. The Bergamo province and other relatively well-connected provinces by public transport (such as Milan, Lecco, and Brescia) exhibited a slightly lower market share by car than the average.

For employee flows, we also relied on a specific survey conducted by the airport management company. The survey was distributed to the airport's employees and those employed by other companies operating at BGY, such as handling services, security, commercial activities, and authorities. The resulting sample consisted of about 436 observations (about 10% of the total employees at BGY). The survey provided detailed information about employee home-to-work habits regarding origin, access mode, and working hours (entry and exit time). Owing to the highly granular information collected in the survey, for employee flows, we did not explicitly model mode choices; rather, we relied on observed data by re-scaling them to match the entire population of airport employees.

4.2.2. Micro-simulation model

The micro-simulations were conducted using the open-source software Simulation of Urban MObility (SUMO), a microscopic, multimodal, space-continuous, time-discrete traffic simulation tool. It was developed by the German Aerospace Centre (DLR) in 2001 and has been released under the GNU General Public License since 2002 (Lopez et al., 2018).[3] In each simulation step, SUMO models individual vehicles, considering their specific characteristics, such as departure time, physical properties, emission class, and their position and route.

For the purpose of this study, the traffic simulations were conducted simultaneously considering all the vehicles using the network. Passenger and employee flows were derived from the meso-scope assessment described in Section 4.2.1 by associating them with one of the entry points of the simulation area. Specific inputs were required to model other airport-related flows such as commercial and cargo-related flows and public transport services. Mobility demand related to airport cargo activities and commercial vehicles was estimated using cargo volume data and the historical records of customs access. Public transport flows departing from or arriving at BGY were specified in the micro-simulation using the detailed timetable provided by public transport service providers.

The road network near the airport is the other key input of the micro-simulation model. Our analysis focused on the section of the access road network exclusively used by airport users. This portion corresponds to where the airport management company can implement infrastructure interventions to mitigate congestion and other negative externalities. To recreate the road network near BGY in SUMO, we used the street graph gathered from Open Street Map. This preliminary network was thoroughly verified and corrected to match the real road network adjacent to the airport, including specific infrastructure aspects such as traffic lights and parking entrances and exits. Fig. 3 represents the SUMO modeling of the access road network at BGY as of 2019. BGY terminal is confined between a major motorway and the airport runway. Currently, the only two ground access points to the airport are local roads from the north and south, representing entry points 1 and 2 in the simulation area, respectively. Due to the large share of access via private vehicles, the airport has different parking lots: short-stay and drop-off parking (P1) in front of the terminal and long-stay parking (P2) next to the terminal. A few years ago, to accommodate the increasing passenger flows, a new long-stay parking lot (P3), connected to the terminal by a shuttle service, was opened west of the terminal. Airport employees used a reserved parking lot east of the terminal. In addition to the road network, we defined traffic assignment zones (TAZs), namely zones within the network that generate or attract specific vehicle flows. The TAZs correspond to the entry points of the last-mile ground access network and various arrival points, such as parking lots, bus stops, and taxi parking areas.

Based on network specification and mobility demand, the micro-simulation model, once calibrated, provided different outputs disaggregated at the individual vehicle level and aggregated at the street/lane level. The simulation outputs mainly include conventional traffic congestion measures, such as travel and waiting times, occupancy, density, and pollution metrics. To estimate polluting emissions, we relied on the HBEFA emission repository.[4] The vehicles used in the simulations were defined based on the distribution of environmental classes in the current fleet used in Italy. In this study, we focused on CO_2 and PM_x emissions. However, the proposed approach can readily estimate emissions of other pollutants in the HBEFA database, such as greenhouse gases beyond CO_2 (e.g., CH_4 and N_2O) and air pollutants (e.g., NOx, CO, and HC).

Overall, these outputs enabled the analysis of the airport access road network's performance, including identifying potential traffic bottlenecks and environmental impacts. Such information allowed us to evaluate the effectiveness of both historical and future interventions on the BGY access road system.

[3] The SUMO suite has been used extensively to answer a wide range of research questions, from small-scale simulations for testing new traffic control systems (such as traffic light algorithms and AI-based dispatching of vehicles for railway traffic) to simulations of larger areas (Krajzewicz et al., 2005, 2012; Kusari et al., 2022). For example, SUMO provided traffic forecasts for the City of Cologne authorities during the Pope's visit in 2005 and FIFA Soccer World Cup in 2006.

[4] HBEFA 3.1 — https://www.hbefa.net.

