Report on Feasibility to Reduce Emissions During Aircraft Taxiing

Prepared for the
California Air Resources Board,
by Roland Berger

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DISCLAIMER

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The work described in this report was conducted by an international Roland Berger team in cooperation of the California Air Resources Board personnel.

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ABBREVIATION AND SYMBOLS

Abbreviation / Symbol	Definition
AEDT	Aviation Environmental Design Tool
AMS	Amsterdam Airport Schiphol
AP	Auxiliary Power (context: APU)
APU	Auxiliary Power Unit
ATC	Air Traffic Control
BUR	Hollywood Burbank Airport
CAI2024	California Aircraft Inventory 2024
CAPEX	Capital Expenditure
CARB	California Air Resources Board
CDG	Paris Charles de Gaulle Airport
DER	Designated Engineering Representative (FAA)
DEL	New Delhi Airport
EASA	European Union Aviation Safety Agency
EIA	U.S. Energy Information Administration
FAA	Federal Aviation Administration
FAT	Fresno Yosemite International Airport
$\mathrm{FP}_{\mathrm{MIM}}$	Flight Percentage with Minimum Infrastructure Modification
GSE	Ground Support Equipment
IRR	Internal Rate of Return
KLM	Koninklijke Luchtvaart Maatschappij (Royal Dutch Airlines)
LAX	Los Angeles International Airport
LGB	Long Beach Airport
LTO	Landing and Take-Off cycle
NEO	New Engine Option (Airbus aircraft variant)
NPV	Net Present Value
OEM	Original Equipment Manufacturer
OAK	Oakland San Francisco Bay Airport
ONT	Ontario International Airport
PoC	Proof of Concept
PSP	Palm Springs International Airport
SAF	Sustainable Aviation Fuel
SAN	San Diego International Airport
SBA	Santa Barbara Airport
SBP	San Luis Obispo County Regional Airport
SFO	San Francisco International Airport

SJC	San Jose Mineta International Airport
SNA	John Wayne Airport, Orange County
SMF	Sacramento International Airport
SR	Service Road
T&D	Transmission & Distribution (of electricity)
TCO	Total Cost of Ownership
Taxitow	Zero-Emission Taxitow with Pilot Control Capabilities
TLTV	Towbarless Towing Vehicle
USD	United States Dollar
WB	Wide-Body (aircraft)
ZE	Zero-Emission

EXECUTIVE SUMMARY

This study assesses the feasibility, operational implications, and economic performance of Zero-Emission (ZE) aircraft taxiing solutions in California, with the objective of identifying options that are technically mature, operationally compatible with airport constraints, and capable of delivering material fuel savings at scale. The analysis was conducted in three steps: (i) a review of currently available ZE taxiing technologies, (ii) an assessment of the operational and infrastructure constraints associated with the most applicable solution, and (iii) an outside-in evaluation of costs and benefits at both airport and state level. The analysis focuses on direct operational impacts and cost-benefits; whereas detailed modelling of emissions reductions to improve regional air quality and broader externalities were not assessed as part of this work.

The review of currently available on-board ZE taxiing technologies that would be permanently installed to the aircraft (e.g., WheelTug and Green Taxi Aerospace) indicates material limitations to the full deployment of most solutions, despite improvements in operational safety and a reduced reliance on ground support equipment. Indeed, their lower operating speeds and added aircraft weight could limit the economic and emissions-related benefits, particularly where hybrid engine-on operations are required to maintain schedules. In addition, these systems are still undergoing certification as of Q1 2026 and lack large-scale, real-world airport deployment, limiting confidence in their near-term applicability.

Among on-ground solutions, Smart Airport Systems TaxiBot (referred to as TaxiBot in the document) emerges as the most mature and operationally proven option for near-term deployment. TaxiBot is a specialized zero-emission towing vehicle that allows aircraft to move between the gate and runway without using their main engines. TaxiBot was selected to illustrate ZE Taxiing deployment because, as of the publication of this report in May 2026, it is the only readily available solution that enables extended engine-off taxiing at speeds comparable to conventional taxiing, has demonstrated large-scale operational success, and offers the greatest potential for emissions reduction. More broadly, this report focuses on the feasibility of deploying and scaling up ZE taxiing solutions (Zero-Emission Taxitow with Pilot Control Capabilities, or “taxitow”). Indeed, pilot-controlled ZE taxiing can be done at a speed comparable to conventional taxiing and has demonstrated successful large-scale operations at some major international airports, making it the most viable candidate for CARB to support near-term ZE taxiing deployment focused on fuel burn reduction during ground operations.

The Safety and Risk Management panel convened key stakeholders to assess the operational impacts, safety risks, and mitigation strategies for implementing ZE Taxiing, focused on commercial operations-assisted taxiing at California airports. Insights from the panel highlight the need for rigorous guidelines, comprehensive training, and phased trials to ensure safe and effective technology roll-out, with learnings directly informing what airports and operators should anticipate for successful implementation. One key takeaway of the safety panel is that TaxiBot encountered only two operational issues at AMS, neither of which affected safety. No safety-related incidents were reported at New Delhi, Bengaluru, or Paris CDG airports.

The assessment of the operational constraints concludes that ZE taxiing is compatible with approximately 79% of commercial aircraft movements from gate to runway in California (taxi-out). This number is driven by the type / family of the aircraft and taxitow accreditation. At present, TaxiBot is fully certified for the Boeing 737 and Airbus A320 families, which encompass the most widely used narrow-body aircraft in commercial aviation. The Airbus A321XLR is expected to receive certification by 2026, further expanding the A320 family’s scope. Additionally, certification for the Embraer family and the Airbus A220 is anticipated by 2026, while the Boeing 737 Max is projected to be certified by the end of 2026. Major wide-body aircraft from the A330, A350, B777, and B787 families are expected to be certified by 2029, with the potential for extension to other aircraft models as required by airlines.

ZE taxiing deployment is not expected to create material operational delays from gate to runway. Some targeted and addressable infrastructure adaptations are required at specific locations, primarily related to service-road connectivity for ZE taxiing equipment to return to the gate and localized pavement adjustments. At smaller airports (e.g., SBP[1]), certain runways and taxiways are expected to be incompatible with ZE taxiing, due to land constraints. Results vary by types of airports, which is why we bucketed all 14 airports studied into 4 categories, each represented by one persona airport. We summarized key results below:

All 14 largest California airports:

	Compatible flights	FP_{MIM}	# of taxitows	Net benefits (NPV, USD m)
	79%	98%		
25% ZE taxiing			31	-104
50% ZE taxiing			51	-35
75% ZE taxiing			70	+53
100% ZE taxiing			114	+50

LAX [group 1 persona airport]:

	Compatible flights	FP_{MIM}	# of taxitows	Net benefits (NPV, USD m)
	79%	100%		
25% ZE taxiing			5	+11.8
50% ZE taxiing			10	+50.7
75% ZE taxiing			16	+85.1
100% ZE taxiing			32	+90.6

LGB [group 2 persona airport]:

	Compatible flights	FP_{MIM}	# of taxitows	Net benefits (NPV, USD m)
	99%	100%		
25% ZE taxiing			*1 taxitow allows to cover 50% of flights*	
50% ZE taxiing			1	+1.8
75% ZE taxiing			2	+2.2
100% ZE taxiing			4	-1.5

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[1] One runway at SBP (accounting for ~14% of flights) cannot support ZE taxiing operations due to insufficient width

SJC [group 3 persona airport]:

	Compatible flights	FP_{MIM}	# of taxitows	Net benefits (NPV, USD m)
	86%	87%		
25% ZE taxiing			1	-9.6
50% ZE taxiing			3	-9.0
75% ZE taxiing			4	-5.1
100% ZE taxiing			6	-4.9

SBP [group 4 persona airport]:

	Compatible flights	FP_{MIM}	# of taxitows	Net benefits (NPV, USD m)
	75%	86%		
25% ZE taxiing			*1 taxitow allows to cover 100% of flights*	
50% ZE taxiing				
75% ZE taxiing				
100% ZE taxiing			1	-5.6

At scale, ZE taxiing primarily delivers benefits through reduced jet fuel consumption, with up to ~16 million gallons potentially avoided per year across the 14 Californian airports studied under full deployment. These fuel savings underpin both the environmental relevance and the economic assessment developed in this study.

From a cost/benefits perspective, benefits mostly come from large airports where ZE taxiing equipment utilization can be the highest and the distance from gate to runway is the longest, and at coverages of 50-75%, when the equipment isn't scaled to match peak traffic. Large hubs such as LAX show positive net economic benefits across all penetration levels, with ~75% deployment consistently delivering the strongest return on investment. Moving from intermediate to full (100%) coverage primarily allows to address additional movements during traffic peaks, requiring additional ZE taxiing equipment with lower average utilization and diminishing marginal returns. At smaller airports, lower daily utilization structurally limits the economic attractiveness despite the ease of deployment.

Sensitivity analysis confirms that operational delays, fuel prices, and aircraft adaptation costs are the most influential drivers of the business case. Higher fuel prices, including more aggressive SAF phase-in scenarios, materially improve economics, and ownership structures that enable depreciation-related tax shields further enhance net benefits. Conversely, higher aircraft adaptation costs and operational delays (albeit not expected) could have the strongest negative impact on net cost-benefits. The analysis found that, from a statewide perspective, currently available zero-emission taxiing technologies offer substantial potential to reduce CO_2 emissions at California airports.

INTRODUCTION

As detailed in the 2020 Mobile Source Strategy and the 2022 State Strategy for the State Implementation Plan, CARB is exploring concepts to reduce emissions from aircraft operations. Current strategies investigated by CARB include implementing reduced-emission or zero-emission taxiing, and minimizing the use of auxiliary power units (APUs) while aircraft are stationary.

Transitioning to zero-emission ground operations for aircraft is essential to achieving federal air quality standards, lowering health risks for airport workers and surrounding communities, and reducing greenhouse gas emissions linked to airport activities.

This study concentrates exclusively on a specific initiative known as zero-emission or low-emission taxiing. This approach enables aircraft to taxi to and from the runway without relying on their engines while the APU remains operational. The initiative aims to reduce fuel consumption and emissions during ground operations, contributing to more environmentally friendly airport practices.

The study is structured into a series of focused chapters, each addressing a critical aspect of the project's objectives and methodology. Below, we introduce each chapter and summarize its core content.

