Decarbonizing airport access

A review of landside transport sustainability

Mahesh, Srinath; Calvert, Simeon C.

DOI
10.1016/j.trd.2025.104625

Publication date
2025

Document Version
Final published version

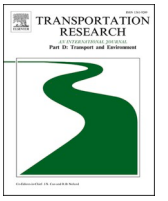
Published in
Transportation Research Part D: Transport and Environment

Transportation Research Part D 140 (2025) 104625

Contents lists available at ScienceDirect

Transportation Research Part D

journal homepage: www.elsevier.com/locate/trd



Decarbonizing airport access: A review of landside transport sustainability

Srinath Mahesh [*], Simeon C. Calvert [1]

Department of Transport and Planning, Faculty of Civil Engineering and Geosciences, Delft University of Technology, Delft, the Netherlands

ARTICLE INFO

Keywords:
Airport emissions
Landside sustainability
Net-zero
Sustainable airports
Green airport
Climate change

ABSTRACT

The demand for air transport has experienced rapid growth, raising significant environmental concerns. Previous studies on airport sustainability have mainly focussed on airside areas; while literature pertaining to landside transport sustainability and emissions reduction approaches is limited. This paper addresses this gap by presenting a comprehensive review and critical assessment of the existing studies aiming to inform policymakers and researchers. Based on a holistic approach and an interdisciplinary perspective, the reviewed literature is classified into four categories: travel behaviour, transport infrastructure, transport policy, and sustainability. Within these categories, key findings are identified, along with a concise overview of the strategies employed by large airports to achieve their net-zero targets. Main solutions include increasing the attractiveness of public transport, providing electric vehicle (EV) infrastructure, and promoting low/zero emission vehicles. Moreover, the exploration of innovative fuel technologies (such as hydrogen), fast-charging EVs, and autonomous shuttle buses also has immense potential.

1. Introduction

Over the past century, the demand for civil aviation has grown exponentially, resulting in a rapid global surge of air traffic and supporting infrastructure. According to ICAO's compilation of annual global statistics, about 2.3 billion passengers were carried in 2021, which was 28.1 % higher than the previous year (ICAO, 2022). Further, in terms of passenger traffic in total scheduled revenue passenger-kilometres (RPKs) performed, the total increase was 22.4 % with the highest increases in North America (72.6 %), and Latin America and Caribbean (43.7 %). Moreover, fuelled by increasing middle-class populations and rising disposable incomes, the demand for air travel is expected to double by 2040 (IATA, 2023). This surge in air travel has brought about significant challenges, including problems related to landside accessibility and traffic congestion around airports (Wadud, 2020; Zuniga-Garcia and Machemehl, 2021), and increased emissions of greenhouse gases (GHGs) and other pollutants (Masiol and Harrison, 2014; Rupcic et al., 2023; Stacey, 2019). As a result, it is imperative to address these issues and prioritize sustainability of travel to and from airports.

Abbreviations: ACRP, Airport Cooperative Research Program; AV, autonomous vehicle; BRT, bus rapid transit; CO_2, carbon dioxide; EV, electric vehicle; GHG, greenhouse gas; IATA, International Air Transport Association; ICAO, International Civil Aviation Organization; LEZ, low emission zone; MNL, multinomial logit model; MRT, mass rapid transit; NO_2, nitrogen dioxide; $PM_{2.5}$, particulate matter of size less than 2.5 μm; PT, public transport; ULEZ, ultra low emission zone; ZEZ, zero emission zone.

* Corresponding author at: Room 4.02, Building 23, Delft University of Technology, 2628CN, Delft, the Netherlands.
E-mail addresses: S.Mahesh@tudelft.nl (S. Mahesh), S.C.Calvert@tudelft.nl (S.C. Calvert).
[1] Address: Room 4.18, Building 23, Delft University of Technology, 2628CN, Delft, the Netherlands.

https://doi.org/10.1016/j.trd.2025.104625
Received 10 July 2024; Received in revised form 14 October 2024; Accepted 25 January 2025
Available online 2 February 2025

In the context of sustainability of airports, the focus of the researchers and stakeholders has primarily been on reducing the emissions from the aircraft (such as by adopting sustainable aviation fuels or SAFs) and relatively limited attention has been directed towards the role of landside transportation systems (Masiol and Harrison, 2014). Although, in terms of the magnitude, emissions from the aircraft are many times higher than the emissions from fossil fuel powered vehicles in the vicinity of the airport, reducing the emissions in the landside area is a low-hanging fruit in achieving sustainability. Notably, the landside area includes transportation infrastructure, parking facilities, access roads, and other amenities that cater to the passengers and employees travelling to and from the airport (Janić, 2019).

The sustainability of the landside area is reliant on the behaviour of the travellers; thus, it is crucial to understand the travel behaviour of the individuals who travel to/from the airports for various reasons including to catch a flight, to drop-off or pick-up passengers, to work, or to shop. The travel behaviour in the context of airport differs significantly from typical urban travel patterns; thereby presenting unique factors that influence passengers' travel choices. First, most people do not travel to the airport on a daily or weekly basis, except airport employees, and instead access the airport once or twice in a six-to-twelve-month period because airport-related trips are often associated with recreational activities. Second, due to the recreational nature of the trip, passengers may be more inclined to pay a premium for their airport travel, unlike their daily work trips. Additionally, the need to carry luggage creates a preference for door-to-door service. Finally, the high cost of missing a flight, coupled with uncertainty around check-in times and security clearance, leads airport travellers to prioritize reliability in their travel time over travel cost. These factors have a significant impact on the mode choice, route choice, and departure time choice of the travellers, and should be considered while developing strategies to improve landside sustainability.

To the best of the authors knowledge, there is no paper that reviews the existing literature on landside sustainability and emissions reduction approaches of airports, and measures taken to mitigate the emissions at various airports with a focus on the landside transportation systems. This paper fills this gap by providing a comprehensive review and synthesis of the existing knowledge in this domain, followed by critical analysis of the findings and directions for future research.

The following research questions provide motivation for this paper: (1) How sustainable are the airport landside access transport systems and what are the ongoing efforts to improve sustainability? (2) What are the key factors or criteria that have been (or can be) used to assess the sustainability of the landside area of an existing airport? (3) Based on the current knowledge, how can sustainability be further improved by enhancing transport systems to access airports? (4) What are the most important and promising directions for future research that can aid policymakers?

The objectives of this review paper are threefold. Firstly, this paper aims to review the existing peer-reviewed literature and reports to identify and summarize the efforts towards landside emissions reduction and sustainability practices at airports worldwide. Secondly, this paper aims to provide a summary of knowledge intended towards practitioners and professionals seeking to stay informed about the emerging trends and best practices for achieving a sustainable airport landside. Finally, this paper intends to provide recommendations to the policymakers and directions for researchers aimed at reducing landside emissions and improving sustainability in the future.

The rest of this paper is organized as follows: Section 2 presents the methodology adopted which includes the procedure for search and selection of papers, data extraction, and analysis process. Section 3 presents the results of the literature review and synthesis beginning with an examination of travel behaviour in the context of landside access, encompassing aspects such as the mode share of public transportation and the mode choice behaviour of passengers and airport employees. Subsequently, the paper evaluates the infrastructure and policies relevant to landside transportation systems and presents the summary of literature focussing on the landside sustainability. Finally, an overview of the key strategies and initiatives to achieve net-zero targets, as mentioned in the recent annual or sustainability reports of large airports is presented. Based on the review, Section 4 presents the main findings catering to the interests of a wide range of readers including researchers and policymakers. Lastly, Section 5 provides the conclusions of this review paper.

2. Methodology

This section presents the methodology adopted in this study, which includes the procedure for search and selection of papers, criteria for inclusion of the papers, and databases used for literature search. Also, the data extraction and analysis process, and criteria for classification of the reviewed literature is presented in detail.

2.1. Search query and scope

The overall goal of the search process is to obtain literature delving into aspects related to airport landside access and its environmental impacts. To this end, the search strings (or keywords) consisted of a combination of "airport" with terms such as "public transport", "landside emissions", "carbon footprint", "environmental impact", "sustainability efforts", and "sustainable aviation". We apply an iterative search process, wherein the search terms are adjusted based on the initial search results. This allows us to enhance the search effectiveness and enable a comprehensive exploration of the available literature pertaining to airport landside sustainability and emission reduction approaches. The various publication types considered are peer-reviewed journal papers, reports, conference papers, book chapters, and grey literature.

With regard to the scope, this paper reviews the landside emission reduction and sustainability of airports particularly from the perspective of ground transportation to and from the airport. This includes the transportation of arriving and departing passengers, crew members, and employees working in the airport. Thus, papers which evaluate the mode choice behaviour of travellers, landside sustainability, and related aspects such as infrastructure and policies are included in the review. However, papers focussing explicitly

on the emissions resulting from airside area, such as the emissions from the aircraft, and from the other vehicles operating in the vicinity of the taxiway were not considered in scope. We also do not consider papers on sustainability aspects related to the transportation of goods and for energy needs within the terminal building. To maintain consistency and ease of analysis, only papers written in English-language are considered. By limiting the scope to English-language publications, the review aims to ensure accessibility and facilitate understanding for a wider audience. In relation to the search period, the search process began in September 2023 and continued till October 2024.

2.2. Search process, screening, and analysis

Three main databases are used, namely ScienceDirect, Scopus, and Google Scholar, for literature search (journal papers, conference papers, and book chapters). The rationale for selecting multiple databases is to ensure comprehensive coverage, robustness of review, up-to-date snapshot of literature, and to utilize their unique search features, filters, and citation tracking options. In addition to these three databases, we searched the websites of large airports to find relevant annual reports and sustainability reports. Both forward and backward snowballing technique was used to find additional relevant literature. The first screening of the literature was based on the title, abstract, and keywords. Papers found relevant after the first screening were reviewed in further detail. The initial search resulted in 612 hits out of which seventy-eight papers were found to be relevant after preliminary screening. Moreover, with regards to the annual sustainability reports, each report was included for further review.

Following a detailed review of the seventy-eight papers obtained after preliminary screening, forty-seven papers were found to be relevant. The data extraction and analysis process involved comprehensively reviewing these articles with a view of extracting important characteristics and findings. After reviewing the full text of these articles, we extracted the following information: (1) article details (such as name of author(s), title, publication year), (2) airport/location of the study, (3) objective, (4) methodology, (5) key variables considered, and (6) main findings. The articles were then categorized into either one of the four categories: travel behaviour, transport infrastructure, transport policy, or landside sustainability, based on the study's objective and main findings. In total, there were nineteen studies in the travel behaviour category, twelve in transport infrastructure, nine in transport policy, and seven in the landside sustainability. A tabular representation was created to provide an overview of studies within each of the four aforementioned categories. We also reviewed several annual or sustainability reports of large airports to identify their emission reduction targets and the strategies planned to attain this goal. The strategies were further categorised into three groups: transport infrastructure, transport policy, and environment. The transport infrastructure related aspects included vehicle electrification, use of renewable fuels, and cycling and pedestrian infrastructure. Strategies relating to transport policy included promoting public transport, regulation of transport network companies, and parking policies. Low emission zones, zero emission vehicles, and monitoring of ultrafine particles (UFPs) were some of the aspects related to the environment.