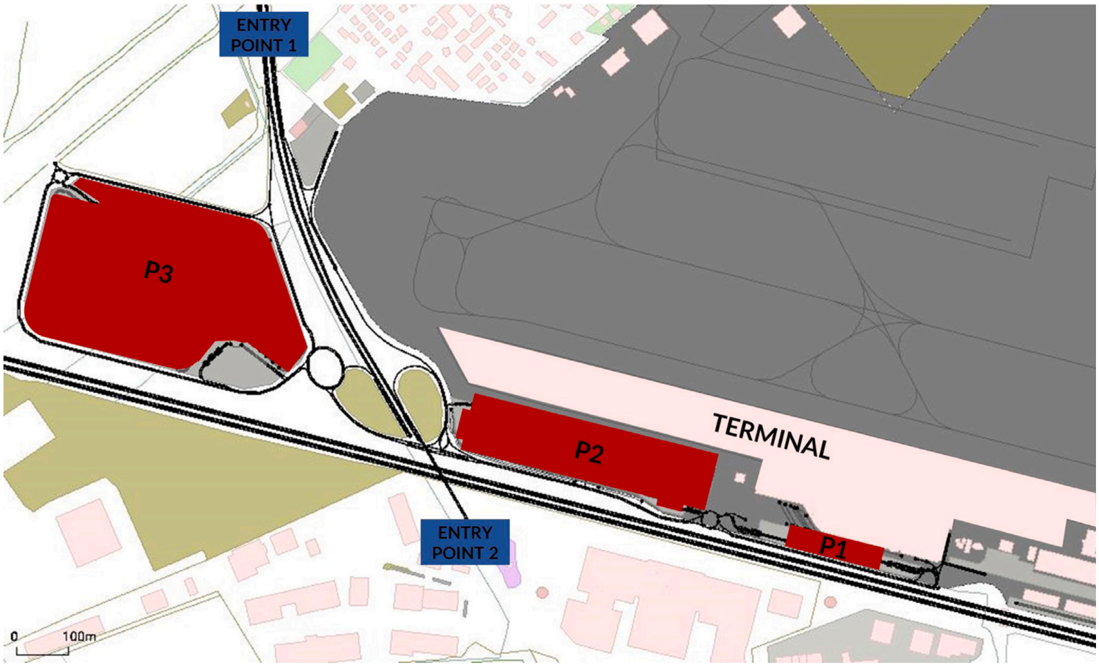


Fig. 3. SUMO modeling of the access road network at BGY as of 2019.

Table 3
Calibration accuracy metrics: GEH and SQV statistics.

Calibration accuracy	GEH		SQV	
	Threshold	Counts (%)	Threshold	Counts (%)
Very good match	GEH < 5	63.6%	SQV > 0.9	54.5%
Good match	5 < GEH < 10	36.4%	0.85 < SQV < 0.90	39.4%
Acceptable match			0.80 < SQV < 0.85	6.1%

4.3. Calibration

To ensure that the micro-simulation model accurately reflects the specific context, we conducted a careful calibration and validation process using on-field traffic counts collected by the airport management company. This process fine-tunes the model's parameters to guarantee the accuracy of the simulation model regarding the actual behavior of the transportation system. The main parameters calibrated concern the use of the different parking lots serving the airport, average size of travel parties, and number of trips of shuttles connecting to external parking lots.

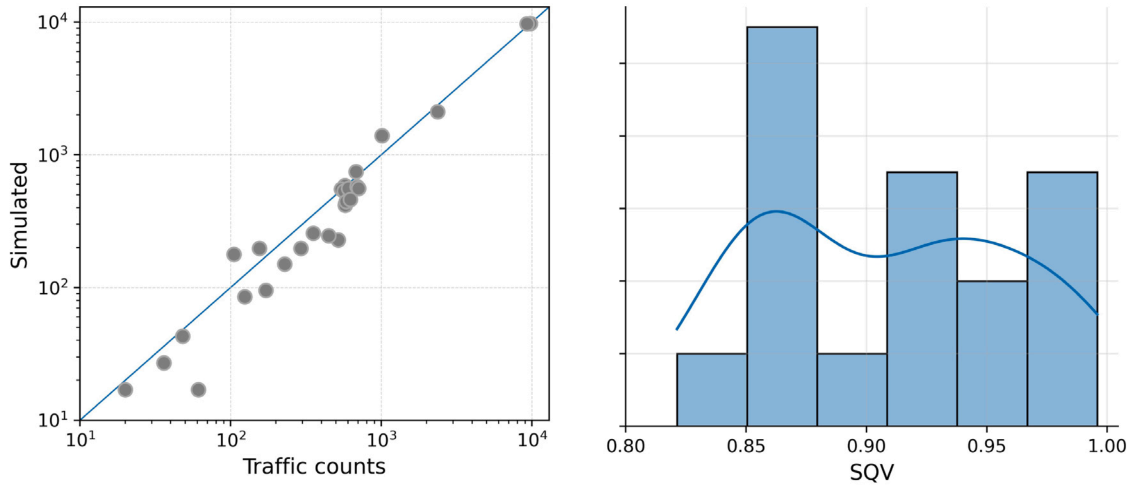
The calibration process used on-field traffic data representative of a typical mid-July weekend day in 2019. Specifically, we leveraged traffic counts collected by the airport management company on July 6^{th} and 7^{th}, 2019, in different portions of the access road network and data from the entrances and exits of the airport parking lots. Real traffic counts—both hourly and daily—were then compared with simulated traffic volumes collected by loop detectors specified in the micro-simulation model to closely replicate the location where real traffic counts were conducted. Fig. 4(a) compares the simulated traffic flows with the on-field traffic counts. Overall, the micro-simulation model accurately replicates the flows on the real road network. To further evaluate the calibration performance of the micro-simulation model, we applied the Geoffrey E. Havers (GEH) statistic (Highway Agency, 1996), a commonly used metric to evaluate the goodness-of-fit of a simulation model, considering both the absolute difference and percentage difference between simulated and observed flows. The GEH statistic is denoted as follows:

$$GEH = \sqrt{\frac{2(M-C)^2}{M+C}} \quad (1)$$

where M is the traffic volume from the simulation model and C is the real-world traffic count. The Highway Agency (1996) goodness-of-fit criterion suggests that a simulation model achieves a very good match with a real transport system when the GEH is less than 5, while a good match is for a GEH between 5 and 10. In our case, approximately 64% of the counts have a GEH of less than 5, with the rest lower than 7.5, thus demonstrating a good fit (Table 3). As the GEH statistic depends on the magnitude of the values, its interpretation with counts of different duration (e.g., daily vs hourly values) cannot be straightforward (Friedrich et al., 2019). Recently, Friedrich et al. (2019) proposed the Scalable Quality Value (SQV) statistic, which solves the GEH problems by leveraging a specific scaling factor based on the magnitude of the count considered. SQV values above 0.90 demonstrate very good matching between simulation and real traffic counts, while values between 0.85 and 0.90 reveal a good match. In contrast, values below 0.8 indicate a potential model misspecification. Fig. 4(b) reports the statistical distribution of SQV measures for our micro-simulation model. Overall, analyzing the SQV measure, the model appears adequately calibrated (median SQV equal to 0.91) and able to accurately replicate the actual access road system to BGY.

5. Empirical results

This Section discusses the results of the proposed real-world case based on BGY airport. In Section 5.1, we evaluate the effectiveness of infrastructural interventions implemented in the airport access road network implemented over the last few years. In Section 5.2, we then leverage the proposed model to evaluate future scenarios of passenger growth and appraise the impact of introducing new access modes (i.e., rail) or modifying existing alternatives in mitigating access road network congestion.



(a) Traffic counts vs simulated flows. **(b)** SQV statistic distribution.

Fig. 4. Micro-simulation model calibration statistics.

Table 4
Historical assessment simulation output—congestion KPIs.

Scenario	Travel time (s)						Waiting time[a] (s)					
	Mean	Δ_1	Δ_2	SD	Δ_1	Δ_2	Mean	Δ_1	Δ_2	SD	Δ_1	Δ_2
2013 scenario	145.3	–	–	28.7	–	–	21.2	–	–	13.3	–	–
No intervention	157.5	*+8.4%*	–	51.1	*+78.1%*	–	33.4	*+57.4%*	–	45.7	*+243.1%*	–
Change in modal share	156.1	*+7.5%*	*−0.9%*	35.4	*+23.3%*	*−54.8%*	30.8	*+45.1%*	*−12.3%*	20.3	*+52.4%*	*−190.7%*
2019 scenario	150.6	*+3.6%*	*−3.8%*	34.0	*+18.5%*	*−4.8%*	26.5	*+24.6%*	*−20.5%*	15.9	*+19.1%*	*−33.3%*

[a] Duration in which the vehicle stops or travels below the ideal speed.
Notes: Δ_1: Variation with respect to the 2013 scenario.
Δ_2: Variation with respect to the previous scenario.

Table 5
Historical assessment simulation output—emission KPIs.