- **Chapter 1 - Assessment of available and emerging ZE technologies:** The first chapter sets the technical foundation for the study. It details a comprehensive assessment of both current and emerging ZE taxiing technologies. The chapter evaluates technology readiness, scalability, operational and regulatory factors, and identifies commercialization timelines and challenges. The goal is to provide a clear understanding of the technological landscape, including solutions not yet on the market, and to benchmark their efficiency, cost-effectiveness, and environmental impact
- **Chapter 2 - Analysis of real-world application:** Building on the technology assessment, the second chapter investigates real-world deployments of ZE taxiing solutions globally. It examines case studies and demonstrations in the United States, Europe, and other regions, with a focus on their relevance and applicability to California airports. The findings are synthesized into an evaluation scorecard, highlighting lessons learned and best practices for California's context
- **Chapter 3 - Selection of California airports:** The third chapter describes the process for selecting a representative sample of California airports for in-depth analysis. It shortlists 4-5 airports that reflect the diversity of operational environments across the state. The selection is informed by data collection on airport size, configuration, operational strategies, and stakeholder willingness. The aim is to ensure that the chosen airports serve as effective proxies for the broader set of commercial airports in California
- **Chapter 4 - Trial Safety and Risk Management (SRM) panel:** Safety is paramount in the adoption of new technologies. This chapter outlines the organization and facilitation of a trial SRM panel. The panel convened experts from airlines and airport authorities and associations to identify major safety risks focused on commercial aviation and develop mitigation strategies
- **Chapter 5 - Operational and infrastructure assessment:** Chapter five focuses on the operational and infrastructural readiness of the selected airports. It evaluates current energy supply, operational procedures, and infrastructure, identifying the modifications required to support higher penetration rates of ZE taxiing. The analysis

considers the impact of these changes on airport efficiency and compliance with regulatory requirements

- **Chapter 6 - Modeling of ZE taxiing:** A core deliverable of the project, this chapter presents the development of a simulation model to analyze the real-time use of ZE taxiing equipment at the selected airports. The model incorporates data on runway layouts, flight operations, and ZE taxiing equipment specifications to estimate the number of units required, electric load, infrastructure limitations, and the impact on airport efficiency. The model also identifies barriers to achieving 100% ZE taxiing implementation
- **Chapter 7 - Cost-benefit analysis:** The final analytical chapter leverages the simulation model to conduct a comprehensive cost-benefit analysis. It estimates the capital, infrastructure, operational, and fuel costs associated with different levels of ZE taxiing penetration at each airport. The results are then extrapolated to provide a statewide investment estimate, grouping all commercial airports according to their similarity to the selected case studies

While the objective is to evaluate the implementation of low-emission taxiing as a means to reduce pollutant emissions at California airports, the calculation of these emissions falls outside the scope of this report. This task will be undertaken by the CARB team, whose expertise will be utilized for a comprehensive emissions assessment. Accordingly, this report is limited to evaluating jet fuel savings and does not convert these savings into emissions reductions and related health benefits.

This document provides insights gathered from research utilizing publicly available information and past experiences of the consultancy, along with a series of 20 interviews conducted with key stakeholders, including airports, airlines, ground handlers, & regulators. It synthesizes their feedback to present a comprehensive overview of the findings.

A comprehensive overview of the applied methodology is provided in each results section below.

1 Assessment of available and emerging ZE technologies

1.1 Context

Low-emission taxiing solutions allow aircraft to taxi from the terminal gates to the runway for departure (taxi-out) or from the runway to the gates after arrival (taxi-in) without relying on the engines, while the Auxiliary Power Unit (APU) is operational. Engine start-up and warm-up can occur during taxiing or while awaiting clearance for take-off.

These solutions provide several benefits, including:

- Reduced emissions, pollution, and noise around airports (e.g., TaxiBot reports reductions of up to 85% of CO2 emissions and Noxious gases)
- Lower jet fuel consumption (e.g., TaxiBot reports reductions of up to 85% of jetfuel usage during taxiing) thereby limiting engine run time and ultimately improving engine lifespan
- Immediate taxiing post-pushback, potentially minimizing congestion at the gate
- Decreased risk of foreign object damage into engines (e.g., TaxiBot reports reductions of 50%)

1.2 Technology overview

This section highlights the 4 primary low-emission taxiing solutions or procedures that are currently available or nearing availability. These include:

On-ground solutions utilizing specialized towing vehicles:

- **TaxiBot:** A towing vehicle that the cockpit crew controls directly after the pushback is completed by the tug driver. It features an interface mechanism that allows pilots to steer using the aircraft's existing cockpit controls. Taxiing speed is managed by the pilot through the aircraft brakes.
- **EcoTug Procedure**: This procedure, known as the 'Aircraft Extended Towing Procedure' (AETP), is a taxiing concept that utilizes an electric aircraft tow tractor, specifically designed for wide-body aircraft. The aircraft is towed by a vehicle operated by a driver and an additional operator. The AETP is based on the existing dispatch towing process which is typically employed only in rare instances of failure or emergency situations.

On-board solutions featuring electric taxi systems integrated into the aircraft:

- **WheelTug:** Hybrid solution utilizing two electric motors, each powered by the APU and positioned in the aircraft's nose wheels. Pilots control the movement through a control panel in the cockpit which allows to reverse from the gate and steer the aircraft, supported by an optional camera system called WheelTug Vision, which offers comprehensive visibility from near ground level.
- **Green Taxi Aerospace:** Electric motor mounted on the main landing gear, powered by the aircraft's APU. In the cockpit, a pilot interface unit enables the crew to reverse to back away from the gate, manage the aircraft's speed and direction, with steering unchanged from pilots' typical taxiing,

Other large electric aircraft tugs are commercially available and in use at airports, but are not included here as they are not designed with the intent of taxi passenger-loaded aircraft nor have procedures been designed to use them in emergency taxiing scenarios.

1.3 Technology assessment

The following table compares these four solutions:

Table 1: Comparison of ZE taxiing solutions across key dimensions (at the time of study)

	TaxiBot	EcoTug	WheelTug (WT)	Green Taxi Aerospace
Development & manufacturing	• Developed by Israeli Aerospace Industries (IAI) as the concept owner • Manufactured by TLD Group (first prototype built in 2011) • Sold under Smart Airport Systems (SAS)	• The vehicle suggested for the procedure is a certified towbarless pushback, manufactured by Trepel, but can be applied with any other GSE certified to perform on heavy aircraft	• WheelTug designs & manufactures the electric systems - its assembly line is located in Baltimore, Maryland • The system installation is carried out directly at WheelTug authorized regional MROs	• The Electric Green Taxiing System (EGTS) was the original system developed as a retrofit by Safran & Honeywell. The project is now solely managed by Safran, who is working on a new solution for the new next generation of aircraft called eTaxi™, although this is not expected to be available until 2035+ or later • Concurrently, Green Taxi Aerospace, a separate startup based in TX & founded in 2021, has developed a technology meant for retrofit aircraft known as Green Taxi Aerospace™, based on the same concept, supported by a former L3 VP involved in the eTaxi™ project.
Unit cost	• USD 2.32 million (referred to as "m" in the document) for purchase (EUR 2 m, with exchange rate as of March 2026) • Leasing options are available, with charges yet to be determined	• USD 0.41-0.58 m (EUR 0.35-0.5 m, with exchange rate as of March 2026)	• The system would be offered on a 'power-by-the-hour' leasing model, with pricing tied to the airline's estimated cost savings. Savings are projected by the company at USD 1,626 per cycle per aircraft, of which 50% would be paid to WheelTug as the solution fee	• The system will be offered through a leasing model, with an estimated annual pricing of USD 200 k per year

	TaxiBot	EcoTug	WheelTug (WT)	Green Taxi Aerospace
Tests & demonstrations	• Currently deployed at airports in New Delhi, Bengaluru and Amsterdam (see detailed feedback in below section)	• First successful test by KLM conducted in 2023 in Amsterdam with a commercial 787 passenger aircraft • Proof of Concept with Norse canceled at CDG airport due to limited airport buy-in & denial from the French civil aviation authority DGAC (Direction Générale de l'Aviation Civile)	• Testing conducted at Memphis International Airport with an AlbaStar 737-800 (without passengers) • Two-year feasibility study, known as "FASTGate," at Mumbai Airport assessed operational viability & indicated potential increase in efficiency of 2-3 additional flights per gate per day, improving from the current average of 8 • The company does not deem further demonstrations necessary, beyond future in-service aircraft (once the solution is certified) • Ongoing laboratory tests (e.g., controlled gear drop tests, shimmy, steering, static stiffness) are conducted to complete certification requirement • Claimed received letters of interest from 25+ airlines for 2,600+ WheelTug systems, which	• No known live tests • The company has recently signed a partnership agreement with Delta Airlines and is in active collaboration with Envoy (American), SkyWest, Horizon, Republic and United Airlines along with Embraer

	TaxiBot	EcoTug	WheelTug (WT)	Green Taxi Aerospace
			is standard practice in the airline industry for non-certified technology (e.g., agreements with Vueling & AlbaStar in 2022)	
Advantages	• Pilots directly control the solution, enhancing safety • The system can taxi at speeds of up to 23 knots (acceleration from 0 to 23 in 55 sec), aligning with the current speed range for aircraft • No additional weight on the aircraft, which is a critical advantage compared to on-board solutions that would increase in-flight fuel consumption & emissions[2]	• No modifications needed for aircraft systems • No additional weight on the aircraft	• Pilots directly control the aircraft, enhancing safety • No vehicle operator is needed • Eliminates the need for infrastructure upgrades & procedural detours by removing the requirement for coupling & decoupling the aircraft, as well as utilizing service roads for return • Eliminates the need for a pushback tractor, thereby reducing costs, and risks of FOD-induced damage • Enhances maneuverability by allowing the wheels to wheelback or turn up to 78 degrees, compared to the usual maximum of 45 degrees,	• Pilots directly control the aircraft, enhancing safety • No vehicle operator is needed • Eliminates the need for infrastructure upgrades & procedural detours by removing the requirement for coupling & decoupling the aircraft, as well as utilizing service roads for return • Eliminates the need for a pushback tractor, thereby reducing costs, and risks of FOD-induced damage

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[2] As an estimate, the FAA reports 0.003 incremental gallons of fuel consumed per flight hour per pound of weight added

	TaxiBot	EcoTug	WheelTug (WT)	Green Taxi Aerospace
			providing more flexibility for a smoother entry/exit from gate & potentially reducing congestion • Optional camera & sensor systems enhance visibility of surroundings, incl. areas behind & underneath aircraft	
Drawbacks	• Requires an operator for the journey from the apron to the decoupling area & back (approximately 45 minutes in large hubs) • Larger vehicle than typically used in the apron area (29.5 ft length x 13.1 ft width), also needs sufficient space at aprons & a dedicated area for decoupling, connected to wide service roads for return • Requires modifications for Airbus aircraft (no modifications needed for Boeing or Embrarer (E170/175/190/195/295) • Airbus considers aircraft may necessitate more frequent replacement of the brake manifolds. This would also require a software update to track the number of brake cycles & determine when replacements are needed, potentially limiting large-scale usage	• Aircraft towing is controlled by operators instead of the pilots • Repeated or prolonged use over long distances could subject the aircraft structure to high forces, potentially causing damage; however, risk is yet to be evaluated • Reduced taxiing speed (estimated at 17 knots) (Both latter drawbacks were mentioned by AMS stakeholders as the main cause for which they do not plan to proceed with the solution) • Requires 2 operators for	• The system adds approximately 200 kg (around 440 lbs) of in-flight weight, which would increase in-flight fuel consumption & emissions (no fuel trade-off considered in this assessment) - To be further evaluated by CARB • Reduced taxiing speed (estimated at 7 knots), considered sufficient to operate around terminals where speed is relatively low, however when taxiing at higher speed, it is recommended for use in hybrid mode, with one or	• The system is expected to add an in-flight weight of up to 140 kg (approximately 300 lbs), which would increase in-flight fuel consumption & emissions (no fuel trade-off considered in this assessment) - To be further evaluated by CARB • Reduced taxiing speed (estimated at 16 knots) • Installation requires 2 overnight sessions • No APU modification is required & the system can be removed in one overnight