2.3. Classification of the reviewed literature

The reviewed literature is classified into four categories: travel behaviour, transport infrastructure, transport policy, and environment. This classification is based firstly, on the themes of the reviewed papers, and secondly, on the understanding that these aspects play a crucial role in achieving sustainability in the landside area. To elaborate, firstly, gaining an understanding of the travel demand side, including individual preferences and choices, is crucial for framing effective policies and developing appropriate infrastructure to promote sustainable travel behaviour. The goal here is to promote the use of public transportation and active modes of travel, such as buses, trains, bicycles, and walking, to reduce reliance on private vehicles. Secondly, the impact of transport infrastructure (supply side) on travel behaviour must be considered. The focus here is on evaluating the impact of a well-designed and accessible transportation infrastructure that facilitates the use of active modes of transportation, public transit systems, and clean vehicles to access the airport. Thirdly, there is evidence that transport policies play an important role in enhancing landside sustainability by influencing travel behaviour and transport infrastructure. Thus, the formulation and implementation of effective transport policies are crucial in promoting sustainability. For example, policymakers need to invest in public transportation systems, offer incentives for EVs, and implement parking management strategies. Finally, it is important to understand the existing landside sustainability aspects and its relationship with the previous three categories. Assessing the current air quality status in and around the airport and implementing continuous environmental monitoring systems are vital.

In summary, to create a more sustainable landside of airports, it is crucial to recognise and address the four key categories focussing on promoting eco-friendly travel behaviour, improving transport infrastructure, implementing suitable transport policies, and prioritizing landside sustainability. By understanding and acting upon these categories, airports can make progress towards sustainability and contribute to a greener aviation sector. The detailed review of the relevant studies is presented and discussed in the following section.

3. Airport landside sustainability and emissions reduction

In this section, we present the results and summary of the literature review pertaining to airport landside sustainability and emissions reduction. This begins with the impact of travel behaviour, followed by the impact of landside infrastructure, transport policy, and landside sustainability, and lastly, a summary of the highlights of the net-zero plans and key strategies of large airports. In each sub-section, an overview of the reviewed studies is presented in a tabular form.

Table 1
Overview of studies focussing on the travel behaviour in the context of airport landside access.

Region	Author(s) (year)	Airport(s)/ location(s)	Objective	Main finding	Modes considered				
					Bus	Car	Metro	Rail	Taxi
Europe	Castillo-Manzano (2010)	Seven airports in Spain	Mode choice behaviour of passengers of low-cost airlines for travel to airport	Passenger using low-cost carrier is 6 % less likely to take taxi to airport, and 2 % more likely to use public transport	✓	×	×	×	✓
	Budd et al. (2014)	Manchester Airport, UK	Identify segments of airport passengers with greatest potential to reduce car use	Attitude-behaviour gap hinders positive environmental attitude being translated into sustainable mode usage	✓	✓	×	✓	✓
	Birolini et al. (2019)	Milan-Bergamo airport, Italy	Investigate air passengers' choice of access mode at low-cost airports	Low-cost airline passengers are not exclusively cost-driven for access mode choice and value access time savings	✓	✓	×	✓	✓
	Bergantino et al. (2020)	Apulia, Italy	Analyse residents' decisions regarding airport access mode	Frequency of public transport is pivotal	✓	✓	✓	×	✓
	Vasconcelos (2020)	Lisbon, Portugal	Explore mode choice behaviour of air passenger	Cost of ride-hailing and number of bags are significant variables	✓	✓	✓	✓	✓
	Colovic et al. (2022)	European airports	Analyse the mode choice behaviour of passengers	Increased reliability of public transport modes will encourage their usage	✓	✓	✓	✓	✓
	Risby et al. (2022)	Bristol, UK	Analyse the airport employees surface access habits	Convenience and reliability are common factors, and cost and family commitments are secondary factors affecting mode choice	×	×	×	×	×
	Graham et al. (2023)	UK	Assess ground access journeys of ageing passengers	Ease of journey and comfort are key factors, environmental concerns play minimal role	✓	✓	×	✓	✓
	Warnock-Smith and Fake (2023)	Bristol, UK	Assess journey-to-work of employees	Trip cost and convenience significantly influence commuting choices, with limited regard for environmental impact	✓	✓	×	✓	×
	Yilmaz et al. (2023)	27 UK airports	Assess the employee related ground access strategies	Initiatives encouraging remote working and active travel will be the focus in future	✓	✓	✓	✓	✓
Asia	Jou et al. (2011)	Taoyuan International Airport, Taiwan	Investigate airport ground access mode choice after introduction of an MRT	Out-of-vehicle TT and in-vehicle-TT are two important factors affecting outbound travellers' choice of airport access mode	✓	✓	✓	✓	✓
	Alhussein (2011)	Riyadh, Saudi Arabia	Identification of access mode characteristics and users	Income, luggage, travel access time, and nationality significantly affect mode choice	✓	✓	×	×	✓
	Chang (2013)	Taipei International Airport, Taiwan	Study mode choice of elderly passengers	Safety is the most important factor for elderly and elderly less likely to use public transport	✓	✓	✓	×	✓
	Alkaabi (2016)	Dubai, UAE	Model airport employees' commuting mode choice	Income, employment status, parking permit and parking reimbursement are key factors	✓	✓	✓	×	✓
	Gokasar and Gunay (2017)	Istanbul, Turkey	Analyse ground access mode choice using MNL model	Distance to airport, destination, trip cost, automobile ownership and employment status were significant variables	✓	✓	×	×	✓
	Zaidan and Abulibdeh (2018)	Doha, Qatar	Analyse mode choice characteristics of passengers	Trip and socioeconomic characteristics significantly affect mode choice	✓	✓	×	×	✓
	Muthkur and TR (2021)	Bengaluru, India	Study surface access to airport	Preference for private cabs due to ease of carrying luggage and door-to-door service	✓	✓	×	×	✓
	Shao et al. (2023)	Xi'an Xianyang, China	Explore the effect of low-carbon incentives on ground access mode choice	Travellers prioritize emissions reduction and consciously prefer sustainable mobility options	✓	✓	✓	×	✓
	Varzeghani et al. (2023)	Mehrabad, Iran	Understand mode choice for ground access to airport	Business travellers and those who drive to the airport are less likely to switch	✓	✓	✓	×	✓

Note: MNL: multinomial logit; MRT: mass rapid transit; TT: travel time.

3.1. Impact of travel behaviour

Understanding travel behaviour in the context of airports landside access is crucial for developing sustainable transportation solutions. Landside access refers to the modes of transport used by passengers and employees for travelling to and from airports, and encompasses the choices individuals make regarding transportation modes, such as cars, taxis, buses, rail, or other alternatives. Studying travel behaviour, in this context, is essential as it provides insights into the factors influencing mode choices and helps identify opportunities for promoting sustainability. By understanding the preferences, needs, and decision-making processes of travellers, stakeholders can develop strategies to encourage the adoption of more sustainable modes, reduce congestion and emissions, thereby enhancing the overall efficiency in landside access. The reviewed literature in this context is presented in Table 1.

Travel motivation – Travel needs and preferences of various segments of travellers accessing the airport – such as those embarking on leisure trips, business travel, shopping excursions, or returning from trips – vary significantly. For instance, a person travelling for leisure may be less concerned about the travel time of the access mode compared to a business traveller. Similarly, the landside access time may be of higher importance when going to the airport to catch a flight, and of less importance when arriving from a trip and returning home. Further, individuals who are preparing to take a flight may tend to prioritize factors such as travel time and reliability of the airport access mode over travel expenses. The complexities of travel behaviour are further compounded by considerations such as selecting specific airlines, airports, deciding whether to fly or not, and determining the frequency of air travel. With regard to the choice of air travel, one emerging trend that has gained significant traction is the environmentally conscious behaviour of travellers (Gössling and Dolnicar, 2023). Increasingly, individuals, particularly certain groups of the younger population, are opting to fly less or avoid air travel altogether. Instead, they are choosing alternative modes, such as rail, when available, as it is considered more environmentally friendly. There is also a growing preference for "green airlines" that prioritize sustainable practices and have the lowest emissions (Baumeister et al., 2022; Mayer et al., 2012). Thus, it is important to recognize that travel motivation and behaviour in the context of airport is complex and dynamic, requiring a deeper understanding of the underlying factors and preferences of travellers.

Transport modes – Road-based access modes, including private cars, conventional taxis, ride-hailing services (also referred to as transportation network companies or TNCs), and buses, dominate the modal share for landside transport in most airports, and rail-based transport options such as train or metro are not always available at airports. This is seen more often in cases where newly constructed larger airports are situated at a considerable distance from the city centre, beyond the reach of existing rail or metro lines. However, wherever available, the rail services have a major contribution in the total share of public transport. The private cars are used either to drop-off/pick-up passengers (which generates four trips) or parked at the airport for the duration of the traveller's trip (which generates two trips). Private cars are often preferred due to their higher convenience from door-to-door service, ease of carrying luggage, perceived reliability, and safety. Several studies also highlight the high share of taxi trips to access or egress the airport which is not the best option from a sustainability standpoint (Castillo-Manzano, 2010; Muthkur and Nikhil, 2021; Vasconcelos, 2020). The decision to use a taxi can be influenced by several factors including the desire for a dependable mode, the preference to avoid transfers, concerns about safety, and in some cases the availability of travel allowances. To achieve landside sustainability, it is vital to assess the characteristics and performances of the existing modes and encourage the choice of sustainable modes such as public transport, walking, and cycling.

Mode choice – The choice between public and private modes of transport for airport access is significantly influenced by the characteristics of each mode, as highlighted by a number of studies in Europe and other regions. For instance, Castillo-Manzano (2010) examined the behaviour of passengers choosing low-cost and network airlines in Spanish airports, specifically focusing on the city-airport connection and access mode choices. It is seen that low-cost carrier passengers preferred rented cars and public transport compared to taxi. Bergantino et al. (2020) conducted research in an Apulian context (Italy) and found that increasing the frequency of direct bus services had a positive impact on the proportion of passengers opting for buses. Notably, the authors emphasized the price sensitivity of non-airport users compared to airport passengers, highlighting that a higher-priced frequent bus service might not attract non-airport users. Colovic et al. (2022) extended the analysis to multiple European countries and concluded that improving the reliability and reducing waiting times of public transport modes would encourage a shift from private cars to public transport. Additionally, Chang (2013) examined data from Taipei, Taiwan and made an intriguing observation that elderly passengers preferred low-cost public transport, while younger passengers showed a greater interest in having a high-frequency public transport service available. These four studies collectively emphasize the significant role of factors such as frequency, reliability, price sensitivity, and demographics in shaping the choice between public and private transport modes.