Scenario	CO_2 emissions						Particulate matter (PM_x)					
	Tot. (t)	Δ_1	Δ_2	g per pax[a]	Δ_1	Δ_2	Tot. (kg)	Δ_1	Δ_2	mg per pax[a]	Δ_1	Δ_2
2013 scenario	8.4	–	–	285.9	–	–	1.3	–	–	42.8	–	–
No intervention	13.4	*+59.1%*	–	294.2	*+2.9%*	–	2.0	*+59.1%*	–	44.1	*+2.9%*	–
Change in modal share	13.2	*+56.4%*	*−2.7%*	289.2	*+1.1%*	*−1.8%*	2.0	*+57.0%*	*−2.0%*	43.5	*+1.6%*	*−1.3%*
2019 scenario	11.6	*+38.1%*	*−18.2%*	259.1	*−9.4%*	*−10.5%*	1.8	*+38.9%*	*−18.2%*	39.0	*−8.9%*	*−10.5%*

[a] Emissions from all vehicles (except for freight and employee vehicles) out of total passengers using ground modes to access the airport (i.e., interconnecting passengers are not considered).
Notes: Δ_1: Variation with respect to the 2013 scenario.
Δ_2: Variation with respect to the previous scenario.

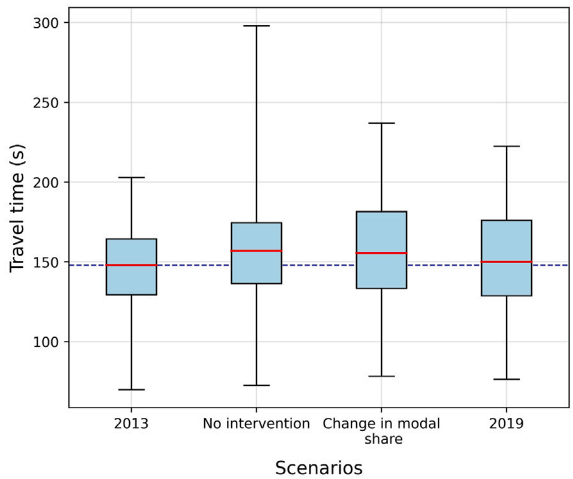
5.1. Historical assessment

We consider the period 2013–2019, in which various improvements on the access road network were implemented. Among them, it is worth mentioning the opening of the new long-stay parking lot (P3) connected to the main terminal by a bus shuttle and an overall reconfiguration of the intersections near the terminal. These interventions were implemented to accommodate growing passenger flows and mitigate congestion on the ground access system. Our analysis considers two baseline scenarios that accurately replicate the performance of the BGY ground access network in 2013 and 2019.

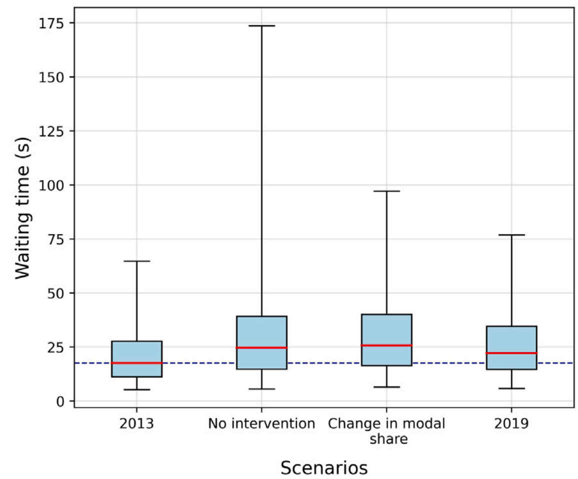
Additionally, for a better grasp of the mitigating impact of the investments undertaken, we formulate two counterfactual scenarios: (i) a no-intervention scenario, and (ii) a change in modal preference scenario. The no-intervention scenario models the performance of the access road network supposing no infrastructural investments were made between 2013 and 2019. This involves simulating access to the airport for 2019 flows using the 2013 road network and modal preferences. By comparing this scenario and the 2013 baseline, the increase in negative externalities (congestion and pollution) in the case of non-mitigated growth (from a last-mile ground access network perspective) of activities at BGY can be estimated. Similar to the no-intervention scenario, the change in modal preference scenario considers 2019 passenger flows using the 2013 access road network but accounts for the changes in modal preferences that occurred between 2013 and 2019. This scenario compared with the no-intervention scenario thus provides a proxy of the effect of changes in passenger access mode choices over time. Ultimately, by comparing the change in the modal preference scenario with the 2019 baseline, we can gauge the extent to which infrastructure interventions have contributed to mitigating congestion and pollutant emissions.

Tables 4 and 5 report the main congestion and pollution key performance indicators (KPIs) resulting from the different simulation models, while Fig. 5 depicts travel and waiting time distributions in the different scenarios.

Considering the no-intervention counterfactual, we estimate a substantial worsening of congestion on the airport access network and, consequently, increased pollutant emissions. Specifically, it is estimated



(a) Travel time.



(b) Waiting time.