	TaxiBot	EcoTug	WheelTug (WT)	Green Taxi Aerospace
		the trip from the gate to the decoupling area & back (approximately 45 minutes in large hubs) • Although slightly smaller than TaxiBot, larger & longer vehicle than typically used in the apron area (23.0 ft length x 13.1 ft width) needs sufficient space at aprons & dedicated area for decoupling, connected to wide service roads for return	two engines operating to provide thrust (Both drawbacks above were mentioned by AMS stakeholders as the main reasons for which they do not plan to proceed with the solution) • Installation requires 2 overnight sessions (however allowing aircraft to operate with partial installation thus minimizing downtime). No APU modification is required & the system can be removed in one overnight	
Certification	• Certified by EASA & FAA for narrow-body aircraft under Supplemental Type Certificate. This includes the following families: B737 (excl. Max) & A320 • Certification for A220, & B737 Max expected by Q2/Q3 2026, Embraer certification expected by May 15th • Airport-deployment approval from the FAA is pending	• The procedure known as dispatch towing is certified by EASA for use, but not approved by airports for regular taxiing • Only applicable to wide-body Boeing aircraft. No dispatch towing for Airbus or narrow-body aircraft with standard	• The system is not currently certified, but the company reports that their Certification Plan has been formally accepted by the FAA • The company aims to achieve FAA certification by end of 2027. A Supplemental Type Certificate is required, starting with the 737NG	• The system is not currently certified, but the company reports the FAA validated their Certification Plan • The company partnered with StandardAero's Organization Designation Authorization to guide the system through regulatory approval over the next 2 years, involving 10 DERs as well (FAA-designated engineering representatives). A Supplemental Type Certificate is required • The rollout would begin with the

	TaxiBot	EcoTug	WheelTug (WT)	Green Taxi Aerospace
		pushback tractor due to mechanical resistance not taken into account by the equipment and the procedure in case of operations beyond typical pushback (nose landing gear fragility)	(including its variants) • Designated Engineering Representatives (DERs) from the FAA have been involved in observing lab tests and analyzing results as part of the certification process	Embraer E175 & E170 regional jets, with plans to expand to other commercial & military aircraft. The development is partly financially supported by a USD 5.6 million grant from the FAA
Further development	• Ongoing engineering prioritized for most common wide-body aircraft from A330, A350, B777, B787 families (could be extended to other aircraft as needed by airlines)	• No further development planned	• Future plans for the A220, A320 CEO/NEO, & 737MAX	• The company plans to expand to all regional jets and single-aisle aircraft models, with the technology applicable to all twin-aisle and business jet aircraft in the future including A220/A320/A321, B737/B757/B767/B777, MHIRJ CRJ 700/900, and any wheeled jet with an APU
Powertrain	• Available in a hybrid Diesel powertrain • Electric model launched in Q1 2026 • Uncertain timeline for hydrogen models (likely post-2030)	• The vehicle is available in diesel, hybrid, & electric models, with a hydrogen model currently under development, though no timeline announced	• Electric system powered by the APU	• Electric system powered by the APU
Production capacity	• Capable of manufacturing 16 TaxiBots simultaneously, with a 9-month lead time	• Not communicated	• Plans to increase output to 50-60 systems per aircraft type monthly. There are no identified obstacles to achieving	• The company reports no limitations on footprint requirements, allowing for the production of up to 200 units per month if needed

TaxiBot	EcoTug	WheelTug (WT)	Green Taxi Aerospace
		higher throughput • Est. delivery dates projected to begin end of 2027/early 2028, contingent upon completion of the current funding round & certification of the solution	

Note: In addition to the 4 solutions previously mentioned, Safran is currently developing the eTaxi solution, which also utilizes an electric motor in the main landing gear powered by the APU and is still in the R&D phase. This solution is intended exclusively for new aircraft models, which are not expected to be available until 2035 or later. It is specifically designed for narrow-body aircraft and will be certified as part of the new aircraft's certification process. The solution will be optional and removable at the airline's request, although no firm commitments have been reported to date. A key advantage of this solution compared to other on-board technologies is its anticipated taxiing speed of 20-30 knots, which, while still below typical aircraft taxiing and on-ground solutions speed, exceeds that of competing on-board technologies. The additional in-flight weight has not been disclosed, and the unit cost is yet to be determined. The company reports no limitations on production capacity.

This comparison of the solutions was based on several key criteria:

- **Safety**: Pilot control is preferred for steering fully loaded aircraft with passengers, as airlines and airports generally do not accept operator-controlled alternatives due to safety concerns
- **Airport efficiency**: Solutions that approach standard taxi speeds (up to 30 knots, typically limited to 10-20 knots by turns and congestion) are favored, as slower speeds can cause delays and reduce airport efficiency. The same rationale applies to procedural detours
- **Cost**: Requirements such as manifold replacement, vehicle pushback purchase, operator involvement, infrastructure upgrades, and aircraft modifications directly affect deployment and recurring costs. FODs constitute both a risk and a cost factor
- **In-flight weight**: Solutions that add no extra weight to the aircraft are advantageous, as additional weight increases in-flight fuel consumption and emissions (FAA estimates 0.003 extra gallons per flight hour per pound added).
- **Vehicle maneuverability**: The width of towing vehicles can restrict movement at gates, impacting operational flexibility

2 Real-world applications of ZE Aircraft Taxiing

2.1 Overview of case studies

The findings of this section are gathered from a series of interviews conducted with key stakeholders, including airports (DEL, BLR, AMS, CDG) and airlines (Air India Express, KLM, Air France). It synthesizes their feedback to present a comprehensive overview of the findings.

The TaxiBot is the only solution that has been implemented at large scale at an airport, allowing to collect real-world feedback to date:

- **New Delhi and Bengaluru:** DEL and BLR airports were the first to implement TaxiBot operations since 2018, with 2 and 1 TaxiBots in service, respectively. Collectively, they have completed over 2,500 trips, primarily operated by Air India Express and SpiceJet. However, operations are currently suspended following Celebi's loss of its license to operate at Indian airports (for reasons unrelated to TaxiBot or zero-emission taxiing), which was part of a collaboration with KSU Aviation[3] under the TaxiBot India framework.
    - There is no confirmed date for the resumption of operations:
        - **Air India Express:** Some modified Airbus aircraft are up for renewal and will therefore no longer be available for TaxiBot use. The airline is likely to shift its focus to Boeing aircraft, as they do not require modification, and may aim to resume operations next year, with a commitment to exclusively pursue electric models going forward.
        - **SpiceJet** is reportedly facing financial restructuring challenges, likely making TaxiBot operations a lower company priority.
    - The TaxiBots were acquired at the request of the airports, and operators have reported efficient and successful operations with minimal impact on airport efficiency. However, the current number of TaxiBots is insufficient for large-scale deployment, and no additional purchases have been announced at this time. As a comparison, AMS airport with an equal traffic volume plans to deploy over 46 units.
- **Amsterdam**: AMS airport acquired two TaxiBots in 2020, launched a Proof of Concept (PoC) for commercial flights in April 2024, and is currently scaling operations, and has completed up to 130 TaxiBot operations since. (as of May 2026). The airport aims to expand its fleet to up to 46 vehicles by 2031, with plans to introduce additional electric models (AMS currently has 1 electric TaxiBot). Currently, the TaxiBots are exclusively utilized on the Polderbaan, the longest runway, operating about 40% of the time depending on wind direction. AMS intends to gradually deploy the TaxiBots across other runways but must first assess feasibility in terms of infrastructure—such as creating decoupling areas and adapting service roads—and operational considerations, as each runway has unique characteristics and constraints.
    - To date, AMS has successfully secured commitments from all key stakeholders to carry out trials, including air traffic control (LVNL) and major airlines like KLM and easyJet. easyJet primarily operates Airbus aircraft, which necessitates a modification and software update to monitor braking cycles - The company has modified one aircraft, and plans to modify 3 additional ones by September 2026. In terms of ground handling, KLM's ground handling division is currently the only operator involved.

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[3] KSU Aviation specializes in semi-autonomous aircraft taxiing systems within the aviation industry

    - AMS has developed a Concept of Operations (ConOps) and a roadmap for the next steps, which include additional testing and validation for other areas of the airport outside of Polderbaan runway before making final deployment decisions. This will involve extensive trials in live operations to gather insights, refine processes, and determine the effectiveness of the measures in reducing pollution. This approach will also ensure that all stakeholders, including the ATC, are engaged and informed throughout the process, which has proven to be a best practice for securing buy-in and scaling operations.
- **Paris**: CDG airport has leased 1 TaxiBot, which was tested on 38 flights with Air France in 2023. No further plans for larger-scale deployment have been confirmed. Major stakeholders have shown reluctance to adopt the solution more broadly:
    - Ground handlers have cited the high cost of the vehicles' ownership/leasing and operation, and air traffic control has expressed worries about maintaining adequate staffing to ensure the safe dispatch of vehicles on a large scale.
    - Air France has expressed concerns regarding possible time delays during taxiing, primarily attributed to decoupling zones that create detours for aircraft. The taxiing speed has not been identified as a significant issue. The company prefers to prioritize other pollution reduction strategies that would not risk to impact punctuality, including single-engine taxiing and utilizing airport power when at gate. In addition, the risk of machine failure on the taxiway has contributed to the concerns.