Trip purpose – There is a relative dearth of research considering trip purpose as a determinant of mode choice. One recent study, considering the purpose of the trip, by Varzeghani et al. (2023) in Mehrabad, Iran focusses specifically on business travellers and conclude that those business travellers who drive are less likely to switch to public transport. Moreover, as expected, most of the studies focus on the travel behaviour of passengers and limited attention has been given to understanding the travel behaviour of employees. The employees working at airports access the airport on a daily basis, thereby leading to a different set of travel behaviour and transportation requirements; understanding this is crucial for promoting the use of public transportation modes, which is currently low among employees (Risby et al., 2022; Warnock-Smith and Fake, 2023). Several studies have shed light on this topic, revealing valuable insights which point again towards the important role of travel time and reliability of public transport. For instance, Risby et al. (2022) conducted a study at Bristol Airport (UK), which found that approximately 34 % of employees start work between 6 pm and 6 am, with 86 % of them favouring their own vehicles for accessing the airport. The study revealed that factors such as travel time, reliability, and convenience were "highly important" in influencing their mode choice. However, the study also highlighted the challenge of changing employees' commuting behaviour due to their habitual reliance on personal vehicles. Similarly, Yilmaz et al. (2023) examined 27 UK airports and reported that over 95 % of employees at smaller airports predominantly use private cars. The study emphasized the need

for direct buses, discounted public transport tickets, and more frequent services to encourage a shift towards public transportation. In Dubai, Alkaabi (2016) found that unlike in the UK, most airport employees preferred public transport mainly because the airport was located close to the city. However, the proposed approaches for increasing the share of public transport were similar to the studies by Risby et al. (2022) and Yilmaz et al. (2023), focusing on discounted prices/passes, faster travel options, and availability during specific work hours. These studies collectively highlight the importance of considering the unique needs of the airport employees when designing transportation solutions.

Influence of environmental concerns – There is evidence of growing awareness about the environmental impact of air travel which influences the travel behaviour (e.g. choice of airline or frequency of air travel). However, conflicting findings are observed regarding the influence of environmental concerns on ground access mode choice. For instance, a recent study conducted by Graham et al. (2023) in the UK focused on analysing the mode choice of ageing passengers and found that environmental concerns played a minimal role in their decision-making process. On the other hand, Shao et al. (2023) investigated the impact of low-carbon incentives on mode choice in Xi'an Xianyang, China and concluded that travellers prioritized emission reduction and showed a preference for sustainable mobility options. These disparities highlight the variations in behaviours and preferences among individuals in different regions and contexts. More studies are necessary to understand how environmental concerns of an individual impact ground access mode choice.

In conclusion, the reviewed literature pertaining to landside sustainability from the perspective of travel behaviour highlights a number of key influencing factors. Firstly, we note that the impact of luggage, preference for door-to-door service, and the needs of business travellers cannot be overlooked. Secondly, the distance to the airport emerges as a significant variable that influences travel behaviour. The proximity of the airport to the passengers' origin or destination affects their mode choice and the associated environmental impacts. As expected, the quality of public transport also holds importance with factors such as frequency, reliability, and ease of travel significantly impacting passengers' decision to use public transportation. Thus, investments in robust and efficient public transport systems that cater to the needs of airport travellers can encourage the shift from private vehicles to more sustainable modes. Also, considering the travel behaviour of airport employees is vital for promoting sustainability, and providing active travel options as well as supporting remote working arrangements can reduce the reliance on single-occupancy vehicles. Lastly, safety concerns, particularly for elderly passengers, need to be considered for promoting an inclusive public transport system.

3.2. Impact of landside infrastructure

Landside infrastructure refers to the physical facilities and systems that support transportation in the vicinity of airports. It encompasses various elements such as road and rail infrastructure, bicycling infrastructure, pedestrian infrastructure, EV charging infrastructure, and parking infrastructure. To achieve landside sustainability, investing in and developing a robust landside

Table 2
Overview of studies focussing on the landside infrastructure of the airport.

Subject	Author(s) (year)	Airport/location (s)	Objective	Main finding
Ground access	Coogan (2008)	USA, Europe, and Asia	Identify desirable attributes of public transport (rail and van/buses)	High-frequency, direct services and off-peak hour services are important
	Orrick and Frick (2012)	Seven airports in USA	Examine how airport operators address bicycle access	Airport operators do not consider bicycle access by passengers as important segment, more potential for employees
	Reddy et al. (2016)	Delhi, Mumbai and Bengaluru, India	Understand the rail-based public transport access to airports	Connecting airport using existing metro links is more viable than building dedicated rail links
	Liu (2020)	Thirty-five airports in China	Assess the ground accessibility to major Chinese airports	Public transport needs significant improvement, need to reduce the hassles in making transfers
	Bali (2023)	Amsterdam, the Netherlands	Explore feasibility of car-free landside area	Car-free area is possible by improving public transport and active modes (walking/cycling)
Electrification	Silvester et al. (2013)	Amsterdam, the Netherlands	Explore design scenarios for the implementation of EVs	Possible to create a sustainable and comfortable urban area with well integrated electric mobility
	Richard (2014)	Several airports in North America	Summarize and describe state of EV charging stations at airport parking facilities	Airport sponsons are interested in recovering costs for providing EV charging stations by adding extra charges
	Sperling and Henao (2020)	USA	Importance and impact of EVs in cities and airports	City airports may be a critical location for providing fast-charging infrastructure
	Guo et al. (2023)	London city, UK	Techno-economic assessment of wireless charging for electrifying airport shuttle buses	Wireless charging enables electric shuttle buses to carry smaller batteries
AVs	Wang and Zhang (2019)	Florida and San Francisco, USA	Evaluate the impact of AVs on ground access and parking	AVs will significantly affect airport operation and revenue generated through parking
	Iclodean et al. (2020)	X	Review of autonomous shuttle bus	Shuttle buses can be useful in niche areas of public transport and through airports
	Hájnik et al. (2021)	Europe	Evaluate the use of electric and AVs at airports in Europe	Use of EVs and AVs reduces emissions from the airport
	Karam et al. (2024)	USA	Estimate the impact of privately-owned AVs on airport demand	Growing share of passenger leakage to large hub airports due to AVs

Note: EV: electric vehicle; AV: autonomous vehicle.

infrastructure is crucial. The availability and quality of infrastructure plays a significant role in shaping travel behaviour and mode choice decisions. For instance, it has been reported that areas with well-developed public transportation infrastructure tend to have a higher share of public transport usage, and vice versa (Buehler and Pucher, 2012; Georgakopoulos et al., 2023). Additionally, the presence of dedicated bicycle lanes and pedestrian-friendly walkways can encourage the adoption of sustainable modes of transportation and reduce reliance on private vehicles (Adsule and Kadali, 2024; Aziz et al., 2018; Hong et al., 2020). Literature related to landside infrastructure is classified into three categories: ground access, electrification, and autonomous vehicles (AVs) (Table 2).

Ground access – Regarding ground access by public transport, two studies evaluated the existing public transport infrastructure to the airport. The research conducted in India emphasizes the importance of leveraging existing public transport links rather than building new infrastructure to improve passenger connectivity (Reddy et al., 2016). In China, it has been reported that public transport systems need improvement to reduce transfer hassles (Liu, 2020). Concerning ground access by bicycles, based on a study on seven airports in the USA, Orrick and Frick (2012) reported that bicycles have limited potential for passenger access but show greater potential for employees. This review examined policy documents and research literature to identify eight influential elements in promoting bicycle access to airports including factors such as location, access roads, self-perceived environmental stewardship, spending restrictions on non-aviation transportation improvements, proximity to transit, and policies to reduce environmental impacts. While the review noted that passengers are free to use bicycle facilities, the convenience and logistical challenges may hinder their utilisation. However, the case study of Portland International Airport (PDX) demonstrated that developing employee bicycle facilities can eventually lead to increased demand from passengers, thus leading to increased sustainability of the landside area. It should however be noted that PDX is an outlier as bicycles are extraordinarily popular in Portland unlike other North American cities, and providing bicycling infrastructure and parking facilities may not be financially beneficial everywhere. More studies are needed to explore the role of ground access infrastructure (such as public transport and bicycle) in enhancing landside sustainability.

Ground access by rail – Rail-based transportation is essential for decarbonizing large airports in metropolitan areas. The ACRP Report 4 (Coogan, 2008) identifies several desirable attributes of rail access to airports considering locations in the USA, Europe, and Asia. The key attributes of effective rail services include direct connections, walkable access between stations and terminals, a comprehensive network, and minimal travel time to gates. The report also highlights that frequent service, ideally with wait times of 10 min or less, enhances usability, and travellers with few or no checked bags are more likely to use the rail service. Furthermore, rail services contribute to reducing congestion and decarbonizing airport access wherever provided. Integrating rail with other modes (such as bicycles) for first and last mile connectivity could be a successful solution, particularly for airport employees.

Electric vehicles (EVs) – With growing numbers of EVs, providing charging infrastructure at airports is crucial and studies indicate that airport operators are facing new challenges in providing and managing EV charging infrastructure, which is typically located in the parking lots. For instance, the study by Richard (2014) highlights that airports are concerned about future trends and technology, the potential for generating revenue, and the advantages and disadvantages of installing EV charging stations in their parking lots. An open and important question, in this context, is whether to introduce an additional charge for using EV charging stations. In some West Coast airports in the USA, the demand for charging exceeds the current supply, leading operators to install additional stations and increase the number of parking spaces dedicated to EVs. Newer airports face challenges in determining the optimal number and location of charging stations, as well as the required electrical infrastructure. In this regard, Sperling and Henao (2020) explored the emerging trends, describing airports as "engines of regional economic growth" and emphasising the need for evolving airport infrastructure to accommodate more passengers with sustainability in mind. The authors state that airports could serve as testbeds for data-driven insights towards improving the financing of multimodal, right-sized electric transportation, though there are uncertainties around future parking demand that may impact the viability of such investments. Clearly identifying EV infrastructure requirements and catering to the needs of EV users is essential to reducing emissions from landside activities.

Autonomous vehicles (AVs) – With regards to AVs, in a review conducted by Iclodean et al. (2020), autonomous shuttle buses in Korea were examined, highlighting their potential benefits in terms of improving transportation efficiency and reducing congestion. In another study related to AVs, Hájnik et al. (2021) reports that the adoption of EVs and AVs can contribute to a significant reduction in emissions from airports, promoting sustainability within the aviation industry. However, Karam et al. (2024) conclude that AVs could potentially lead air travellers to favour large-hub airports which are located farther compared to the local airports, resulting in increased emissions. These findings related to AVs provides insights that can inform efforts towards enhancing their infrastructure considering sustainability.

Summary – The literature reviewed in this section highlights the varying degrees of research focus on different elements of landside infrastructure with more studies needed on certain aspects. For instance, while there is a growing body of research on EV charging infrastructure, studies on bicycle infrastructure and pedestrian infrastructure are limited. Also, there are fewer studies examining the impact and potential of shared mobility services in airport landside access. However, there is promising research on the use of EVs and AVs in reducing emissions, as well as on the operation of shuttle buses. To fully realize the potential of landside sustainability, there is a need for business models that encourage both airport operators and users to invest in and utilize charging and parking infrastructure. Additionally, there is significant potential for improving bicycle infrastructure, particularly for employees, to further promote sustainable modes.

In conclusion, the transport infrastructure related to ground access by public transport (including buses and rail), electrification, and autonomous vehicles (AVs) plays a crucial role in achieving a sustainable landside environment at airports. Considering ground access, bicycles are often not considered by airport operators as an important segment due to longer travel distances from home to the airport, difficulty in carrying luggage, and potential revenue loss for airport operators. From a financial viewpoint, the cost of providing the infrastructure related to bicycles may not justify the expected benefits in all contexts. It is also highlighted that instead of building dedicated rail links, utilizing existing rail connections can be a practical and sustainable approach. The introduction of EVs

Table 3
Overview of studies focussing on the landside transport policy.