Fig. 5. Box-and-whisker plots of the travel and waiting time in the different scenarios, reporting the 25^{th} and 75^{th} percentiles (box) and 1^{st} and 99^{th} percentiles (whiskers).

that the increase in vehicular load resulting from the growth of airport activities (without any intervention on the local access system) would have significantly increased both the average per-vehicle travel time (+8.4%) and its variability (+78.1%), indicating a severely overloaded road system. The same conclusions emerge considering the increase in waiting times (+57.4%), namely the duration that vehicles stop or travel at a lower speed than desired. These results also highlight that the high growth in passengers at BGY (+54.6%) would have implied a relevant increase of access-related CO_2 emissions—from 8.4 to 13.4 tons per day—and particulate emissions. Notably, the increase in travel time and congestion would not occur uniformly throughout the day but would be mainly concentrated during the most congested (peak) hours. Specifically, the road system would experience higher pressure between 8 and 10 in the morning when departure and arrival flights overlap.

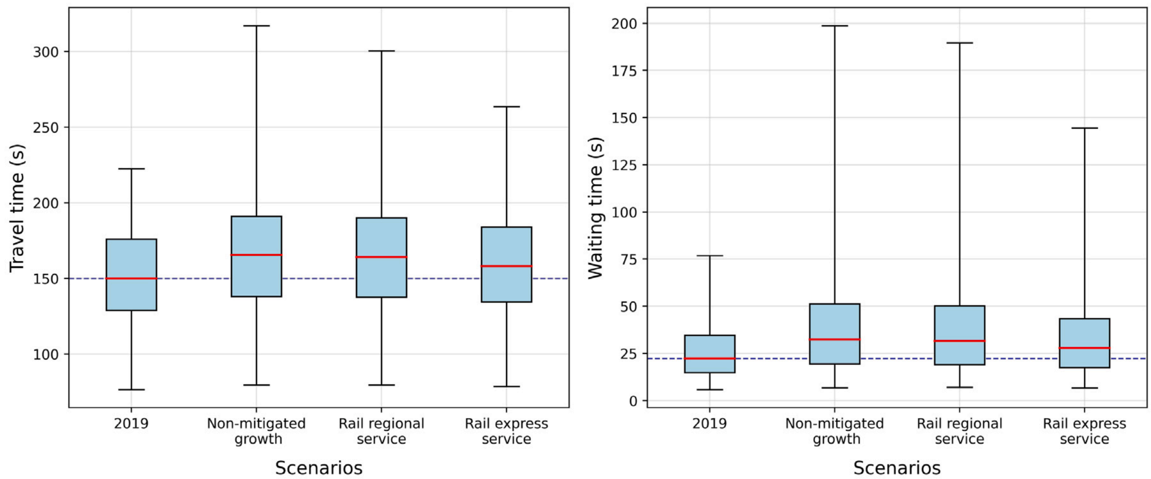
Analyzing the effects of changes in access mode preferences over time (i.e., comparing no-intervention with the change in modal share scenario), we observe how the increase in the use of public transport to access the airport between 2013 and 2019 contributed to reducing the congestion in the airport's neighborhood. Specifically, both access travel and waiting time variability are significantly reduced. Furthermore, the higher use of public transportation and shift to external parking facilities yield a slight reduction in total and per-passenger CO_2 emissions (−2.7% and −1.8% vs the no-intervention scenario, respectively).

Finally, the effectiveness of infrastructural investments implemented by the BGY management company between 2013 and 2019 can be evaluated by comparing the network performance under the change in modal share scenario and that in the 2019 baseline. Overall, the implemented access infrastructure modifications have contributed to significantly mitigating negative impacts resulting from increased passenger flows. Specifically, the new configuration of the access network has limited the increase in both travel and waiting times. The former increased by only 3.6% compared to 2013 levels, while an increase of up to 8.4% is estimated in the case of no interventions on the access road network. Waiting time increased by 24.6% whereas in the absence of modification to the access system, it would have been higher than 57%. The main benefits are concentrated in the morning peak hours, during which, in the no-intervention scenario, we observed an increase in congestion and queuing. Thus, the modifications to the access infrastructure succeeded in increasing access network resilience and avoiding congestion during these hours, consequently curbing the increase in waiting and travel times. From an environmental perspective, the infrastructural investments made after 2013 facilitated the mitigation of the increase in negative externalities resulting from the growth of activities at BGY, with an increase in last-mile airport access emissions that is less than proportional with respect to passenger growth (+38% of overall emissions vs +54.6% of passengers). Overall, the estimated daily CO_2 emissions from last-mile BGY accessibility in 2019 equals 11.6 tons. This value should be compared with the estimated emissions in the case of no intervention and assuming the sole variation of passenger modal preferences, equal to 13.2 CO_2 tons. Thus, the new infrastructure configuration generates daily savings of about 1.6 CO_2 tons. The mitigation impact on emissions following the access network reconfiguration becomes evident when assessing the pollutant levels per passenger, which from 2013 to 2019—even in the face of a relevant increase in the number of passengers—decreased. The per-passenger last-mile access CO_2 emissions fell from 294 g per passenger in the case of no intervention on the access road network to 259 g in 2019 (−11.9%). The same trend is observed for particulate matter emissions being reduced by 11.6%. This can be primarily traced back to the expansion of the airport-owned parking areas west of the terminal and use of low-emission shuttles connecting the new parking area (P3) with the airport terminal.