Currently, TaxiBot usage is restricted to taxi-out operations for several reasons:

- The taxi-in process relies on existing aircraft speed and typically employs only one engine, which reduces the potential benefits of using TaxiBot
- The taxi-in process generally results in significantly lower emissions, as it is shorter in duration (as an order of magnitude, reported taxi-out time is 150% longer on average vs. taxi-in time for the top 10-15 airports in California)
- The engines are required to cool down before a tug can be connected, thereby further limiting feasibility
- Landing is a critical flight phase: adding an extra step—such as coupling with a TaxiBot—increases operational complexity. For taxi-out, however, aircraft already connect to a pushback at the gate, so integrating TaxiBot requires fewer procedural changes compared to standard operations

TaxiBot is thereby not utilized during taxi-in operations in either DEL, BLR, AMS or CDG airports

Figure 1: Mapping of global TaxiBot deployments (POCs and ongoing operations)

2.2 Feedback following the solution’s deployment

Feedback from major global airports on TaxiBot usage includes the following:

Table 2: Feedback from key airports on TaxiBot usage

Category	Operational challenge	Mitigation solutions
Infrastructure	• A dedicated decoupling zone must be established near the runways to enable the TaxiBot operator to disconnect the vehicle from the aircraft	• CDG utilized the de-icing zone when it was not in use (over 90% of the time). AMS has a designated holding pad adjacent to the Polderbaan runway (previously a de-icing area)
Infrastructure	• Service roads need to be adequately wide to accommodate larger vehicles that typically do not operate on these routes (e.g., TaxiBot’s dimensions are: 13 ft 7.8 in (width) × 29 ft 6.3 in (length) × 6 ft 6.7 in (height)	• AMS, DEL, BLR, & CDG have performed little to no infrastructure improvements for operations (e.g., at CDG: markings were added, and continuous paving of a service road area was adjusted, at AMS ciment pads were added to enlarge the service roads from the Polderbaan, for both TaxiBot and fire trucks) • However, some areas remain inaccessible (e.g., certain tunnels & narrow roads at CDG still restrict access to specific runways, while AMS will require extensive construction works for future runways)

Category	Operational challenge	Mitigation solutions
Infrastructure	• Apron space must be sufficient to prevent congestion while maneuvering large vehicles	• CDG airport has implemented light modifications to accommodate larger vehicles (e.g., space at certain gates was expanded by clearing posts)
Infrastructure	• Large vehicles necessitate substantial storage space in dedicated hangars	• Currently, the number of vehicles is limited. However, dedicated areas will likely be needed in the future. The final decision will also depend on whether the TaxiBots are intended to replace existing pushback tugs or serve as an additional resource • AMS is exploring several potential locations, each situated near the areas where the vehicles would be operated, for optimization purposes. This consideration is particularly important since a single large storage area for all vehicles is not available
Infrastructure	• Adequate energy supply & charging infrastructure is essential for electric models	• Presently, there are no electric vehicles. In the future, a clear roadmap with local utilities is required to plan for energy load • In addition, sufficient charging points will need to be installed to support both fast charging during idle periods & slower overnight charging (The charging power can reach up to 2x100 kW, supported by a battery pack of 420 kWh for the E-TXB. Consequently, charging from 20% to 100% would take approximately 1 hour & 40 minutes. TaxiBot operators would be responsible for planning charging schedules) • AMS aims to secure the necessary electricity to support its TaxiBotting roadmap by 2028 • Diesel vehicles could also provide significant jet fuel savings while energy infrastructure is developed
Air Traffic Control (ATC)	• The change in procedures may increase workload for ATC teams	• This can possibly be offset by optimized procedures, especially if the aircraft taxis immediately after pushback, which would help reduce congestion at the gates
Airline Operations	• Taxiing with a TaxiBot is estimated to be slightly slower than non-towed aircraft & introduces a decoupling step & potential detour, potentially impacting efficiency & crew engagement costs. For example, aircraft on the Polderbaan runway in AMS can reach speeds of up to 27 knots with engines on, while the TaxiBot is limited to 23 knots	• Repeated operations are expected to enhance the learning curve, ultimately reducing the duration difference. Currently, the decoupling duration is approximately 1.5 minutes, with a target of 1 minute. Indian airports no longer report time loss, partly due to saved time from immediate towing after push-back, but airport-specific measuring is required
Airline Operations	• Pilot training is necessary, which incurs costs & may hinder large-scale readiness, complicating TaxiBot operations planning	• Training at AMS currently takes less than 30 minutes, causing minimal disruption to standard programs and enabling rapid onboarding of large numbers of pilots. The use of visuals or videos could further facilitate adoption (all KLM B737 pilots are reported to have completed the training). However,

Category	Operational challenge	Mitigation solutions
		procedures at US/California airports can differ, with distinct operational and training approaches. Pilot training could for instance extend beyond a 30-minute CBT incl. hands-on practice time. • In the initial phase, TaxiBot operations may be limited to home carriers, since not all pilots—nationally or globally—will be trained. Some airlines may choose to train all pilots by aircraft type rather than by home base.
Airline Operations	• Airbus aircraft must undergo modifications to connect with the TaxiBot • In addition, usage is expected to increase wear on brake manifolds, which are typically rarely replaced during the aircraft's lifespan (requiring 6,000 cycles) & may need to be replaced	• Aircraft modification costs are relatively low (USD 17.4 k, i.e., EUR 15 k, with exchange rate as of March 2026) & can be performed during standard overnight maintenance • Airbus is reportedly exploring solutions with Safran for future developments to enhance the durability of brake manifolds. However, airlines require a software update that tracks the number of cycles before a replacement is necessary, which is yet to be made available • Airlines with a predominance of Boeing aircraft can scale more easily
Ground Handler Operations	• The operation of the TaxiBot requires handlers to be engaged for a longer duration (~45 minutes for a large hub), as opposed to a few minutes for a typical pushback, necessitating a larger workforce	• A gradual ramp-up in adoption could facilitate the recruitment & training of sufficient operators. Training for operators is estimated to take 2-3 hours, depending on their prior experience level, & utilizes a simulator to keep costs low • The additional incurred costs from longer workforce engagement shall then be recharged to airline as a revenue for the ground handler
Ground Handler Operations	• The purchase, leasing, & operation of the equipment involve relatively high costs	• Currently, these costs are borne by AMS & CDG airports during trial phases. In the future, an additional usage fee for the TaxiBot is likely to be implemented. DEL & BLR have reportedly established a cost per minute for airlines, with the generated revenue shared between the operator of the TaxiBot & the airport
Ground Handler Operations	• Maintenance is critical for effective deployment & longevity of the vehicle (& its batteries), but it is considered relatively complex for TaxiBots & requires a high level of expertise	• Maintenance could be initially conducted by the OEM (TLD SAS). A dedicated team would need to be established with low turnover to ensure continuous training & gradually take over maintenance responsibilities within 1-2 years

2.3 Key takeaways

Onboard solutions like WheelTug and Green Taxi Aerospace enhance operational efficiency by eliminating the need for a pushback tug and reducing the requirement for infrastructure upgrades, such as disconnect areas and service roads. Additionally, limiting GSE and human operations below the wing can limit the risk of accidents and aircraft damage.

However, these systems have a **maximum speed ranging** from **7 to 20 knots** (Safran's eTaxi system can reach the 20-30 knots threshold, but currently available solutions WheelTug and Green Taxi Aerospace only reach 7 and 16 knots respectively), which may necessitate airlines operating in a **hybrid mode** with one or two engines running to ensure schedule adherence. This would limit the anticipated benefits for **local air quality**. Additionally, the **extra weight** of these systems—between 300 and 440 lbs—**offsets some of the potential pollutant** emission reductions (not taking into account any potential fuel trade-off strategies).

It is important to note that both solutions are **currently undergoing certification processes**. The lack of live demonstrations at airports poses challenges in fully evaluating their operational impacts and potential reductions in emissions.

While in Europe, use of such solutions remains at the discretion of airports, operations in the United States requires FAA approval. WheelTug aims to achieve FAA certification by end of 2027, via a Supplemental Type Certificate (STC). Green Taxi Aerospace partnered with StandardAero to guide them through STC regulatory approval over the next 2 years, involving FAA DERs.

On-ground solutions like TaxiBot and EcoTug generally require **infrastructure upgrades** to support operations. While it is possible to start with a single vehicle using available space, larger-scale deployments often need additional modifications—such as creating dedicated disconnect areas near runways and adapting service roads for vehicle return to the gates. These changes can impact airport efficiency, particularly if disconnect areas require detours from standard taxi routes

However, airports like Delhi and Bengaluru have reported **no adverse effects on efficiency** due to their capability to tow aircraft directly to the runway post-pushback, highlighting the importance of strategically placing disconnect areas to optimize operational efficiency.

Among the available on-ground solutions:

- **Dispatch towing** methods like the **EcoTug** procedure raise concerns regarding safety, speed (limited to 17 knots), and potential aircraft damage (yet to be evaluated), leading airports to decline participation in proof-of-concept trials. Other large electric aircraft tugs are commercially available and in use at airports, but are not included here as they are not designed with the intent of taxi passenger-loaded aircraft nor have procedures been designed to use them in emergency taxiing scenarios.
- In contrast, the TaxiBot allows aircraft to keep **engines off until warming up** is necessary before takeoff (3-5 minutes), operating at **speeds consistent with typical taxiing** (up to 23 knots). This capability could enhance emissions performance, aligning with the study's objectives. Notably, the TaxiBot is the only solution that has been implemented large scale at an airport, having been utilized in over **2,500 operations** at the Delhi and Bengaluru airports (both commercial and cargo) and up to **130 operations** at Amsterdam airport as of May 2026.

Takeaway: While CARB is not seeking to mandate a specific technology, as any requirement would be technology-neutral, RB was asked to identify a leading candidate in this study to serve as the basis for the subsequent tasks of the feasibility analysis. Relying on the aim to support the introduction of a readily available solution that maximizes engine-off taxiing while maintaining speeds comparable to conventional taxiing, the TaxiBot seems the most viable candidate to date.

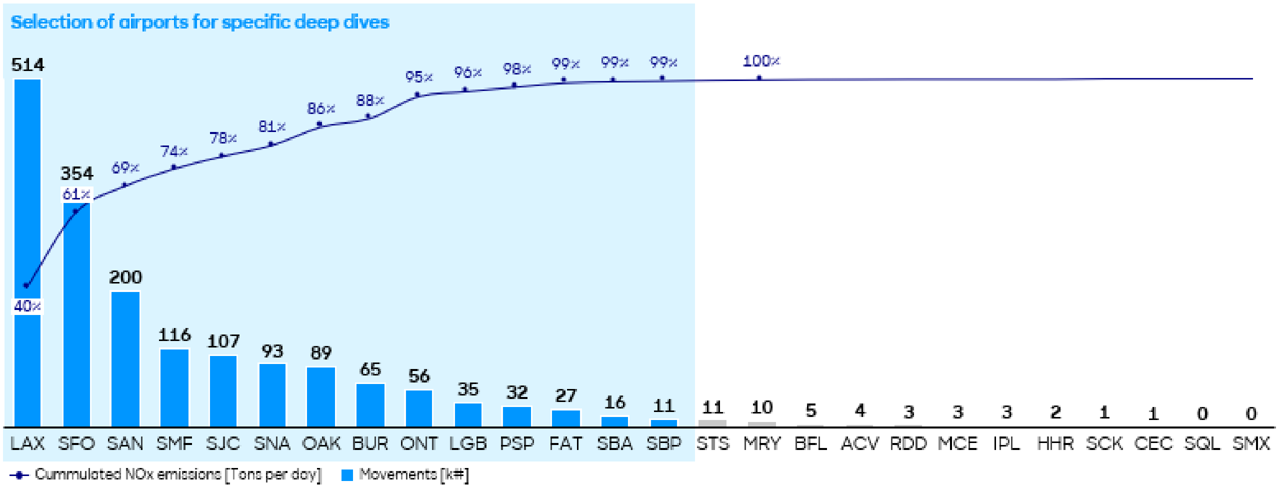
3 Grouping of California airports and selection of a short-list

3.1 Methodology

In this module, a shortlist of 4 airports has been established for further evaluation. We collected real-world data on several key metrics from publicly available sources across various airports in California. This assessment was conducted in collaboration with CARB to determine which airports should be included in the final shortlist, ensuring that the selected airports adequately represent the broader spectrum of commercial airports in the state.