Subject	Author(s) (year)	Airport/location	Objective	Main finding
Public transport	Matheys et al. (2008)	Brussels, Belgium	Analyse current passenger transport to and from airport	Capacity of public transport needs to be increased and a new tramline is proposed
	Orth et al. (2015)	Zurich, Switzerland	Determine whether the non-aeronautical activities are beneficial for operating public transport services	Non-aeronautical development contributes to public transport use
	Oprea et al. (2018)	Bucharest, Romania	Develop methodology for correlating transport capacity and transport schedules	More frequent buses for both arriving and departing passengers
	ITF (2018)	Mexico City and five other airports	Review planning framework for airport expansion and decisions to invest in rail, metro, and bus links	Prioritize investments in public transport to relieve congestion and pollution
Ride-hailing	Mandle and Box (2017)	USA	Review opportunities and challenges posed by TNCs	Increased congestion at 46 % of airports with 5–30 % decrease in taxicab trips and parking customers down by 5–10 %
	Henao and Marshall (2019)	Denver, Colorado, USA	Investigate the impact of ride-hailing on parking	Ride-hailing could reduce parking demand
	Leiner and Adler (2020)	USA	Identify strategies for adapting landside access programs	Reduced use of taxis, establish performance indicators to reduce impact on emissions; permit operations that reduce deadhead trips and provide incentives for EV/AFVs
	Wadud (2020)	JFK, Newark Liberty International, and LaGuardia, USA	Investigate the effect of the entry of ride-hailing services on airport parking patronage	Introduction of ride-hailing services caused a significant reduction in the number of cars parked
	Dong and Ryerson (2020)	JFK and LGA, New York, USA	Investigate the effect of introducing ride-hailing services on taxi trips, train trips, and parking	High-quality transit services connecting airport with city centres could continue to serve as crucial access mode*
	Zuniga-Garcia and Machemehl (2021)	Austin, USA	Evaluate impact of transportation network companies on airport ground access	Ground access speeds were higher during the period when TNCs were not operating
	Swami et al. (2023)	Guwahati, India	Examine the use of ride sourcing taxi services	Age, luggage, convenience, and travel information are significant factors

Note: TNCs represent transportation network companies, also called as ride-hailing platforms. These companies provide transportation services using smartphone applications such as offering on-demand vehicle with a driver. In other words, they connect passengers seeking a ride with nearby drivers providing rides.
*The travel patterns and share of public transport in other North American cities may differ significantly from those in New York City.

holds great potential for sustainability; however, until they become more economically viable, financing and subsidy programs are necessary to facilitate their widespread adoption. It is also emphasized that EV charging infrastructure for buses and taxis should be a key focus area. Moreover, the integration of EVs and AVs can significantly impact landside emissions and air quality. However, to realize these benefits, dedicated infrastructure upgrades and careful planning are essential.

3.3. *Impact of transport policy*

Transport policy refers to the set of regulations, guidelines, and strategies implemented by governments and transportation authorities to manage transportation systems. In the context of airports, transport policies play a crucial role in addressing various challenges related to landside access including congestion and emissions. These policies encompass a range of factors, including investment in new infrastructure such as EV charging stations, increased operation of public transport, regulation of ride-hailing services, and the implementation of parking charges. To ensure efficient and sustainable landside access, airports and transportation authorities need to develop and implement effective transport policies that balance the needs of different stakeholders, promote sustainable modes, and address the environmental and economic impacts. The literature review related to transport policy in the context of airport landside access and sustainability revealed papers focussing mainly on two aspects, namely public transport and ride-hailing (Table 3).

Public transport – Public transport-related policies are crucial for improving accessibility and some studies have rightly examined these at a deeper level. It is well known that, in contrast to urban areas, the demand for travel to and from an airport is often insufficient, falling below the minimum threshold required for operating a financially sustainable public transportation system. The work by Orth et al. (2015) on Zurich airport shows that the impact of non-aeronautical activities, such as shopping and offices, can increase the demand for public transport, making it viable for airports to provide these services. Their work also emphasises the importance of locating the public transport station in close proximity to these passenger-attracting facilities. Furthermore, Oprea et al. (2018) highlights the broader need to improve multimodal transport systems serving airports, including increasing the frequency of bus services. It is found that high-quality transit services continue to serve as crucial access modes for airport landside transport (Dong and Ryerson, 2020). In particular, it is highlighted that the frequency and capacity of public transport needs to be high to make it attractive for both passengers and employees (Matheys et al., 2008; Oprea et al., 2018). These findings relate to promoting non-

aeronautical activities and developing multimodal transport systems underline the significance of cooperation between various stakeholders, such as airport operators, local authorities, and public transport providers, to enhance the integration and accessibility of sustainable transportation options for airport users.

Public transport (employees) – In the context of the USA and Europe, the ACRP report 4 (Coogan, 2008) identified several desirable attributes of public transport for employees. First, it is essential to ensure that the travel time and comfort levels of public transport are comparable to those of private vehicles. The extent and adequacy of the area served by public transport also play a critical role; services should be targeted to regions with a high potential for employment. Additionally, the proximity and accessibility of public transport services at both trip origins and destinations are crucial factors influencing employee choices. Combining dedicated commuter buses with remote parking lots has been successful in several American airports (e.g. Logan Express bus service, Boston, USA). Moreover, the availability, cost, and convenience of parking at the workplace can significantly impact the decision to use public transport. It is also vital to consider the extent and adequacy of public transport service hours and perceived safety, as these factors can deter potential users. Further, the ACRP Synthesis report 127 (Mandle et al. (2023) suggests supporting carpooling and vanpooling, providing subsidy for transit fares, and supplementary bus services for airport employees.

Ride-hailing – In addition to public transport, ride-hailing is also a popular choice for accessing the airport. Ride-hailing is the term used when a passenger uses a smartphone app for securing access to a car with a driver, with the companies providing this service referred to as "transportation network companies (or TNCs)". These companies have indeed made a significant impact on the way people travel to and from the airports. Based on the review of studies focussing on the impact of ride-hailing, it is seen that ride-hailing services have a significant impact on the operation and efficiency of landside transportation, both positive and negative. On the one hand, they can reduce the number of cars parked at airports which means lesser demand for parking (Henao and Marshall, 2019; Wadud, 2020). On the other hand, ride-hailing services can lead to a reduction in speeds on access roads, potentially impacting overall efficiency and congestion levels (Zuniga-Garcia and Machemehl, 2021). It is seen that the quantity of luggage and convenience are two crucial factors that encourage the adoption of ride-hailing services (Swami et al., 2023). Moreover, the possibility of tracking the ride provides a feeling of safety compared to traditional taxi services that do not have this option, which could be of prime importance for a solo traveller in an unfamiliar city. In summary, it is evident that ride-hailing has significantly impacted overall travel behaviour in numerous unprecedented and unanticipated ways, and it is important to formulate and implement suitable policies to regulate their operation near airports while prioritising sustainability. It is important to note here that TNCs may generate more trips and vehicle emissions than private vehicles (drop-off/pick-up) as there are four trips — passenger drop-off, deadhead exit, deadhead return for pick-up, and exit from the airport with passenger — compared to two trips for vehicles parked at the airport. For a detailed generic review of the travel behaviour and sustainability impact of ride-hailing, the reader is referred to Tirachini (2020).

Impact of ride-hailing on parking – The existing research indicates that ride-hailing is impacting traditional airport access trips by

Table 4
Overview of studies focussing on the landside sustainability of the airport.

Subject	Author(s) (year)	Airport/ location	Objective	Main finding	Methodology
Sustainability practices	Ison et al. (2014)	UK and Australia	Examine the spatial and temporal aspects of ground access to airports	Australian airports do not use environmental targets in ground access plans	Review of literature and reports
	Budd et al. (2016)	Six airports in London, UK	Analyse the surface access strategies and examine potential for improved environmental performance	Public transport has a major role in minimising the environmental impact of surface access	Case study
	Harley et al. (2020)	413 small European airports	Investigate range of environmental practices employed and identify factors affecting their adoption	Consumer pressure, regulatory intervention, and airport size have positive effect on adoption of environmental practices	Regression model
	Greer et al. (2020)*	×	Synthesize the current state of environmental sustainability metrics and methods for airports	Electrifying ground transportation and gate equipment can in the short-term help in moving towards sustainability goals	Literature review and synthesis
	Mandle et al. (2023)	USA, Canada, and Europe	Synthesize the initiatives to reduce carbon emissions from vehicles	Carpooling and vanpooling by employees was frequently used carbon reduction measure	Review of literature and reports
	National Academies of Sciences (2015)	USA and Canada	Describe best practices with respect to commercial ground transportation	Use of clean and alternative fuel vehicles, reduction in deadhead trips, and access fees are suggested	Survey of airport staff
Emissions estimation	Miyoshi and Mason (2013)	Manchester Airport, UK	Estimate carbon footprint of passengers on airport surface access	Higher CO_2 emissions and greater cost of damage due to private modes ("drop-off and pick-up" and "minicab" users)	Bottom-up approach
	Corazza et al. (2022)	Ciampino, Rome, Italy	Quantify and compare magnitude of emissions generated by both air and surface traffic	CO_2 emissions from road system is significantly low compared to the emissions from aircraft	Case study
	Ravi and Raju (2022)	IGI Airport, Delhi, India	Study the sustainability initiatives of the airport	Passenger access contributes 11.5 % to total CO_2 emissions	Case study

*The article by Greer et al. (2020) is a review article which does not focus on one airport or region.

private vehicle, thereby reducing the overall demand for parking (Henao and Marshall, 2019). This shift necessitates a well-thought-out policy response from airport authorities to adapt to the changing transportation landscape. In this regard, a key area of focus should be the design of efficient pick-up and drop-off zones for ride-hailing users, addressing critical issues such as passenger safety, customer experience, and the ease of connecting drivers and passengers (Dong and Ryerson, 2020). Moreover, the loss of revenue from reduced parking demand may potentially negate the need for constructing additional parking infrastructure, warranting a re-evaluation of long-term versus short-term parking requirements (Wadud, 2020). To compensate for the loss of parking revenue, airport operators may need to explore business agreements and revenue-sharing models with ride-hailing companies (Wadud, 2020). This approach could help mitigate the impact on airport finances while recognizing the competition posed by ride-hailing services against traditional taxi services. Overall, this analysis underscores the pressing need to assess the impact of ride-hailing on parking, revenue generation, and subsequently on the regulation of ride-hailing to address the challenges related to congestion and sustainability.

Summary – It is evident that appropriate policies are crucial for both public transport and ride-hailing domains. For public transport, factors such as frequency, pricing, comfort, convenience, and capacity play significant roles in attracting passengers. The implementation of correct policies in these areas is essential to ensure their efficiency and sustainability. On the other hand, the rise of ride-hailing services presents complex and dynamic challenges such as impacting public transport ridership, causing a decline in

Table 5
Highlights from the recent annual/sustainability reports of large airports worldwide.