Overall, we observe that the passenger growth between 2013 and 2019 slightly increased (compared to 2013) the congestion in the airport neighborhood and, consequently, the emissions generated. However, the airport operator managed to accommodate this growth by improving the access road system and increasing its resilience. The infrastructural investments made over the years have indeed been effective in managing the growth in passengers, minimizing negative externalities, and even decreasing average per-passenger emissions for last-mile access.

5.2. Future scenarios

To analyze future scenarios, we consider a time horizon of 2030. According to the Italian Airports System Masterplan, BGY is expected to experience steady growth in traffic over the next few years, reaching 19.8 million passengers in 2030 (+43.1% with respect to 2019). The baseline scenario for 2030 does not consider any interventions on the access network (non-mitigated growth scenario). The scenario aims to understand the potential effects of the growth in passenger activities if not actively managed. Besides the direct increase in passenger flows, the baseline scenario for 2030 also considers the expected rise in employee and supplier trips. Based on the 2030 non-mitigated growth scenario, we developed different scenarios to investigate how the airport management company can potentially mitigate the expected



(a) Travel time. **(b)** Waiting time.

Fig. 6. Box-and-whisker plots of the travel and waiting time in the different future scenarios, reporting the 25^{th} and 75^{th} percentiles (box) and 1^{st} and 99^{th} percentiles (whiskers).

Table 6
Future scenarios simulation output—congestion KPIs.

Scenario	Travel time (s)						Waiting time[a] (s)					
	Mean	Δ_1	Δ_2	SD	Δ_1	Δ_2	Mean	Δ_1	Δ_2	SD	Δ_1	Δ_2
Non-mitigated growth	166.8	*+10.8%*	–	46.6	*+37.0%*	–	42.4	*+60.3%*	–	38.2	*+140.5%*	–
Regional service	165.4	*+9.8%*	*−0.9%*	44.1	*+29.7%*	*−5.3%*	40.9	*+54.8%*	*−3.4%*	34.9	*+119.7%*	*−8.6%*
Express service	158.8	*+5.5%*	*−4.8%*	39.5	*+16.3%*	*−15.1%*	34.5	*+30.4%*	*−18.7%*	27.6	*+74.1%*	*−27.6%*

[a] Duration in which the vehicle stops or travels below the ideal speed.
Notes: Δ_1: Variation with respect to the 2019 scenario.
Δ_2: Variation with respect to the non-mitigated growth scenario.

Table 7
Future scenarios simulation output—emission KPIs.

Scenario	CO_2 emissions						Particulate matter (PM_x)					
	Tot. (t)	Δ_1	Δ_2	g per pax[a]	Δ_1	Δ_2	Tot. (kg)	Δ_1	Δ_2	mg per pax[a]	Δ_1	Δ_2
Non-mitigated growth	17.3	*+48.9%*	–	269.7	*+4.1%*	–	2.6	*+48.1%*	–	40.4	*+3.5%*	–
Regional service	16.7	*+43.8%*	*−3.5%*	260.3	*+0.5%*	*−3.5%*	2.5	*+43.3%*	*−3.3%*	39.1	*+0.1%*	*−3.3%*
Express service	15.2	*+30.6%*	*−12.3%*	236.5	*−8.7%*	*−12.3%*	2.3	*+30.4%*	*−12.0%*	35.6	*−8.9%*	*−12.0%*

[a] Emissions from all vehicles (except for freight and employee vehicles) out of total passengers using ground modes to access the airport (i.e., interconnecting passengers are not considered).
Notes: Δ_1: Variation with respect to the 2019 scenario.
Δ_2: Variation with respect to the non-mitigated growth scenario.