This study focuses exclusively on commercial airports, thereby excluding general aviation, reliever airports, military, and public-use airports. Among the 26 commercial airports currently in operation (both primary & non-primary), we have chosen to concentrate on the top 14 airports ranked by total movements utilizing industry leading operational database as source. This selection is justified as these 14 largest commercial airports are responsible for over 99% of aircraft LTO-cycle NOx emissions, according to CARB's latest statewide aircraft emissions inventory model (CAI2024), allowing the study to target locations with the most significant aircraft emissions.

Figure 2: NOx emissions by Californian airports and yearly passenger movements [2024]



- The emissions data indicated a concentrated pattern, with Los Angeles International Airport (LAX) and San Francisco International Airport (SFO) accounting for 61% of cumulative NOx emissions (in tons per day) among the 26 airports in 2024
- When combined with San Diego International Airport (SAN) and Sacramento International Airport (SMF), these four airports dominate the emissions landscape at 74%

This concentration justifies a narrowed focus and supports the rationale for selecting a subset of the 26 airports for further detailed study.

Table 3: The selected 14 airports

IATA code	Airport name
LAX	Los Angeles International Airport
SFO	San Francisco International Airport
SAN	San Diego International Airport
SMF	Sacramento International Airport

SJC	San Jose Mineta International Airport
SNA	John Wayne Airport, Orange County
OAK	Oakland San Francisco Bay Airport
ONT	Ontario International Airport
BUR	Hollywood Burbank Airport
LGB	Long Beach Airport
PSP	Palm Springs International Airport
FAT	Fresno Yosemite International Airport
SBA	Santa Barbara Airport
SBP	San Luis Obispo County Regional Airport

Subsequently, we identified representative groups among the 14 airports. These airports were evaluated using a multi-criteria framework that includes traffic activity, taxi times and infrastructure constraints. These metrics were chosen for their relevance to ZE taxiing deployment:

- **Number of movements**: Number of annual commercial flights (only out movements considered)
- **Aircraft mix**: Mix of annual commercial flights out, categorized by type of aircraft, assessing the applicability of ZE taxiing usage
- **Hourly distribution:** Number of movements out per hour per day, impacting the number of taxitows needed to cover all flights, as well as their utilization rate
- Although we do not deem these last two metrics as differentiating, their evaluation serves as a safeguard to identify any unexpected trends
- **Taxi-out time:** Affects jet fuel consumption and emission savings, impacted by distance from terminals to runway and airport congestion (navigation complexity, access to runways, etc.)
- **Space constraints:** Availability of disconnection zones, condition and layout of service roads informing ease of the return of vehicles

While these metrics were prioritized for this assessment, it is acknowledged that other criteria, such as the availability of sufficient energy grid capacity and charging infrastructure for electric models, could further refine the grouping. However, airports have not yet conducted assessments detailed enough to provide this information, making an external evaluation challenging.

The analysis presented in this document relies on publicly available datasets, including ASPM (Aviation System Performance Metrics), AEDT (Aviation Environmental Design Tool), FlightAware, CARB - CAI2024, and the industry leading operational information database. These sources were chosen for their industry-wide recognition and relevance to operational and environmental performance metrics. While they provide a robust foundation for comparative analysis across airports, it is important to note that discrepancies exist between datasets due to variations in methodology, scope, and update frequency. Although some data was confirmed through airport contacts, other information remains reliant on publicly available data that has not been challenged by the airports, either due to lack of response or insufficient assessment capability.

It is important to note that this assessment does not aim to evaluate the feasibility of implementation or to categorize airports definitively. Instead, it serves to group airports with similar characteristics. One airport from each distinct group was then selected to serve as a case study for deeper financial and operational feasibility analysis. This was primarily based on the airport teams' prior interest in the solution and their availability to provide data and information. This selection does not imply a higher willingness to adopt or feasibility assessment. This approach ensures that the operational diversity of California's airport ecosystem is captured in the implementation analysis.

3.2 Assessment results

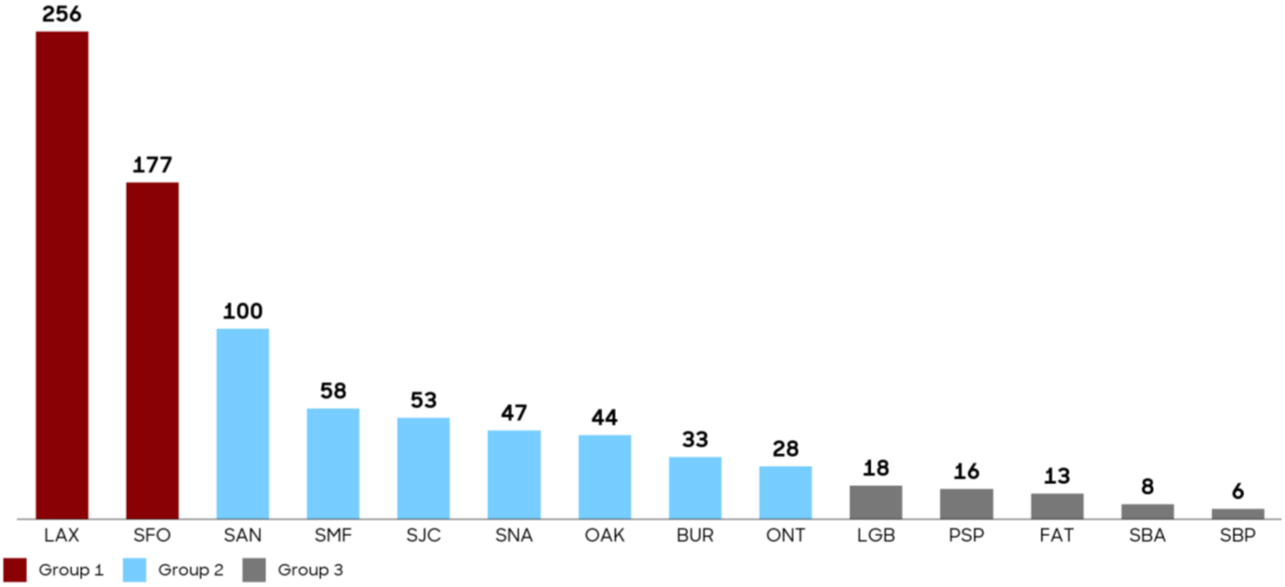
The approach involves systematically reviewing the metrics one by one, creating groups, and further subdividing them into subgroups as necessary based on subsequent metrics.

3.2.1 Movements out

The initial metric used to evaluate the grouping of airports for ZE taxiing deployment is the volume of aircraft movements from commercial passenger flights departing each airport. As previously mentioned, ZE taxiing is primarily applicable for taxi-out movements.

The number of outbound movements serves as a dual indicator, reflecting both overall emissions and the anticipated complexity of traffic operations. At smaller airports, fewer operational staff, particularly within ATC, manage routing with broader scope and reduced need for coordination. Consequently, the theoretical complexity of operations tends to be lower.

Figure 3: Number of movements out [1,000s, commercial passenger aircraft, 2024]



In 2024, the 14 major airports in California exhibited a diverse range of movement levels, leading to their categorization into 3 distinct groups:

- **Group 1:** This group includes high-traffic airports with over 150,000 movements out per year. LAX leads with more than 256,000 movements, followed by SFO with 177,000 movements. These platforms represent the most intensive operational environments and present the greatest theoretical potential for emissions reduction

- **Group 2:** Comprising mid-sized airports, this group features significant traffic levels ranging from 30,000 to 100,000 movements. Airports in this category include SAN, SMF, SJC, SNA, OAK, BUR, & ONT
- **Group 3:** This group consists of smaller airports with fewer than 20,000 movements annually, such as LGB, PSP, FAT, SBA, and SBP. Although their traffic volumes are lower, they still contribute to cumulative emissions and may provide more straightforward implementation pathways

This tiered approach ensures that the study captures a comprehensive range of operational realities, thereby supporting scalable deployment strategies.

This data was sourced from industry leading operational database, and was consistent with airports' own estimates, which helped confirm the accuracy of the data utilized.

3.2.2 Aircraft mix

The aircraft type mix across the 14 selected California airports was analyzed to evaluate compatibility with ZE taxiing technology. The current and forthcoming certification roadmap for ZE taxiing is crucial in determining the feasibility of its deployment.

At present, TaxiBot is fully certified for the Boeing 737 and Airbus A320 families, which encompass the most widely used narrow-body aircraft in commercial aviation. The Airbus A321XLR is expected to receive certification by 2026, further expanding the A320 family's scope. Additionally, certification for the Embraer family and the Airbus A220 is anticipated by 2026, while the Boeing 737 Max is projected to be certified by the end of 2026. Major wide-body aircraft from the A330, A350, B777, and B787 families are expected to be certified by 2029, with the potential for extension to other aircraft models as required by airlines.

All available aircraft movements at the 14 airports were categorized as follows:

In scope: Certified or planned for certification in the coming years, divided into:

  Narrow-body (NB): further categorized into Airbus, Boeing, and Embraer. This distinction is critical, as B737 aircraft require no modifications to operate with the TaxiBot, while A320 aircraft do (see Section 2). Other models are still undergoing certification, and it remains uncertain whether modifications will be necessary—initial indications suggest that A220 and Embraer jets may not require any:

    NB - Boeing

    NB - Airbus

    NB - Embraer

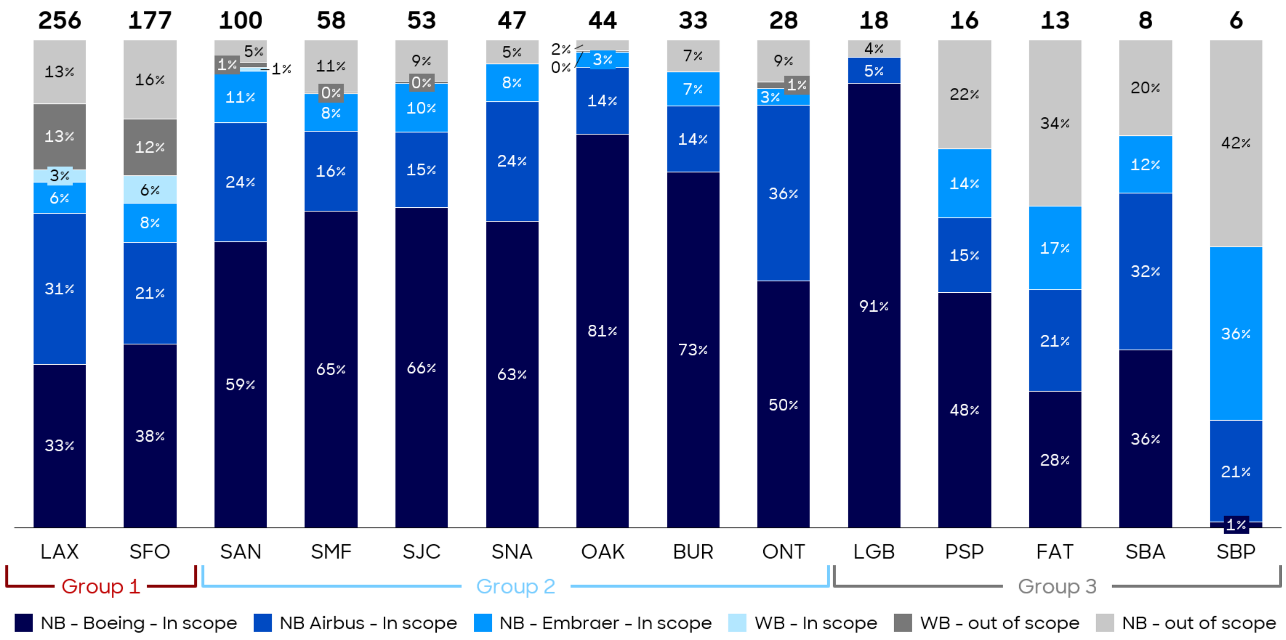
  Wide-body (WB)

Out of scope: Aircraft models not planned for certification:

  Wide-body (WB)

  Narrow-body (NB)

Figure 4: Aircraft mix for movements out [1,000s, %, commercial passenger aircraft, 2024]



The analysis indicates a relatively consistent distribution of aircraft types within Groups 1 & 2:

- **Group 1:** Airports such as LAX and SFO demonstrate a balanced mix of narrow-body aircraft in scope (approximately 70% of movements out) alongside wide-body aircraft that are out of scope. This distribution reflects their status as major international hubs, underscoring their significance due to their higher share of movements.
- **Group 2:** This group stands out as the most favorable, characterized by a high proportion of narrow-body aircraft, particularly Boeing models that require no modifications.
- **Group 3:** Airports exhibit greater variability in aircraft types, as anticipated for smaller airports, with a higher share of regional jets and smaller narrow-body models that fall outside of TaxiBot's design parameters.