Airport (IATA code)	Target/Goal	Key strategies/initiatives/programs			Reference
		Transport Infrastructure	Transport policy	Environment	
Boston Logan (BOS), USA	Net-zero by 2031	• Expanded EV fleet • Hybrid vehicles	• Promote HOVs	×	Massachusetts Port Authority (2022)
Dallas Fort Worth (DFW), USA	Net-zero by 2030	• Vehicle electrification • Renewable fuels	• Enhanced public transportation	×	Dallas Fort Worth International (2018)
Los Angeles (LAX), USA	Carbon neutral by 2045	• Charging infrastructure • Smart parking system (routing info to drivers)	• Clean fleet program • Improve access to employees (biking, carpool, vanpool, PT) • TNCs: Encourage low emission vehicles	• LEZs and ZEZs	Los Angeles World Airports (2019)
Phoenix Sky Harbor (PHX), USA	Net-zero by 2040	• EV charging stations • Electrified people mover (Sky Train)	• Fully electric TNCs	• Carbon removal technologies	Young et al. (2023)
San Francisco (SFO), USA	Net-zero by 2030	EV infrastructure	Transit-first policy	×	San Francisco International Airport (2021)
London Heathrow (LHR), UK	Net-zero by 2050	• On-demand public transport • EV charging stations • Dedicated taxi waiting area	• Cycling and walking plan • Increase use of public transport • Reduce employee travel by car • Annual employee travel survey	• Use of biodiesel as interim solution • Uptake of zero emission vehicles	London Heathrow (2022)
Amsterdam Schiphol (AMS), the Netherlands	Emission-free by 2030	• Extra EV charging stations • Self driving cars, car sharing service for passengers and employees	• Promote public transport	• Zero-emission mobility • ZEZ for vans and lorries • Measurement of UFP concentrations	Royal Schiphol Group (2023)
Dublin (DUB), Ireland	Net-zero by 2050	• EV charging infrastructure	• Access to public transport, walking and cycling	×	Dublin Airport (2022)
Sydney (SYD), Australia	Net-zero by 2030	• Electric bus and vehicle fleet • Shared cycle and pedestrian pathway	×	• Air quality monitoring	Sydney Airport (2022)
Melbourne (MEL), Australia	Net-zero by 2025	• EV pilot program • EV charging infrastructure	×	×	Australia Pacific Airports Corporation (2023)
Brisbane (BNE), Australia	Net-zero by 2025	• Bus rapid transit • EV charging stations	• Enable EVs • Parking incentives	×	Brisbane Airport Corporation (2023)
Toronto Pearson (YYZ), Canada	Net-zero by 2030	• EVs and charging stations	• Improving transit connectivity	• Air quality monitoring	Greater Toronto Airports Authority (2022)
Tokyo Narita Airport (NRT), Japan	Net-zero by 2050	• Fast chargers for EVs • Hydrogen stations	• Promote low emission vehicles • Autonomous bus	• Air quality monitoring	Narita Airport (2022)

Note: Net-zero is for Scope 1 (direct emissions) and Scope 2 (indirect emissions due to consumption of purchased electricity).
Abbreviations: HOV: High-Occupancy Vehicle; IATA: International Air Transport Association; PT: public transport; EV: electric vehicle; LEZ: low emission zone; ZEZ: zero emission zone; TNC: transport network companies; UFP: ultrafine particles.

regular taxi businesses, and a subsequent loss of revenue for airports due to reduced demand for parking. Additionally, congestion issues arise at unexpected locations as ride-hailing services operate in most locations without a dedicated infrastructure. Consequently, it is imperative to carefully regulate and monitor ride-hailing services to ensure ease of travel for commuters, maintain business opportunities for airport operators, and promote sustainability in landside areas.

3.4. Aspects related to landside sustainability

Air pollution and noise pollution are important considerations in the context of airport landside. Air pollution refers to the presence of harmful substances in the air, such as ultrafine particles (UFP), $PM_{2.5}$ (particulate matter with an aerodynamic diameter of 2.5 μm or less), and nitrogen dioxide (NO_2). Noise pollution, on the other hand, refers to excessive or unwanted noise that can have detrimental effects on human health and well-being. The magnitude of emitted air and noise pollution is directly or indirectly influenced by various factors, including travel behaviour, transport infrastructure, and transport policy. For instance, the choices individuals make regarding access modes, and the existing transport infrastructure can impact air and noise pollution levels. Moreover, transport policies that promote sustainable and low emission options can help mitigate the environmental impacts of airport landside access systems. Monitoring indicators such as the concentration of UFP, $PM_{2.5}$, NO_2, and noise levels are increasingly being used to assess the environmental impact and to formulate mitigation plans (Masiol and Harrison, 2014). The relevant literature in this context is classified into two categories, namely, sustainability practices and emissions estimation based on the objective and findings of the study as presented in Table 4.

Sustainability – Studies have examined the environmental performance of airports, their sustainability initiatives, and net-zero plans with limited number of studies in regions outside of Europe. This is a major concern that needs to be addressed to achieve global environmental targets. As for the UK and Australia, Ison et al. (2014) reported that there is a lack of integration of environmental targets in ground access plans, which hampers efforts to reduce pollution levels effectively. Furthermore, Budd et al. (2016) concluded that improving the attractiveness of public transport in the UK should be the focus for achieving higher sustainability. Bearing the adoption of environmental practices in mind, Harley et al. (2020), examined 413 small European airports, underscoring the significance of consumer pressure and regulatory intervention in driving the adoption of environmental practices. More specifically, the electrification of ground transport is identified as a direct and significant factor in mitigating air and noise pollution (Greer et al., 2020). Understanding the impact of the sustainability practices is key for mitigating the environmental consequences of landside activities.

Emissions estimation – In order to accurately assess the environmental impact of airport operations, it is also crucial to quantify the emissions originating from landside access activities as well as those generated by aircraft. Several studies have explored this domain yielding interesting findings. For instance, Miyoshi and Mason (2013) conducted a study at Manchester Airport in the UK, highlighting the significant cost associated with CO_2 emissions resulting from passengers' surface access (10.9 GBP at 2009 prices). The authors identified reducing "drop-off and pick-up" activities as a substantial opportunity for emission reduction. Notably, among various modes, the combined total CO_2 emissions attributed to drop-off and pick-up, private car, and minicab (pre-booked taxi) accounted for 92 %. Similar investigations focusing on the cost of emissions from landside access trips to airports in other regions could prove valuable. In addition to road transport emissions, Corazza et al. (2022) considered the emissions from aircraft, taking into account different aircraft types and operational phases (such as take-off and taxiing). Consequently, the authors quantified emissions from both landside and airside areas. The absence of a high-capacity rail link to the airport and the substantial reliance on passenger cars were identified as major factors contributing to elevated landside emissions. Furthermore, when comparing the annual CO_2 emissions generated by road transportation systems at airports (228,479 kg) and those emitted by aircraft operations (64,278,872 kg), it became apparent that road transportation contributes less than 1 % of the total emissions. The authors propose measures to mitigate emissions from air operations such as reducing taxiing delays, minimizing engine thrust during take-off, and employing dispatch towing (Corazza et al., 2022). These measures can be complex and require collaboration with airline operators; in contrast, it is easier to reduce emissions from landside access activities.

In conclusion, many airports have yet to consider environmental targets in their ground access plans, and there is a lack of uniformity in evaluating environmental practices (particularly outside the USA) and understanding the factors influencing their adoption. To drive sustainable practices, it is crucial to establish standardized evaluation methods and gain a comprehensive understanding of the factors influencing the adoption of environmental initiatives (Jia et al., 2024). Moreover, as reported in one of the studies, although the emissions from landside transport systems are notably lower compared to those from the aircraft, it is more practical and cost-effective to focus on addressing the emissions from landside vehicles, which could be the "low-hanging fruit" in emission reduction efforts. It is emphasized that the emissions in the landside area not only have a direct impact on the health and well-being of passengers and workers, but also more feasible to decrease in the short-term. On the whole, by addressing the challenges related to the adoption of sustainability practices and implementing emission monitoring programs, airports can make significant strides toward creating a greener landside environment.

3.5. Net-zero plans and key strategies of large airports

The net-zero concept is an emissions reduction goal that aims to achieve a balance between the amount of greenhouse gases emitted into the atmosphere and the amount removed from it (Fankhauser et al., 2022). In the context of airports, the net-zero approach is highly relevant as the aviation industry is a major contributor to global GHG emissions and airports have a responsibility to demonstrate the implementation of sustainability practices (Jia et al., 2023). This involves reducing direct emissions from on-site

operations, such as ground vehicles powered by fossil fuels, as well as working with airlines and other stakeholders to address indirect emissions. By striving for net-zero emissions, airports can not only reduce their carbon footprint but also position themselves as climate-friendly mobility centres, appealing to environmentally conscious travellers and aligning with broader societal efforts to combat climate change. The path to net-zero will require significant investments in renewable energy, energy efficiency, sustainable aviation fuels, electric vehicles, and innovative technologies (Chen et al., 2022), but the long-term benefits make it a crucial goal for airports to pursue. It is evident from the annual reports published by the airport operators that most of them are committed to achieving their net-zero targets.

Net-zero targets – Recent annual reports and sustainability reports are valuable resources for understanding the targets and strategies for reducing emissions and promoting sustainability as they outline ambitious goals, including net-zero and carbon–neutral plans. In this context, we reviewed the reports obtained from the websites of airports; and it is encouraging to see that some large airports in developed countries have committed to achieving net-zero emissions within a relatively short timeframe (see Table 5). For example, Melbourne and Brisbane airports aim to achieve net-zero emissions by 2025 (Australia Pacific Airports Corporation, 2023; Brisbane Airport Corporation, 2023). Although the targets are promising, it is important to note that such commitments are primarily observed among larger airports in developed countries, while smaller airports (which are the majority) and those in developing regions may have different priorities when it comes to sustainability. However, lessons learned from the larger airports can to an extent inform and guide the smaller regional airports towards framing net-zero targets and identifying approaches to accomplish them.

Strategies and initiatives – There are several strategies being employed to enhance the sustainability of landside access including setting up EV charging stations, enhancing public transport, establishing Low Emission Zones, monitoring air quality with a focus on ultrafine particles, and utilizing technology to improve parking systems (Table 5). While these strategies are commonly used, each airport also has its unique approaches. For example, airports in cities like London (LHR) recognize the importance of active modes and have developed comprehensive plans for cycling and walking (London Heathrow, 2022). They are also working towards increasing the use of public transport, raising awareness of the available public transport options, and understanding travel behaviour through initiatives such as conducting an annual travel survey. Additionally, the airport is using biodiesel as an interim solution and promoting zero-emission vehicles. In the Netherlands, Amsterdam Airport Schiphol (AMS) has a goal to become emission-free by 2030 (Royal Schiphol Group, 2023) and is actively measuring ultrafine particle concentrations to address air quality concerns. AMS also plans to introduce a car-sharing service in the future, further promoting sustainable transport options. In Tokyo Narita airport (NRT), there are plans to install hydrogen stations to support hydrogen fuel cell vehicles, showcasing their specific approach to alternative fuels (Narita Airport, 2022). Overall, these unique aspects from different airports worldwide highlight the diversity of sustainability initiatives and the adaptability of airports in addressing local challenges.

Summary – The annual reports highlight that airports have recognized the critical need for concerted actions to achieve their net-zero targets. Key strategies include driving technological innovation, implementing regular travel data collection, and conducting rigorous air quality monitoring. With regards to ground transportation, airports are pursuing a range of initiatives, such as the deployment of autonomous and shared mobility solutions. Airports are also focused on making public transit more attractive, such as through the implementation of bus rapid transit systems; and providing dedicated hydrogen fuelling stations to facilitate the use of hydrogen-powered vehicles. Notably, airports like Los Angeles (LAX) and LHR are also developing dedicated plans to incentivize employees to utilize sustainable modes of commuting, including biking, carpooling, and public transit (London Heathrow, 2022; Los Angeles World Airports, 2019). Airports are also exploring the use of autonomous buses, as seen in the case of NRT, to enhance the efficiency and cost-effectiveness of bus transportation. Finally, the reviewed reports highlight the focus on sustainable fuel (biodiesel) to reduce life-cycle environmental impact and the measurement of ultrafine particles.