passenger volume increase at BGY. Specifically, we focused on simulating the impact of introducing a direct rail connection between the BGY and Bergamo railway station—currently under development and expected to be operational by 2026. The new infrastructure will enable direct rail services from BGY to Milan (via Bergamo station) and *vice-versa*, providing a novel (and attractive) transit option for passengers traveling to and from the Milan metropolitan area and municipalities along the Milan–Bergamo axis. The market share that would potentially be attracted by this rail alternative would depend on the type of rail service implemented. Consistent with Birolini et al. (2019), we explore two distinct rail service models: extending the existing regional service and introducing a dedicated airport express service. The regional service is designed with multiple stops, whereas the express service provides a non-stop train journey from Milan to Bergamo Central Station. To gauge attributes for these new rail alternatives, existing train–bus alternative data are adjusted according to the expected relative improvements outlined in the BGY Intermodal Development Plan (Sacbo-Oneworks, 2011). Specifically, extending the regional service yields incremental savings in both IVTT (−10 min) and OVTT (−10 min) without affecting service price. This is expected to increase the number of people who will use the train alternative if this solution is put into practice. However, extending regional trains will offer passengers a transport alternative with the same overall quality and journey comfort as the current setup. Thus, we assume the regional train's ASC equals the current train–bus ASC. Conversely, establishing an express service enhances travel time benefits (a 20 min and 10 min reduction of IVTT and OVTT, respectively) but increases service prices (+8 €). Besides travel time savings, the greatest advantage of the express service is the higher quality of service and better performance compared to existing train–bus alternative. For our analysis, we conservatively assume as a reasonable benchmark the express train's ASC to be equal to the bus's ASC (as in Birolini et al., 2019). This means that people are indifferent between riding the express train and coaches, other things being equal. Based on these assumptions, in the case of extending the existing regional commuter service to BGY, the rail alternative's market share on the Milan–Bergamo corridor was estimated to increase by 2.77%. However, if a dedicated airport express service is implemented, the aggregate rail market share from/to Milan is estimated to increase by 20.2%. Accordingly, we developed two scenarios— "Regional service" and "Express service" in Tables 6 and 7. We implemented these scenarios starting from the 2030 scenario of non-mitigated growth and considering the estimated modal shift resulting from the introduction of direct rail services.

Tables 6 and 7 report the congestion and emissions KPIs resulting from the future scenarios analyzed, while Fig. 6 depicts travel and waiting time distributions in the different scenarios.

When considering a scenario of non-mitigated growth up to 2030, we observe the severe impact of passenger growth on the simulated performance of the access network. Specifically, the average last-mile access time at BGY would increase from 150.6 s to 166.8 s (+10.8%) owing to congestion and waiting times (increasing by 60.3%). The variability of wait and travel times, measures of network saturation and resilience, also exhibit a sharp increase (as shown in Figure 6). From an environmental standpoint, daily CO_2 emissions from accessing the airport due to congestion are estimated to increase from 11.6 to 17.3 tons (+48.9%), more than passenger growth. Similarly, absolute particulate matter emissions are expected to increase by 48%. The increased congestion also results in a higher last-mile CO_2 emission level per passenger, rising from 259.1 to 269.7 g (+4.1%).

Analyzing the rail scenarios, the integrated simulation indicates that the potential introduction of a direct rail link to BGY can mitigate the negative externalities of passenger growth by fostering a more sustainable modal split, i.e., capturing market share from other modes, mainly private cars, and buses. Based on the simulation model, the introduction of a regional service on the new rail line to BGY, which is expected to attract fewer users, is likely to only partially reduce the increase in average travel time (−0.9%) and average waiting time (−3.4%) resulting from expected passenger growth. However, the introduction of the rail mode is expected to provide more sizeable benefits in terms of both daily (−3.5% and −3.3% for CO_2 and particulate matter, respectively) and per-passenger emissions. The per-passenger CO_2 emissions in the case of the introduction of a regional rail service running on the new rail infrastructure are estimated at 260.3 g per passenger, about 3.5% lower than estimated in the non-mitigated growth scenario and slightly above the corresponding 2019 value. In contrast, introducing an airport express service might attract more users and provide significantly higher benefits regarding traffic congestion and pollutant emissions. Compared to the non-mitigated growth scenario, when an express service is implemented at BGY, the last-mile average access travel time is expected to decrease by 4.8% (waiting time would be reduced by 19%). From an environmental perspective, introducing an express rail service is expected to decrease overall CO_2 emissions by 12.3% compared to the non-mitigated growth scenario. Furthermore, the last-mile CO_2 emissions per passenger would decrease to 236.5 grams, well below 2019 (−8.7%). Despite the undoubted environmental benefits, introducing a direct rail service alone is expected to be insufficient in coping with the higher congestion induced by increasing passenger numbers, especially considering morning peak hours. This demands even more attention considering the ambitious industry-wide net-zero commitments (ICAO, 2022). Accordingly, the airport management company is called upon to identify and implement complementary measures to avoid congestion in the surrounding area and effectively accommodate passenger growth.