Overall, the analysis does not reveal significant disparities that would warrant further segmentation at this time, reaffirming the suitability of the existing three-group structure.

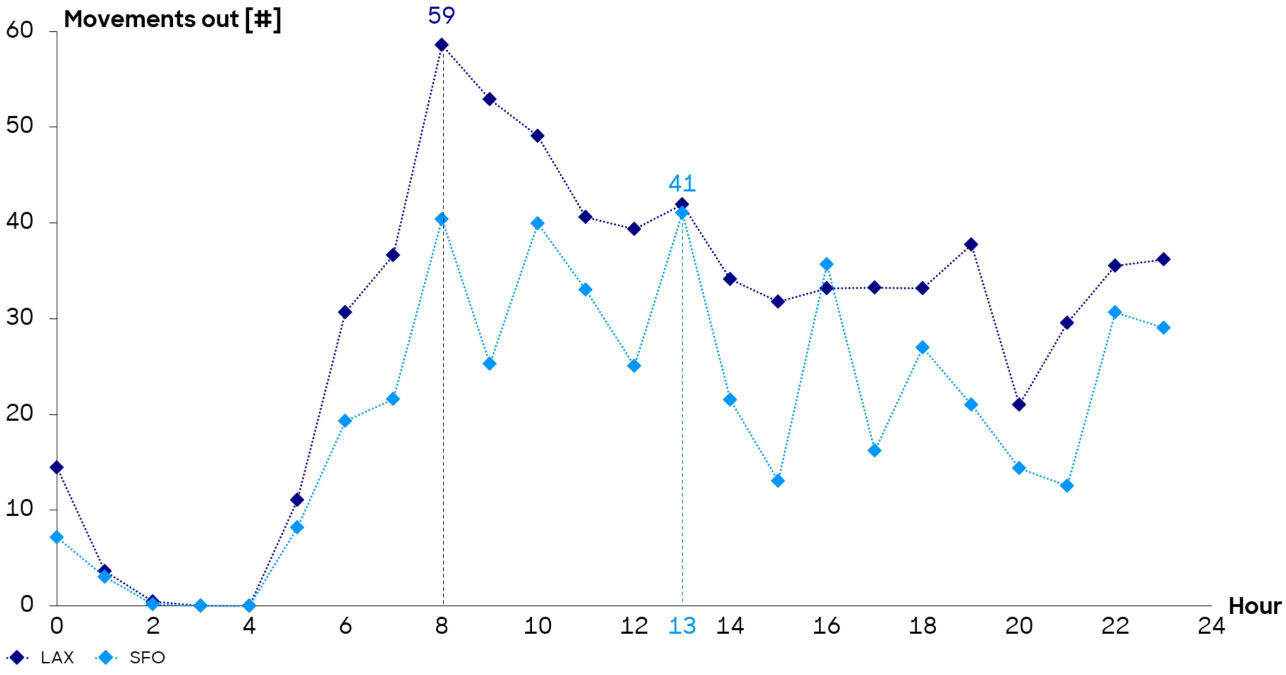
This assessment was conducted using an industry leading operational database as the primary source, with no confirmation or input from airports included at this stage.

3.2.3 Hourly distribution

The daily flight departure distribution was analyzed to evaluate the potential utilization rate of ZE taxiing at each airport. A less concentrated peak curve would theoretically facilitate more consistent use of ZE taxiing throughout the day, thereby enhancing operational efficiency and cost-effectiveness. However, this assertion needs to be verified on a case-by-case basis for each airport, taking into account the time required for each vehicle to return to the gate.

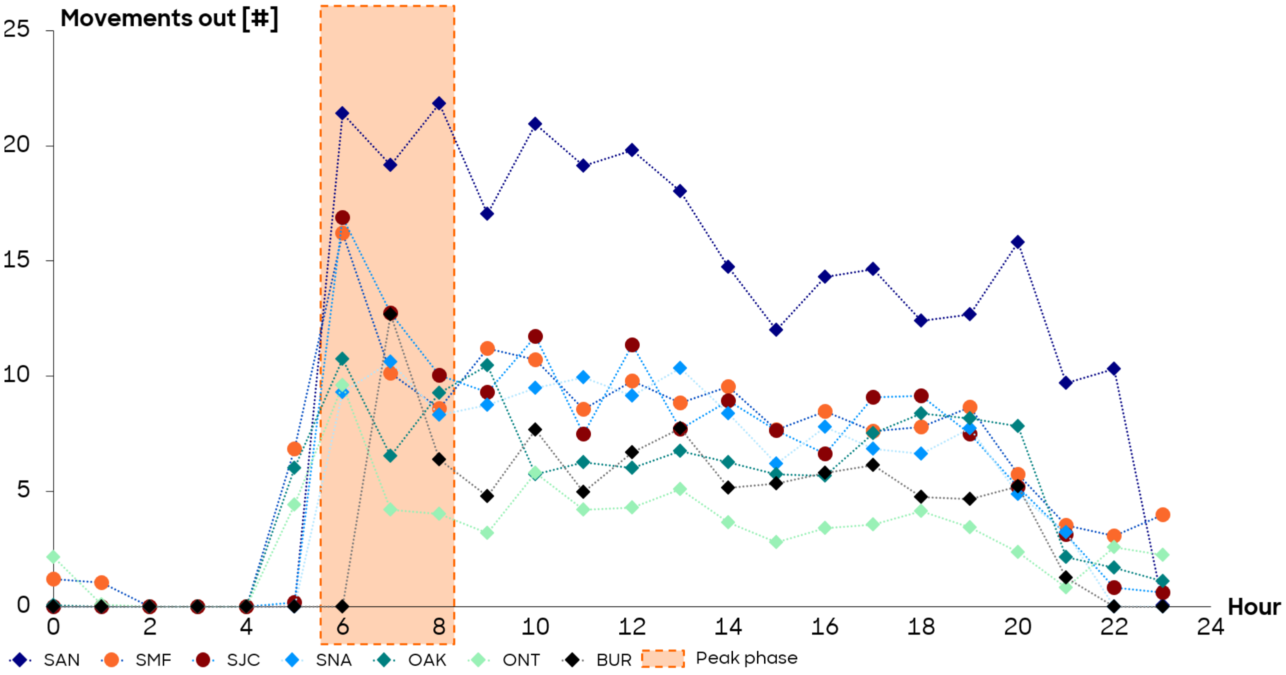
We have assessed this metric for each of our 3 groups to determine if significant differences justify the creation of distinct sub-groups within each category.

Figure 5: Hourly distribution - Group 1 [Daily movements out, based on yearly average, 2024]



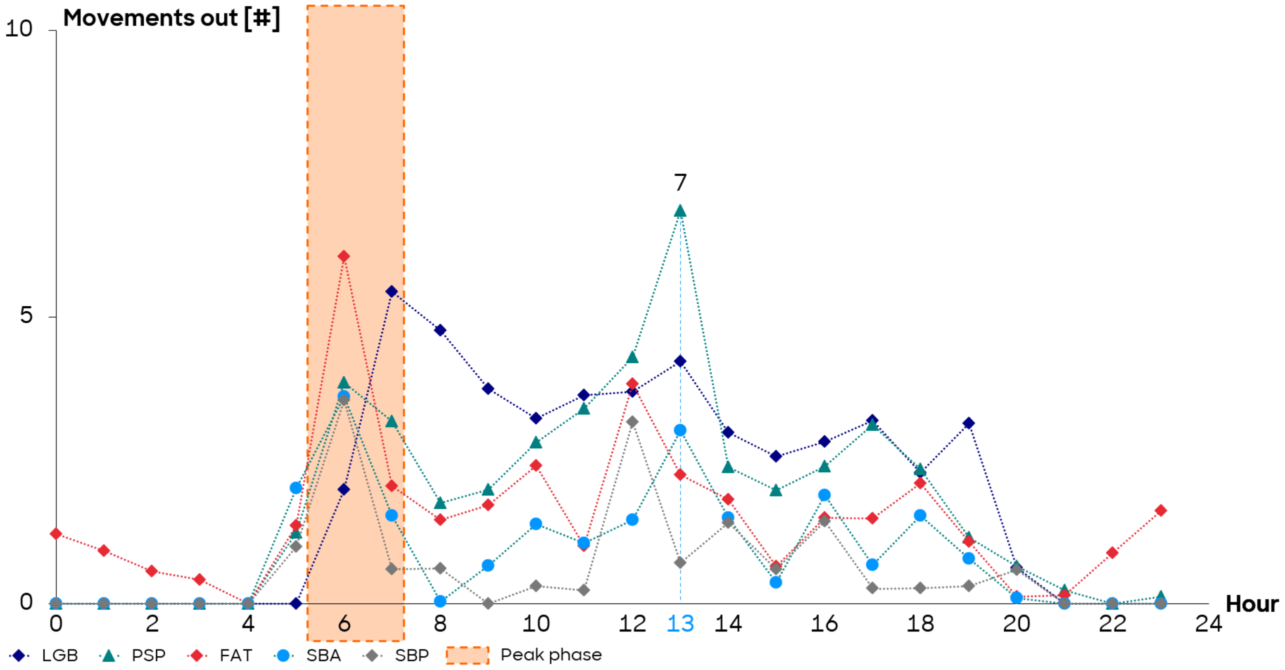
In this context, Group 1 airports - LAX and SFO - show distinct patterns: LAX exhibits a sharp morning peak with up to 59 movements at 8 a.m., while SFO has a more distributed profile with multiple moderate peaks, the highest being 41 movements at 1 p.m. However, since this group is defined primarily by the number of movements, creating sub-groups is not justified, as each would consist of only one airport.