In conclusion, there has been an increased focus on sustainability and emission reduction in large airports worldwide, particularly in the USA, Europe, and Australia. Each airport has implemented or planning to implement a unique array of strategies and initiatives, highlighting the diversity of approaches taken. Key areas of emphasis include the development of EV infrastructure, improvements in public transportation, and the establishment of ZEZs/LEZs. While these efforts are commendable, it is important to note that there is room for improvement, particularly in setting more ambitious net-zero and carbon–neutral targets. Additionally, the exploration of innovative fuel technologies (such as hydrogen), fast-charging EVs, and the integration of autonomous buses, showcases promising advancements in sustainable transportation. Airports can continue to make strides towards achieving their sustainability goals by enhancing these initiatives together with suitable policies and infrastructure, as discussed in the Sections 3.2 and 3.3.

Net-zero means that overall emissions released are offset by the removal or sequestration of an equivalent quantity of greenhouse gases (Fankhauser et al., 2022). On the other hand, carbon neutral refers to a condition where the emphasis is on offsetting emissions by firstly reducing emission as far as possible and then offsetting the remaining emissions by investing in projects that remove an equivalent amount of GHG from the atmosphere (Chen et al., 2022).

4. Findings, recommendations, and research directions

This section synthesizes the key findings from the reviewed literature, on the basis of which we offer recommendations for policymakers and researchers working in the domain of airport landside sustainability.

4.1. Main findings

A literature review was conducted to understand the existing knowledge, case studies, and initiatives towards achieving sustainability in airport landside areas. This is classified into four categories: travel behaviour, transport infrastructure, transport policy,

and sustainability. Emission reduction targets and key strategies regarding landside sustainability obtained from the recent reports of large airports are synthesized, leading to the identification of important factors, key variables, and significant findings. In the following paragraphs, a brief summary of the findings concerning each of the four categories is provided.

Firstly, regarding travel behaviour, studies have mainly focussed on understanding the mode choice behaviour of passengers with the intention of explaining the preference of private cars and there have been limited studies focussed on the behaviour of employees. Moreover, several of the reviewed studies focus on large European airports and indicate that the current share of passengers using private car and taxi is significantly higher compared to the share of public transport users. This preference for private cars and taxis has been mainly attributed to the convenience of door-to-door service, lack of adequate public transport options, and concerns about travel time reliability. Studies show that to promote sustainable landside operations, it is crucial to make public transportation (buses and trains) more attractive by enhancing factors such as frequency and ease of carrying luggage.

When it comes to transport infrastructure, most studies focus on examining and exploring the potential of electric mobility as a means towards reducing emissions. In this context, the charging infrastructure needs, and related technologies have been assessed and this seems to be a promising aspect for further investigation. In addition, some studies have also investigated the infrastructure requirements of bicycles, autonomous shuttle buses, and parking. Several studies have underscored the necessity of improving bicycle access for airport employees, which can be achieved through the implementation of dedicated bicycle lanes, providing secure parking facilities, introducing bike-to-work schemes, and integrating bicycles with public transport. However, more research is needed to better understand how providing appropriate infrastructure affects travel behaviour and the resulting gains in air quality.

The studies on transport policy cover a range of topics including capacity, expansion needs, investment opportunities, regulating ride-hailing services, and taxation. The studies highlight the necessity for increased investment in public transport to alleviate congestion and reduce air pollution. Research indicates that the presence of non-aeronautical developments around airports leads to higher public transport usage, highlighting the importance of incorporating such considerations into airport planning. Moreover, appropriate regulation of ride-hailing services is essential, as studies highlight their impact on parking demand, share of other transport options, and subsequent congestion at arrival and departure locations. These findings highlight the need for a comprehensive understanding of the different policies and their impact on landside sustainability.

Lastly, the studies concerning the landside sustainability explore various crucial aspects, including assessing the air quality, carbon footprint, environmental practices, and emissions. It has been found that the adoption of environmentally friendly practices is positively influenced by consumer pressure, regulatory intervention, and the size of the airport. In terms of direct emissions, research shows that emissions from the landside transport systems are significantly low compared to the emissions from the aircraft. However, this should not be the reason for overlooking the environmental impact of emissions from ground transport, which is a low-hanging fruit in relation to airport-related emission reduction and directly impacts the health of passengers and personnel. Moreover, from the review, it is emphasised that standardization plays a pivotal role in enabling a comprehensive understanding and effective comparison of sustainability practices adopted by different airports.

4.2. Recommendations for policymakers

Based on the review, the following are the major recommendations for policymakers to improve landside sustainability, many of which are already being considered by the relevant stakeholders:

- ***Facilitate public transport and electric vehicles***

Encourage and support the use of public transport options, such as buses, trains, and trams, to provide convenient and sustainable transportation to and from the airport. Since lack of convenience is seen as the most common reason to avoid the use of public transport, specific focus on addressing the problem of first mile and last mile connectivity is needed. Further, promote the adoption of EVs for airport shuttle services and incentivize EV charging infrastructure development to reduce emissions. This would encourage travellers and taxi operators to switch from fossil fuel powered vehicles to EVs, thereby promoting sustainable mobility in and around the airports.

- ***Provide real-time traveller information***

Providing real-time accurate information to the travellers is crucial for enhancing their experience and encouraging sustainable travel behaviour. This could include digital communication channels, information regarding security clearance times and queue times, information of flight schedules, parking availability by parking product, and transport options to and from the airport. While generic information in already available on the website and mobile apps of large airports, there is a need to provide personalized door-to-door travel information which could impact the travel behaviour of passengers.

- ***Develop multimodal transportation systems***

Often large airports are isolated from the city with access possible only using road-based transport leading to an increased reliance on personal vehicles, pick-up/drop-off, and taxi services. It is recommended to develop multimodal transportation systems by integrating different modes such as buses, trains, and bicycles enhancing accessibility and improving overall sustainability. Careful planning and implementation of multimodal transport infrastructure would lead to benefits including reduced reliance on private

vehicles, seamless intermodal transition, and enhancement in the overall travel experience.

- ***Promote carpooling services***

Collaborate with ride-sharing platforms and promote carpooling services for airport passengers and employees. Encourage the use of designated carpooling areas, provide incentives for carpooling, and facilitate the integration of carpooling options into airport apps and websites. Carpooling has potential to act as a substitute for public transport since it may be infeasible to provide high frequency public transport services during off-peak hours, especially to isolated airports. In addition, carpooling can reduce the demand for single-occupancy taxis, which has proven to be one of the access options with the highest per capita CO_2 emissions; other benefits include reduction in traffic congestion and demand for parking spaces.

- ***Collect travel and air quality data***

Periodic surveys should be conducted for understanding travel behaviour of passengers and employees which could include data regarding the passenger transportation modes (such as personal vehicle, public transport, and drop-off), travel patterns (including frequency of trips), and other preferences (e.g. choice of airline/airport, safety, and convenience). The findings from the surveys would help in the evaluation of the current state in terms of sustainable mobility options and their adoption, and form the basis for framing policies aimed at increasing the share of public and active transport. In addition, the air quality should be monitored to understand the present condition and evaluate the impact of any new sustainable mobility and emission reduction measures on air quality. The air quality data can also be used for evaluating the impact of exposure to air pollutants on the health of the personnel working in the landside areas.

4.3. Agenda for future research

Based on the review and limitations of the existing studies, further research on five important topics, encompassing travel behaviour, transport infrastructure, transport policy, and the environment, which would provide evidence to support policymaking is recommended.

- ***Travel behaviour of employees and safety aspects***

While extensive research has focused on understanding passenger travel behaviour, there has been limited investigation into the travel patterns of employees globally. Although their travel routine may not vary day-to-day (which is ideal for providing public transport), the nature of their work may require travel during off-peak hours when public transport services do not operate at all or operate at a reduced frequency. How can public transport be improved to retain or attract employees in different contexts is an open question. Furthermore, it remains unclear how safety aspects impact the mode choice of employees', individuals across various age groups and genders, and in different regions worldwide.

- ***Feasibility and impact of electric and autonomous vehicles***

While there are existing studies analysing the impact of EVs and related infrastructure in the context of airports, additional research is necessary to explore aspects related to fast-charging infrastructure, electrification policies of TNCs and taxis, and shared electric mobility. Research in this direction would help the policymakers in devising new and favourable financing models. Moreover, with regards to autonomous vehicles, studying the potential of AVs in providing transport services (such as the autonomous ride-hailing service operating in Phoenix Sky Harbor International Airport, Arizona, USA), assessing their energy savings, emissions reduction, integration with existing facilities, and evaluating their efficiency would provide insights into their feasibility.

- ***Demand responsive public transport***

Given the unpredictable travel demand patterns to airports, it is crucial to develop public transport systems catering to varying spatial and temporal demands. For instance, there is potential in exploring the operational and financial feasibility of buses that can take different routes, are smaller than the regular buses, and combined with a mobile app. Unfortunately, existing research (presented in Table 3) does not specifically explore the role of demand responsive public transport for trips to and from the airport. Research should focus on evaluating flexible schedules, allowing user requests, and customized vehicle routing to accommodate late-night and early-morning travel. There is also a need to evaluate the environmental benefits of providing demand responsive public transport as opposed to traditional public transport services to airport commuters.

- ***Impact of vehicle access restrictions (LEZs, ZEZs, and car-free zones)***

Research should focus on the impact of implementing low emission zones, zero-emission zones, car-free zones, and access fees near airports in passenger travel patterns and mode choice. Moreover, evaluating their impact on air quality improvement and reduction in vehicle traffic would provide valuable insights for sustainable airport development. Although the benefits of these strategies have been

examined in urban areas, very few studies have been conducted specifically in the context of airports. As airports attract a lot of diesel-powered vehicles carrying both passengers and goods, policies aimed at regulating these vehicles in the vicinity of the airport is in the agenda of policymakers. However, the specific vehicles that should be restricted as part of a LEZ policy, as well as the optimal time period for enforcement (peak hour vs 24-hour), have not yet been thoroughly investigated.

- ***Developing and less developed countries***

The global growth of air travel has been substantial, but the current body of research primarily concentrates on airports in developed nations where priorities and circumstances may differ from developing and less developed nations, creating limitations in applying existing knowledge to the latter context. For instance, from a travel behaviour perspective, the reasons for choosing taxi to travel to the airport in developing countries may be different compared to the same choice in the context of a developed country. Also, the priorities of the policymakers would vary which would impact the landside infrastructure and policies concerning different transportation systems. It is vital to acknowledge and address these disparities to ensure that research findings and strategies are relevant in diverse global contexts.