6. Conclusions

This paper examines the planning and assessment of airport ground access interventions, which have a key strategic role in airport success and sustainable growth, and propounds an integrated modeling framework to support evaluating such interventions. The model combines the granularity of road micro-simulation with broader considerations of the airport catchment area and regional accessibility patterns to accurately replicate airport ground access and evaluate access network performance under different scenarios in terms of both traffic congestion and pollutant emissions. Such an approach simultaneously considers not only passenger flows, but also all trips related to airport activity, such as employee and supplier trips and flows related to cargo activities. The proposed approach serves two primary purposes in supporting airport management companies' planning activities, both at the strategic and tactical levels. First, it can be used to evaluate *ex-post* the effectiveness of prior infrastructure investments in the airport access network. Second, it can preemptively assess the performance of the ground access network in future scenarios characterized by growth in airport activities, changes to the access road network, and introduction of (new) transportation alternatives. These outcomes can ultimately support and enhance the cost–benefit assessments of such infrastructural investments by complementing typical aggregate KPIs in terms of time and generalized travel cost savings with refined and accurate congestion and environmental metrics obtained through micro-simulation, which can be translated into monetary values utilizing appropriate coefficients (e.g., social cost of CO_2 emissions ranging between $29 and $106 per ton of CO_2 (van den Bergh and Botzen, 2015)).

The validity of the proposed framework was tested using a real-world case study based on BGY, the third-largest airport in Italy in terms of passengers and one of the fastest-growing airports in Europe. From a historical perspective, we found that the infrastructural investments implemented at BGY over the period 2013–2019 have effectively mitigated the negative externalities resulting from rapid growth. The analysis of counterfactual scenarios indicates significantly lower congestion and pollutant emission levels than would have occurred if no intervention on the last-mile road access network to the airport would have been implemented. Furthermore, thanks to the improved road system and building of the new parking lot (P3), the per-passenger CO_2 emissions for last-mile access have decreased from 294 g (in the case of no intervention) to 259 g in 2019 (−11.9%). Considering the growth prospects of BGY—expected to reach nearly 19.8 million passengers by 2030 according to the baseline scenario developed in the Italian Airports System Masterplan—we found that, in the case where the expected growth is not properly accommodated, it will cause a significant increase in congestion levels on the access road system, with relevant detrimental effects on both airport attractiveness and pollutant emissions. In this light, the ongoing project to develop a direct rail connection between the airport and regional railway network can potentially contribute to mitigating these negative effects by fostering a more sustainable modal split. The highest mitigation potential comes from establishing a new dedicated airport express service, which would be much more attractive and thus able to capture a higher market share from other modes, mainly private cars, and buses. Notwithstanding, despite the clear reduction in congestion and the environmental benefits that would accrue from opening the rail link (compared to the non-mitigated growth scenario), the results indicate that additional interventions in the access road network will be required to accommodate expected growth in airport activities effectively and to avoid excessive congestion in the surrounding area. Although a decrease in emissions per passenger is desirable, it falls short if offset by the surge in passenger numbers, resulting in an overall increase in airport emissions in absolute terms. This becomes even more critical given the ambitious targets of decarbonization established at the industry-wide level.

The proposed framework is not exempt from challenges and limitations. A primary criticality lies in determining the entry points to the micro-simulation area, and ensuring the consistency of vehicular flows at the interface between the micro-simulation area and area modeled through the meso-scope discrete choice model. This is crucial for achieving a proper integration between the two modules of the framework. Additionally, careful attention must be given to accurately translate dis-aggregated metrics from the micro-simulation, such as travel time and congestion, into the aggregate dimensions considered within the discrete choice model in the meso-scope analysis. This is vital for capturing the impact of interventions in the last-mile access network on passenger and employee mode choice. Considering its limitations, the proposed approach models accessibility outside the micro-simulation area at a meso-scope scale and in aggregate terms.

This may overlook certain nuances in access travel options and disregard the effects of interventions conducted outside the simulated area unless specifically considered or *ad hoc* modeled. Furthermore, the validity of the proposed approach was tested through a case study based on BGY, meaning the results may be, to some extent, contingent on the specifics and peculiarities of that airport. Further validation of the approach would be beneficial, particularly when considering airports of diverse size, with a different passenger mix in terms of business and leisure travelers, and a diverse flight network and airline mix (e.g., with a higher proportion of long-haul flights). These factors have indeed been demonstrated to affect passenger mode choice. Additionally, our current study focuses solely on last-mile CO_2 and PM_x emissions. Future research endeavors could use the proposed approach to analyze the emission patterns of other pollutants.

CRediT authorship contribution statement

Nicolò Avogadro: Conceptualization, Data curation, Formal analysis, Methodology, Writing – original draft, Writing – review & editing. **Sebastian Birolini:** Conceptualization, Methodology, Writing – original draft, Writing – review & editing. **Renato Redondi:** Supervision, Validation. **Paolo Deforza:** Resources, Validation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data that has been used is confidential.

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