Figure 6: Hourly distribution - Group 2 [Daily movements out, based on yearly average, 2024]



Group 2 airports—comprising SAN, SMF, SJC, SNA, OAK, ONT, and BUR—exhibit multiple peak phases throughout the day, with the most significant activity generally occurring between 6 and 8 a.m. While SAN airport experiences a higher peak due to its greater overall number of movements compared to the other airports in the group, the overall structure remains consistent across all airports.

Figure 7: Hourly distribution - Group 3 [Daily movements out, based on yearly average, 2024]



Group 3 airports—LGB, PSP, FAT, SBA, and SBP—exhibit the lowest peak intensities. Most of their activity is concentrated in the early morning hours, particularly between 6 and 7 a.m., although PSP stands out with a distinct peak at 1 p.m. Despite their lower traffic volumes, these airports demonstrate sufficient operational consistency to remain classified within the same group.

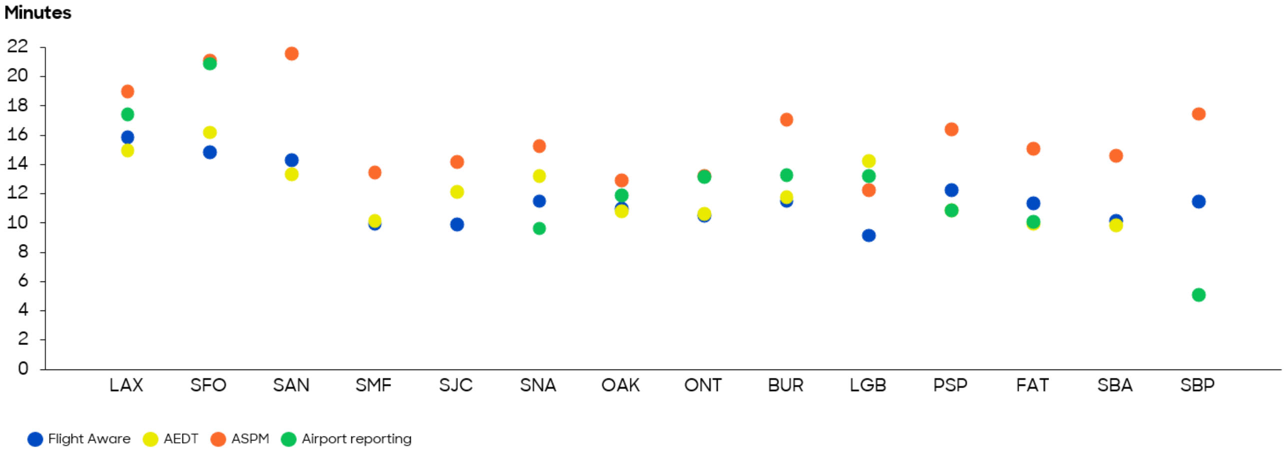
In conclusion, the peak analysis did not reveal any strong differentiating factor in peak distribution that would justify altering the existing group structure or creating new subgroups. While there are variations in peak timing and intensity, these differences are not structurally significant. The patterns remain consistent within each group and do not introduce operational constraints or opportunities that would require a finer segmentation.

3.2.4 Taxi-out time

Taxi-out duration is a critical factor in evaluating the environmental and operational benefits of ZE taxiing deployment.

Several sources measure & report this metric, including two FAA tools (ASPM Air Carrier 2024 data & AEDT, as referenced in the CAI2024 report) & FlightAware (Air Carrier 2024). Additionally, airports provide self-reported approximate values, some of which are included in the SCAQMD report (2023 values).

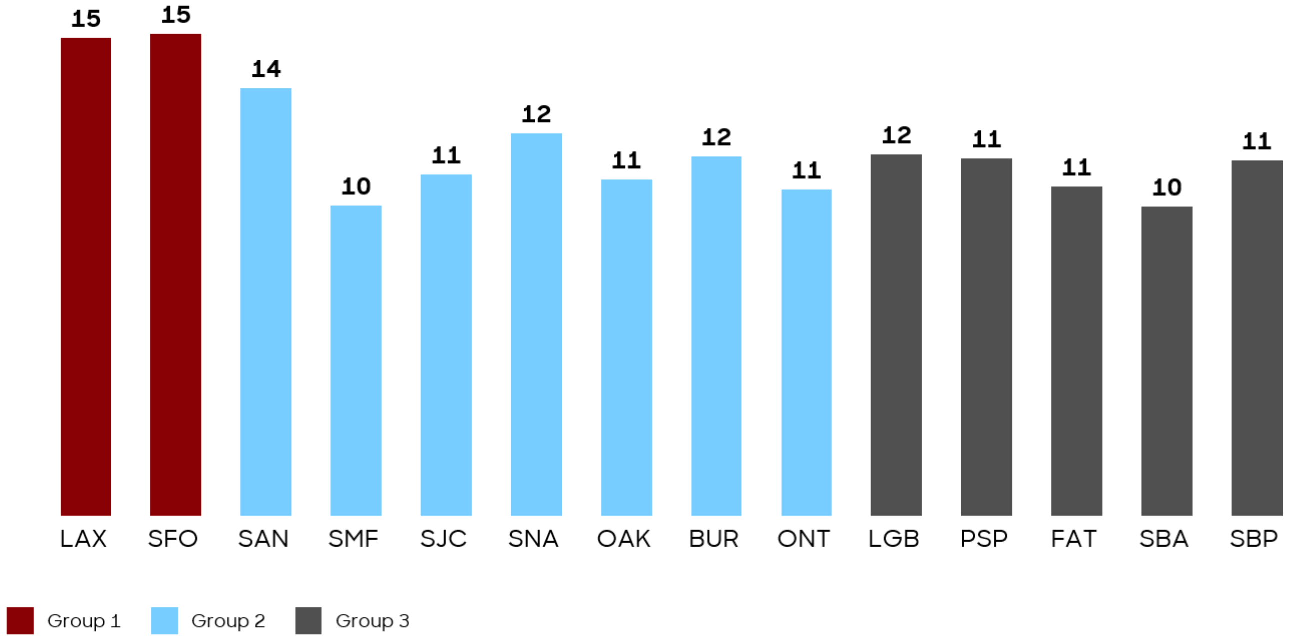
Figure 8: Taxi-out time [Average minutes, variation between sources]



The variability in these values likely stems from differences in how data is defined—for instance, whether timing begins at pushback, engine start, or after engine warm-up. If measured from pushback, it may not account for whether engines are running, as aircraft often wait for ATC clearance before starting engines & taxiing. This inconsistency contributes to discrepancies in reported values. Additionally, most airports do not comprehensively track this data at scale, limiting the reliability of ad hoc measurements.

For this report, given our mandate did not include verifying each data source and acknowledging the limitations of available data, we opted to use an average value from FlightAware and AEDT. These sources are consistent with each other and align more with high-level airport reports, with averaging applied to minimize outliers.

Figure 9: Taxi-out time [Average minutes]



According to the data, all 14 airports exhibit average taxi-out times exceeding 10 minutes, which above the threshold of 3 to 5 minutes considered relevant for low-emission taxiing solutions as they exceed engine warm-up time. Longer taxi durations enhance the potential for fuel savings and emissions reduction, strengthening the business case for zero emission taxiing implementation.

In conclusion, the uniformity of taxi-out durations above 10 minutes and the absence of meaningful variation within groups validate the existing three-group structure, with no need for additional segmentation based on this metric.

3.2.5 Space constraints

The physical layout of each airport was evaluated to assess its compatibility with ZE taxiing operations, focusing on space constraints for decoupling zones, accessibility of service roads for taxitows to return, and overall flow complexity.

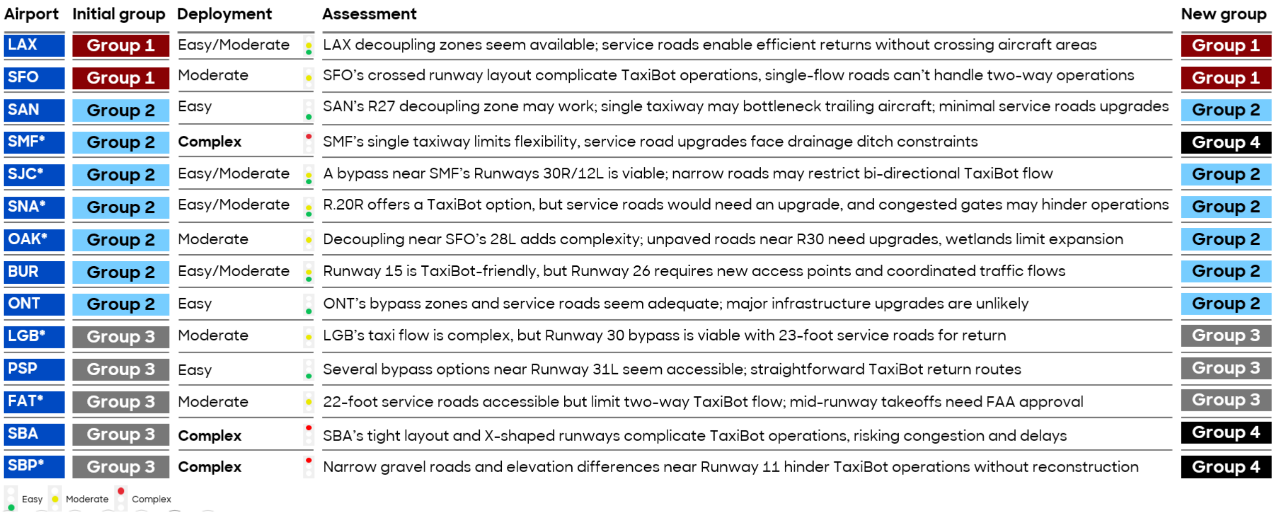
It is important to highlight that TaxiBot dimensions are larger than most ground support equipment (GSE). However, there is GSE of similar or larger size operating at airports, especially those responsible for towing wide-body aircraft. Airports have successfully accommodated these larger GSEs, likely due to their lower numbers & frequency of operation.

This assessment was conducted from an outside-in perspective, with the findings cross-verified with the TaxiBot manufacturer to ensure technical feasibility based on the OEM's inputs. While this methodology offers an initial assessment, a more detailed analysis would necessitate on-site evaluations involving all relevant airport stakeholders—including airport operator, air traffic control, ground handling players and airlines – to validate assumptions, identify operational edge cases, and refine deployment strategies.

Feedback from airports consistently underscores significant feasibility challenges stemming from limited space, often necessitating extensive modifications or, in some cases, making deployment unviable. This report critically examines such feedback to evaluate varying levels of deployment complexity. Input from airport stakeholders who responded to our inquiries—whether via email or through interviews—and provided relevant details regarding space constraints that challenged our assessment are: LAX, SMF, SJC, SNA, OAK, LGB, FAT, SBP.

The infrastructure analysis, considering airport layouts and service road accessibility, led to a revised classification system, expanding from 3 to 4 groups. Airports with significant space constraints ("Complex") were consolidated into Group 4, while the remaining airports, classified as easy or moderate, did not require further subdivision.