5. Conclusions

The remarkable growth in air travel has led to significant negative consequences, including traffic congestion and environmental pollution in the landside areas of airports. In this context, this review paper adopted a holistic approach to examine the landside transport sustainability by considering elements related to both travel demand as well as supply. As observed from the review, achieving sustainable landside operations is a complex challenge involving multiple stakeholders. While private cars and taxis are preferred to access airports, promoting public transportation by improving factors such as frequency and comfort, and understanding traveller needs, is crucial. Upgrading infrastructure, such as bicycle lanes (wherever feasible) and EV charging, can encourage sustainable modes and facilitate multimodal integration. Effective policies regarding public transport and ride-hailing services are also critical for sustainable landside operations. Moreover, quantifying the environmental impact of landside activities is crucial for analysing trends and assessing the effectiveness of the policies. These strategies together provide a roadmap for airports to improve their landside sustainability and progress towards decarbonization of access options.

In conclusion, it is imperative that efforts to address sustainability of airports are streamlined and impactful. Despite the existing challenges towards achieving sustainability, there are reasons to be optimistic, considering the progress made in the past and the potential of emerging technologies, such as electric vehicles and sustainable aviation fuels. In addition, it is noteworthy that many airports (and airlines) are taking steps towards achieving net-zero emissions, and there is growing awareness and support from passengers for greener travel options. However, there remains significant work to be done before airports become fully sustainable and emission-free transportation hubs. In this context, the findings presented in this review paper offer valuable insights regarding approaches aimed towards landside sustainability. Further research is needed to understand the implications of several aspects influencing landside sustainability which would help in formulating future policies and strategies tailored to the needs of the passengers, employees, and stakeholders.

Notes

1. The terms “airport surface access”, “airport ground access”, and “airport landside access” have been used interchangeably referring to the transportation infrastructure that provides connectivity between the airport terminal building and the surrounding areas, thereby facilitating the two-way travel of the passengers, employees and goods.
2. The term “traveller” refers to individuals who engage in various forms of travel, including passengers traveling to the airport to catch a flight, individuals returning home from the airport after alighting from a flight, and airport employees. In contrast, the term “passenger” specifically refers to individuals utilizing flights via the airport and does not include airport employees who work at the facility.
3. Last date of literature search was 14th October 2024

CRediT authorship contribution statement

Srinath Mahesh: Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Simeon C. Calvert:** Writing – review & editing, Supervision, Resources, Funding acquisition, Conceptualization.

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.

Acknowledgements

The authors of this paper acknowledge the funding received from the **TULIPS project** (https://tulips-greenairports.eu). This project has been supported by funding from the European Union’s Horizon 2020 research and innovation programme under grant

agreement No. 101036996. The views expressed in this paper are solely of the authors and do not represent the views of the project funders. The authors thank the two anonymous reviewers' for their constructive comments and unique perspectives, which have made this paper more comprehensive and complete.

Appendix A. Supplementary data

This section provides (i) a review of relevant reports from the Airport Cooperative Research Program (ACRP) in the context of North America, (ii) a summary of studies on the impact of Transportation Network Companies (TNCs) on parking and the share of other transportation modes, and (iii) an overview of relevant publications from parking organizations in the USA. Supplementary data to this article can be found online at https://doi.org/10.1016/j.trd.2025.104625.

Data availability

No data was used for the research described in the article.

References

Adsule, P., Kadali, B.R., 2024. Analysis of contributing factors in decision to bicycle in developing countries context. Transp. Policy 147, 50–58. https://doi.org/10.1016/j.tranpol.2023.12.015.

Alhussein, S.N., 2011. Analysis of ground access modes choice King Khaled International Airport, Riyadh, Saudi Arabia. J. Transp. Geogr. 19 (6), 1361–1367. https://doi.org/10.1016/j.jtrangeo.2011.07.007.

Alkaabi, K.A., 2016. Modeling travel choice behavior of airport employees for commuting to work at Dubai International Airport, UAE. Sustain. Dev. Plan. VIII 1, 577–589. https://doi.org/10.2495/sdp160481.

Australia Pacific Airports Corporation. (2023). Carbon Management Strategy. https://assets-au-01.kc-usercontent.com/be08d7b0-97a1-02f9-2be6-a0c139c3c337/2f8126b3-789c-454e-b7dd-9035b9ead571/APAC_Carbon_Management_Strategy_FY23_FINAL.pdf.

Aziz, H.M.A., Nagle, N.N., Morton, A.M., Hilliard, M.R., White, D.A., Stewart, R.N., 2018. Exploring the impact of walk–bike infrastructure, safety perception, and built-environment on active transportation mode choice: a random parameter model using New York City commuter data. Transportation 45 (5), 1207–1229. https://doi.org/10.1007/s11116-017-9760-8.

Bali, A. (2023). Car-free development in landside airport areas [TU Delft]. https://edepot.wur.nl/653920.

Baumeister, S., Nyrhinen, J., Kemppainen, T., Wilska, T.A., 2022. Does airlines' eco-friendliness matter? Customer satisfaction towards an environmentally responsible airline. Transp. Policy 128, 89–97. https://doi.org/10.1016/j.tranpol.2022.09.016.

Bergantino, A.S., Capurso, M., Hess, S., 2020. Modelling regional accessibility to airports using discrete choice models: An application to a system of regional airports. Transp. Res. A Policy Pract. 132, 855–871. https://doi.org/10.1016/j.tra.2019.12.012.

Birolini, S., Malighetti, P., Redondi, R., Deforza, P., 2019. Access mode choice to low-cost airports: evaluation of new direct rail services at Milan-Bergamo airport. Transp. Policy 73, 113–124. https://doi.org/10.1016/j.tranpol.2018.10.008.

Brisbane Airport Corporation. (2023). Annual Report 2023. https://www.bne.com.au/sites/default/files/no-index/2023-10/BAC-Annual-Report_2023.pdf.

Budd, L., Ison, S., Budd, T., 2016. Improving the environmental performance of airport surface access in the UK: the role of public transport. Res. Transp. Econ. 59, 185–195. https://doi.org/10.1016/j.retrec.2016.04.013.

Budd, T., Ryley, T., Ison, S., 2014. Airport ground access and private car use: a segmentation analysis. J. Transp. Geogr. 36, 106–115. https://doi.org/10.1016/j.jtrangeo.2014.03.012.

Buehler, R., Pucher, J., 2012. Demand for public transport in Germany and the USA: an analysis of rider characteristics. Transp. Rev. 32 (5), 541–567. https://doi.org/10.1080/01441647.2012.707695.

Castillo-Manzano, J.I., 2010. The city-airport connection in the low-cost carrier era: implications for urban transport planning. J. Air Transp. Manag. 16 (6), 295–298. https://doi.org/10.1016/j.jairtraman.2010.02.005.

Chang, Y.C., 2013. Factors affecting airport access mode choice for elderly air passengers. Transp. Res. E: Logist. Transp. Rev. 57, 105–112. https://doi.org/10.1016/j.tre.2013.01.010.

Chen, L., Msigwa, G., Yang, M., Osman, A.I., Fawzy, S., Rooney, D.W., Yap, P.S., 2022. Strategies to achieve a carbon neutral society: a review. Environ. Chem. Lett. 20 (4), 2277–2310. https://doi.org/10.1007/s10311-022-01435-8.

Colovic, A., Pilone, S.G., Kukić, K., Kalić, M., Dožić, S., Babić, D., Ottomanelli, M., 2022. Airport access mode choice: analysis of passengers' behavior in European countries. Sustainability (switzerland) 14 (15). https://doi.org/10.3390/su14159267.

Coogan, M.A., 2008. Ground access to major airports by public transportation. Transp. Res. Board. https://doi.org/10.17226/13918.

Corazza, M.V., Di Mascio, P., Esposito, G., 2022. Airports as sensitive areas to mitigate air pollution: evidence from a case study in Rome. Environments – MDPI 9 (9). https://doi.org/10.3390/environments9090108.

Dallas Fort Worth International (2018). Sustainability Management Plan 2014. https://downloads.ctfassets.net/m2p70vmwc019/1bIsHcqXOoyknAcbaskTSl/42c31e916df2391e3ffc8b0264392138/DFW_Sustainability_Sus_Management_Plan_2014.pdf.

Dong, X., Ryerson, M.S., 2020. Taxi drops off as transit grows amid ride-hailing's impact on Airport Access in New York. Transp. Res. Rec. 2675 (2), 74–86. https://doi.org/10.1177/0361198120963116.

Dublin Airport. (2022). Carbon Reduction Strategy. https://www.dublinairport.com/docs/default-source/sustainability-reports/dublin-airport-carbon-reduction-strategy.pdf.

Fankhauser, S., Smith, S.M., Allen, M., Axelsson, K., Hale, T., Hepburn, C., Kendall, J.M., Khosla, R., Lezaun, J., Mitchell-Larson, E., Obersteiner, M., Rajamani, L., Rickaby, R., Seddon, N., Wetzer, T., 2022. The meaning of net zero and how to get it right. Nat. Clim. Chang. 12 (1), 15–21. https://doi.org/10.1038/s41558-021-01245-w.

Georgakopoulos, D., Nikolaou, D., Roussou, J., Yannis, G., 2023. The impact of mobility characteristics on public transport and road safety performance in selected European cities. Transp. Res. Procedia 72, 1547–1551. https://doi.org/10.1016/j.trpro.2023.11.622.

Gokasar, I., Gunay, G., 2017. Mode choice behavior modeling of ground access to airports: A case study in Istanbul, Turkey. J. Air Transp. Manag. 59, 1–7. https://doi.org/10.1016/j.jairtraman.2016.11.003.

Gössling, S., Dolnicar, S., 2023. A review of air travel behavior and climate change. WIREs Clim. Change 14 (1), e802. https://doi.org/10.1002/wcc.802.

Graham, A., Kruse, W., Budd, L., Kremarik, F., Ison, S., 2023. Ageing passenger perceptions of ground access journeys to airports: A survey of UK residents. J. Air Transp. Manag. 107. https://doi.org/10.1016/j.jairtraman.2022.102338.

Greater Toronto Airports Authority. (2022). Accessibility Plan 2023 to 2026. https://cdn.torontopearson.com/-/media/project/pearson/content/travel/accessibility/pdfs/gtaa_accessibility_plan_2023_to_2026_en.pdf?rev=7d1bed4475d0420ab17c61dbb21cff5f&hash=B3174E764305D92BC78118F2131E804B.

Greer, F., Rakas, J., Horvath, A., 2020. Airports and Environmental Sustainability: A Comprehensive Review. in Environmental Research Letters Vol. 15, Issue 10. https://doi.org/10.1088/1748-9326/abb42a.
Guo, Z., Lai, C.S., Luk, P., Zhang, X., 2023. Techno-economic assessment of wireless charging systems for airport electric shuttle buses. J. Storage Mater. 64. https://doi.org/10.1016/j.est.2023.107123.
Hájnik, A., Harantová, V., Kalašová, A., 2021. Use of electromobility and autonomous vehicles at airports in Europe and worldwide. Transp. Res. Procedia 55, 71–78. https://doi.org/10.1016/j.trpro.2021.06.008.
Harley, G., Timmis, A., Budd, L., 2020. Factors affecting environmental practice adoption at small European airports: An investigation. Transp. Res. Part D: Transp. Environ. 88. https://doi.org/10.1016/j.trd.2020.102572.
Henao, A., Marshall, W.E., 2019. The impact of ride hailing on parking (and vice versa). J. Transp. Land Use 12 (1), 127–147. https://doi.org/10.2307/26911261.
Hong, J., Philip McArthur, D., Stewart, J.L., 2020. Can providing safe cycling infrastructure encourage people to cycle more when it rains? The use of crowdsourced cycling data (Strava). Transp. Res. A Policy Pract. 133, 109–121. https://doi.org/10.1016/j.tra.2020.01.008.
Iclodean, C., Cordos, N., & Varga, B. O. (2020). Autonomous shuttle bus for public transportation: A review. In Energies (Vol. 13, Issue 11). MDPI AG. https://doi.org/10.3390/en13112917.
Ison, S., Merkert, R., Mulley, C., 2014. Policy approaches to public transport at airports-Some diverging evidence from the UK and Australia. Transp. Policy 35, 265–274. https://doi.org/10.1016/j.tranpol.2014.06.005.
ITF (2018). Surface Access to Airports: The case of Mexico City's New International Airport. https://www.itf-oecd.org/sites/default/files/docs/surface-access-airports.pdf.
Janić, M., 2019. Landside Accessibility of Airports. Springer. https://link.springer.com/content/pdf/10.1007/978-3-319-76150-3.pdf.
Jia, X., Macário, R., & Buyle, S. (2023). Expanding Horizons: A Review of Sustainability Evaluation Methodologies in the Airport Sector and Beyond. In Sustainability (Switzerland) (Vol. 15, Issue 15). Multidisciplinary Digital Publishing Institute (MDPI). https://doi.org/10.3390/su151511584.
Jia, X., Macário, R., Buyle, S., 2024. How do airports align with sustainability? An analysis of the world's 150 busiest airports. Sustain. Dev. https://doi.org/10.1002/sd.3029.
Jou, R.C., Hensher, D.A., Hsu, T.L., 2011. Airport ground access mode choice behavior after the introduction of a new mode: a case study of Taoyuan International Airport in Taiwan. Transp. Res. E Logist. Transp. Rev. 47 (3), 371–381. https://doi.org/10.1016/j.tre.2010.11.008.
Karam, S., Ryerson, M.S., Kim, A.M., Li, M.Z., 2024. Autonomous vehicle impacts on airport leakage with demand forecasting and environment implications. Transp. Res. Part D: Transp. Environ. 133. https://doi.org/10.1016/j.trd.2024.104268.
Leiner, C., Adler, T., 2020. Transportation Network Companies (TNCs): impacts to airport revenues and operations—Reference guide. Transp. Res. Board. https://doi.org/10.17226/25759.
Liu, X., 2020. Assessing airport ground access by public transport in Chinese cities. Urban Stud. 57 (2), 267–285. https://doi.org/10.1177/0042098019828178.
London Heathrow (2022). Surface Access Strategy. https://www.heathrow.com/content/dam/heathrow/web/common/documents/company/about/company-information/2022-Surface-Access-Strategy.pdf.
Los Angeles World Airports. (2019). Sustainability Action Plan. https://cloud1lawa.app.box.com/s/63i2teszgnld5aws68xbou6yc0inl5rp.
Mandle, P., Box, S., 2017. Transportation network companies: challenges and opportunities for airport operators. Transp. Res. Board. https://doi.org/10.17226/24867.
Mandle, P., Choi, E., Alandou, N., 2023. Airport programs that reduce landside vehicle carbon emissions: a synthesis of airport practice. Transportation Research Board.
Masiol, M., Harrison, R.M., 2014. Aircraft engine exhaust emissions and other airport-related contributions to ambient air pollution: a review. In: Atmospheric Environment, Vol. 95. Elsevier Ltd., pp. 409–455. https://doi.org/10.1016/j.atmosenv.2014.05.070
Massachusetts Port Authority. (2022). Building for the future 2022 annual report. https://www.massport.com/sites/default/files/2023-10/2022_massport_annual-report_5-3-23.pdf.
Matheys, J., Rogolle, C., Sergeant, N., Boureima, F.-S., Timmermans, J.-M., Rombaut, H., Van Mierlo, J., 2008. Analysis and improvement of "the Last Mile" to and from the national airport as part of the mobility policy in the Brussels urban area. WIT Trans. Built Environ. 101, 447–456. https://doi.org/10.2495/UT080441.
Mayer, R., Ryley, T., Gillingwater, D., 2012. Passenger perceptions of the green image associated with airlines. J. Transp. Geogr. 22, 179–186. https://doi.org/10.1016/j.jtrangeo.2012.01.007.
Miyoshi, C., Mason, K.J., 2013. The damage cost of carbon dioxide emissions produced by passengers on airport surface access: the case of Manchester Airport. J. Transp. Geogr. 28, 137–143. https://doi.org/10.1016/j.jtrangeo.2012.12.003.
Muthkur, A.S., Nikhil, T.R., 2021. Airport Surface Access-Kempegowda International Airport, Bengaluru, Karnataka. Des. Eng. 9, 12874–12885. https://www.researchgate.net/publication/357555952.
Narita Airport. (2022). Environmental Report Digest 2022. https://www.naa.jp/en/environment/pdf_2022/environment2022eng.pdf.
National Academies of Sciences, 2015. Commercial ground transportation at airports: best practices. Transp. Res. Board. https://doi.org/10.17226/21905.
Oprea, C., Dragu, V., Ilie, A., Dinu, O., Burciu, Ş., 2018. Transport modes junction in an airport. Procedia Manuf. 22, 878–885. https://doi.org/10.1016/j.promfg.2018.03.124.
Orrick, P., Frick, K., 2012. Airports and bicycles. Transp. Res. Rec. 2314, 97–104. https://doi.org/10.3141/2314-13.
Orth, H., Frei, O., Weidmann, U., 2015. Effects of non-aeronautical activities at airports on the public transport access system: a case study of Zurich Airport. J. Air Transp. Manag. 42, 37–46. https://doi.org/10.1016/j.jairtraman.2014.07.011.
Ravi, L., Raju, T.B., 2022. GHG emission reduction at airports through sustainable and collaborative initiatives. In: Advances in Sustainable Development. Springer, Singapore, pp. 123–139. https://doi.org/10.1007/978-981-16-4400-9_9.
Reddy, D.S., Babu, K.V.G., Tagore, M.R., 2016. Rail based public transport facility to large Indian Airports. Transp. Res. Procedia 17, 90–97. https://doi.org/10.1016/j.trpro.2016.11.064.
Richard, A., 2014. Electric vehicle charging stations at airport parking facilities. Transp. Res. Board. https://doi.org/10.17226/22390.
Risby, J., Guest, S., Warnock-Smith, D., 2022. A critical analysis of Bristol Airport's employee surface access habits: developing strategic recommendations for reducing private vehicle usage. Res. Transp. Bus. Manag. 43. https://doi.org/10.1016/j.rtbm.2021.100700.
Royal Schiphol Group. (2023). Annual Review 2022 Roadmap most sustainable airports. https://www.schiphol.nl/nl/download/b2b/1679644697/1hUXrh4mJDYmdDHL1rTUaX.pdf.
Rupcic, L., Pierrat, E., Saavedra-Rubio, K., Thonemann, N., Ogugua, C., Laurent, A., 2023. Environmental impacts in the civil aviation sector: current state and guidance. Transp. Res. Part D: Transp. Environ. 119. https://doi.org/10.1016/j.trd.2023.103717.
San Francisco International Airport. (2021). Climate Action Plan. https://www.flysfo.com/sites/default/files/2022-09/SFO_Climate_Action_Plan_FY21_final.pdf.
Shao, M., Chen, C., Lu, Q., Zuo, X., Liu, X., Gu, X., 2023. The Impacts of low-carbon incentives and carbon-reduction awareness on airport ground access mode choice under travel time uncertainty: a hybrid CPT-MNL model. Sustainability (switzerland) 15 (16). https://doi.org/10.3390/su151612610.
Silvester, S., Beella, S.K., Van Timmeren, A., Bauer, P., Quist, J., Van Dijk, S., 2013. Exploring design scenarios for large-scale implementation of electric vehicles; The Amsterdam Airport Schiphol case. J. Clean. Prod. 48, 211–219. https://doi.org/10.1016/j.jclepro.2012.07.053.
Sperling, J., Henao, A., 2020. Electrification of high-mileage mobility services in cities and at airports. In: Dinh, T. (Ed.), Intelligent and Efficient Transport Systems - Design. Control and Simulation, Modelling, pp. 65–92.
Stacey, B., 2019. Measurement of ultrafine particles at airports: a review. Atmos. Environ. 198, 463–477. https://doi.org/10.1016/j.atmosenv.2018.10.041.
Swami, L., Ahmed, M.A., Jena, S., 2023. Understanding ground access dynamics at Lokpriya Gopinath Bordoloi International Airport, Guwahati: a case study analysis. Innovative Infrastructure Solutions 8 (12). https://doi.org/10.1007/s41062-023-01301-8.
Sydney Airport. (2022). Sustainability Report 2022. https://assets.ctfassets.net/v228i5y5k0x4/6xifKAhXFEnQr7SrgY98MQ/6c4791ef089dc0fea048d8a11a991190/Sydney_Airport_SR_2022.pdf.

Tirachini, A., 2020. Ride-hailing, travel behaviour and sustainable mobility: an international review. Transportation 47 (4), 2011–2047. https://doi.org/10.1007/s11116-019-10070-2.

Varzeghani, N.M., Naderan, A., Taheri, A., 2023. Transportation mode choice analysis for accessibility of the mehrabad international airport by statistical models. Int. J. Transp. Veh. Eng. 17 (2). https://www.researchgate.net/publication/368574509.

Vasconcelos, A. S. R. (2020). Exploration of Passenger Mode Choice Behaviour on Lisbon Airport [Instituto Universitario De Lisboa]. https://repositorio.iscte-iul.pt/bitstream/10071/22255/1/Master_Ana_Reis_Vasconcelos.pdf.

Wadud, Z., 2020. An examination of the effects of ride-hailing services on airport parking demand. J. Air Transp. Manag. 84. https://doi.org/10.1016/j.jairtraman.2020.101783.

Wang, Y., Zhang, Y., 2019. Impacts of automated vehicles on airport landside terminal planning, design, and operations. Transp. Res. Rec. 2673 (10), 443–454. https://doi.org/10.1177/0361198119850473.

Warnock-Smith, D., Fake, J., 2023. Assessing sustainable journey-to-work solutions around stated and revealed employee preferences: the case of Bristol International Airport. Transp. Res. Proc. https://bnu.repository.guildhe.ac.uk/id/eprint/18810/1/18810_WarnockSmith_D%20Preprint.pdf.

Yilmaz, O., Frost, M., Timmis, A., Ison, S., 2023. Investigation of employee related airport ground access strategies from a post-COVID perspective. Transp. Res. Rec. 2677 (4), 39–50. https://doi.org/10.1177/03611981211033280.

Young, S., Duvall, A., Henao, A., & Gonder, J. (2023). Inaugural technologist in communities scanning tour: automated and electrified on-demand mobility. https://www.nrel.gov/docs/fy24osti/87448.pdf.

Zaidan, E., Abulibdeh, A., 2018. Modeling ground access mode choice behavior for Hamad International Airport in the 2022 FIFA World Cup city, Doha, Qatar. J. Air Transp. Manag. 73, 32–45. https://doi.org/10.1016/j.jairtraman.2018.08.007.

Zuniga-Garcia, N., Machemehl, R.B., 2021. Impact of transportation network companies on ground access to airports: a case study in Austin, Texas. Transp. Res. Record 2675 (12), 13–27. https://doi.org/10.1177/03611981211031205.