Figure 10: High level view of space constraints - Outside-in assessment



Airport	Initial group	Deployment	Assessment	New group
LAX	Group 1	Easy/Moderate 🟡🟢	LAX decoupling zones seem available; service roads enable efficient returns without crossing aircraft areas	Group 1
SFO	Group 1	Moderate 🟡	SFO's crossed runway layout complicate TaxiBot operations, single-flow roads can't handle two-way operations	Group 1
SAN	Group 2	Easy 🟢	SAN's R27 decoupling zone may work; single taxiway may bottleneck trailing aircraft; minimal service roads upgrades	Group 2
SMF*	Group 2	**Complex** 🔴	SMF's single taxiway limits flexibility, service road upgrades face drainage ditch constraints	Group 4
SJC*	Group 2	Easy/Moderate 🟡🟢	A bypass near SMF's Runways 30R/12L is viable; narrow roads may restrict bi-directional TaxiBot flow	Group 2
SNA*	Group 2	Easy/Moderate 🟡🟢	R.20R offers a TaxiBot option, but service roads would need an upgrade, and congested gates may hinder operations	Group 2
OAK*	Group 2	Moderate 🟡	Decoupling near SFO's 28L adds complexity; unpaved roads near R30 need upgrades, wetlands limit expansion	Group 2
BUR	Group 2	Easy/Moderate 🟡🟢	Runway 15 is TaxiBot-friendly, but Runway 26 requires new access points and coordinated traffic flows	Group 2
ONT	Group 2	Easy 🟢	ONT's bypass zones and service roads seem adequate; major infrastructure upgrades are unlikely	Group 2
LGB*	Group 3	Moderate 🟡	LGB's taxi flow is complex, but Runway 30 bypass is viable with 23-foot service roads for return	Group 3
PSP	Group 3	Easy 🟢	Several bypass options near Runway 31L seem accessible; straightforward TaxiBot return routes	Group 3
FAT*	Group 3	Moderate 🟡	22-foot service roads accessible but limit two-way TaxiBot flow; mid-runway takeoffs need FAA approval	Group 3
SBA	Group 3	**Complex** 🔴	SBA's tight layout and X-shaped runways complicate TaxiBot operations, risking congestion and delays	Group 4
SBP*	Group 3	**Complex** 🔴	Narrow gravel roads and elevation differences near Runway 11 hinder TaxiBot operations without reconstruction	Group 4

🟢 Easy 🟡 Moderate 🔴 Complex

Our assessment of each airport can be found in full text below:

- **LAX (Easy/Moderate)**: Decoupling zones at LAX seem identified and may not need additional infrastructure. Service roads appear wider than other airports, parallel to runways, and efficient for return paths without crossing aircraft areas. A planned airfield extension could ease layout constraints, and fluid GSE traffic flows supports smoother integration. The assessment was carried out visually using Google Maps measurements to assess layout and width over sections of each service road.

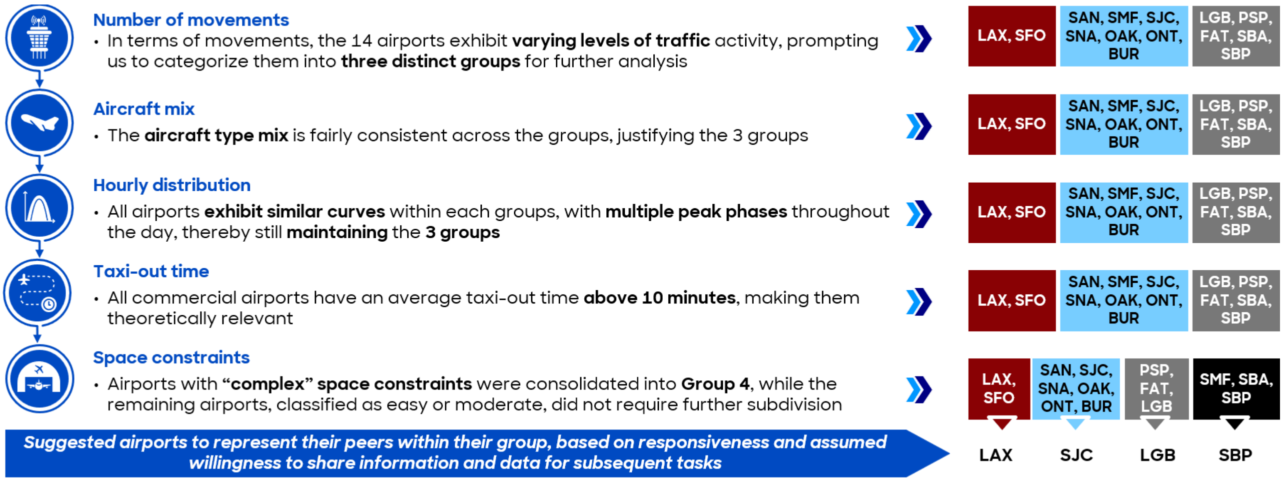
- **SFO (Moderate)**: SFO's crossed ("X") runway layout adds operational complexity. A potential decoupling zone has been identified near runways 28L and 1L, but key uncertainties remain, such as whether taxitows would need to complete a full circuit to return (which would be lengthy) or could be authorized to cross taxiways. Additionally, the proximity of taxiways to terminal areas seems to pose a risk of congestion due to frequent aircraft movement. While a single taxitow may theoretically return from the decoupling zone, the single-flow service road does not appear to accommodate two taxitows crossing paths—though such scenarios are expected to be rare, particularly at ramp-up
- **SAN (Easy)**: A decoupling zone on runway 27 appears to offer a technically viable location for ZE taxiing operations. However, SAN's single taxiway may pose a bottleneck risk, as any delays in decoupling could force trailing aircraft to wait. Infrastructure requirements for deployment seem minimal, with no major investments needed for service roads connecting the runway to the terminal
- **SMF (Complex)**: SMF's single taxiway, featuring only one runway entry point without a bypass option, limits flexibility as using a bypass would reduce the runway length required for safe takeoff. Modifications to service roads, such as adding overrun pads, may be needed; however, space constraints on the airfield—caused by a dense network of drainage ditches—present considerable challenges
- **SJC (Easy/Moderate)**: A bypass zone near runways 30R and 12L has been identified for early entry and decoupling, though its feasibility may require FAA validation. Return operations could utilize existing two-lane, 20-foot-wide service roads, but these are too narrow to accommodate bi-directional taxitow flows. Efforts to widen the roads could be limited by FAA guidelines regarding proximity to non-movement area (e.g., FAA Advisory Circular 150/5300-13B Airport Design is the FAA's primary guidance document for planning and designing civil airports in the US to ensure airport infrastructure supports safe and efficient aircraft operations)
- **SNA (Easy/Moderate)**: Runway 20R, from which the majority of flights depart, appears to offer a relatively straightforward deployment option, with a bypass potentially supporting disconnection, as available pads are used for other ground activities. However, service roads likely require upgrades and congested gate areas may complicate ZE taxiing operations
- **OAK (Moderate)**: Decoupling near 28L may be feasible with a bypass, though existing traffic flows are already complex. Returns could require either a lengthy full circuit or ATC approval to cross active taxiways. While a bypass pad on Runway 30 is viable, significant upgrades to unpaved service roads would be needed. Additionally, jurisdictional wetlands and proximity to San Francisco Bay limit options for widening or improving these routes
- **BUR (Easy/Moderate)**: Runway 15 appears well-suited for ZE taxiing operations with a manageable layout, while Runway 26 seems more complex, requiring careful coordination for routing and service road access. New access points may be needed, and traffic flows and permissions will likely require further discussion
- **ONT (Easy)**: ONT appears to have bypass zones and service roads in place, potentially offering a suitable layout for ZE taxiing operations. Significant infrastructure upgrades seem unlikely

- **LGB (Moderate)**: LGB's taxi flow is complex, with unpredictability from other general aviation traffic. However, 95% of commercial departures use Runway 30, where a bypass could be utilized, though access to the 23-foot-wide service roads would need to be established
- **PSP (Easy):** Several bypass options appear suitable for taxitow disconnection. Service roads near Runway 31L seem easily accessible, potentially enabling straightforward return routes.
- **FAT (Moderate):** The airfield's wide service roads appear accessible but are constrained to single-direction use due to their 22-foot lane width, limiting two-way taxitow flow. Mid-runway takeoffs could help reduce congestion during end-of-taxiway decoupling but would require FAA approval
- **SBA (Complex):** SBA's constrained airfield layout and X-shaped runway configuration poses challenges for ZE taxiing deployment, potentially increasing congestion and delays. Limited access to service roads from the taxiway network further complicates return routing
- **SBP (Complex):** The gravel, narrow, and sloped service roads appear unsuitable for Ze taxiing without reconstruction. On runway 11, the service road's lower elevation relative to the taxiway would require significant modifications to a neighboring property's retaining wall. With mid-field takeoffs currently unauthorized, bypass-based decoupling is not feasible. Future improvements might involve acquiring adjacent land for a staging area, though no decisions have been made

As a result, SMF, SBA, and SBP were assigned to Group 4, providing a more nuanced and operationally relevant perspective on deployment feasibility. The resulting four-group structure appears to capture both operational impact and practical possibility to deploy with greater accuracy.

The assessment grouped the 14 airports into 4 categories, with LAX, SJC, LGB and SBP recommended as representatives for their respective groups. This decision was based on the responsiveness of these airports' stakeholders during our interactions and their relatively greater availability of information, which also facilitates data collection for subsequent tasks requiring more detailed and verified data.

Figure 11: Airport grouping outcome



Number of movements

- In terms of movements, the 14 airports exhibit **varying levels of traffic** activity, prompting us to categorize them into **three distinct groups** for further analysis

Aircraft mix

- The **aircraft type mix** is fairly consistent across the groups, justifying the 3 groups

Hourly distribution

- All airports **exhibit similar curves** within each groups, with **multiple peak phases** throughout the day, thereby still **maintaining** the **3 groups**

Taxi-out time

- All commercial airports have an average taxi-out time **above 10 minutes**, making them theoretically relevant

Space constraints

- Airports with **"complex" space constraints** were consolidated into **Group 4**, while the remaining airports, classified as easy or moderate, did not require further subdivision

Suggested airports to represent their peers within their group, based on responsiveness and assumed willingness to share information and data for subsequent tasks

LAX, SFO	SAN, SMF, SJC, SNA, OAK, ONT, BUR	LGB, PSP, FAT, SBA, SBP	
LAX, SFO	SAN, SMF, SJC, SNA, OAK, ONT, BUR	LGB, PSP, FAT, SBA, SBP	
LAX, SFO	SAN, SMF, SJC, SNA, OAK, ONT, BUR	LGB, PSP, FAT, SBA, SBP	
LAX, SFO	SAN, SMF, SJC, SNA, OAK, ONT, BUR	LGB, PSP, FAT, SBA, SBP	
LAX, SFO	SAN, SJC, SNA, OAK, ONT, BUR	PSP, FAT, LGB	SMF, SBA, SBP
LAX	SJC	LGB	SBP

4 Trial Safety & Risk Management (SRM) Panel

4.1 Context and approach

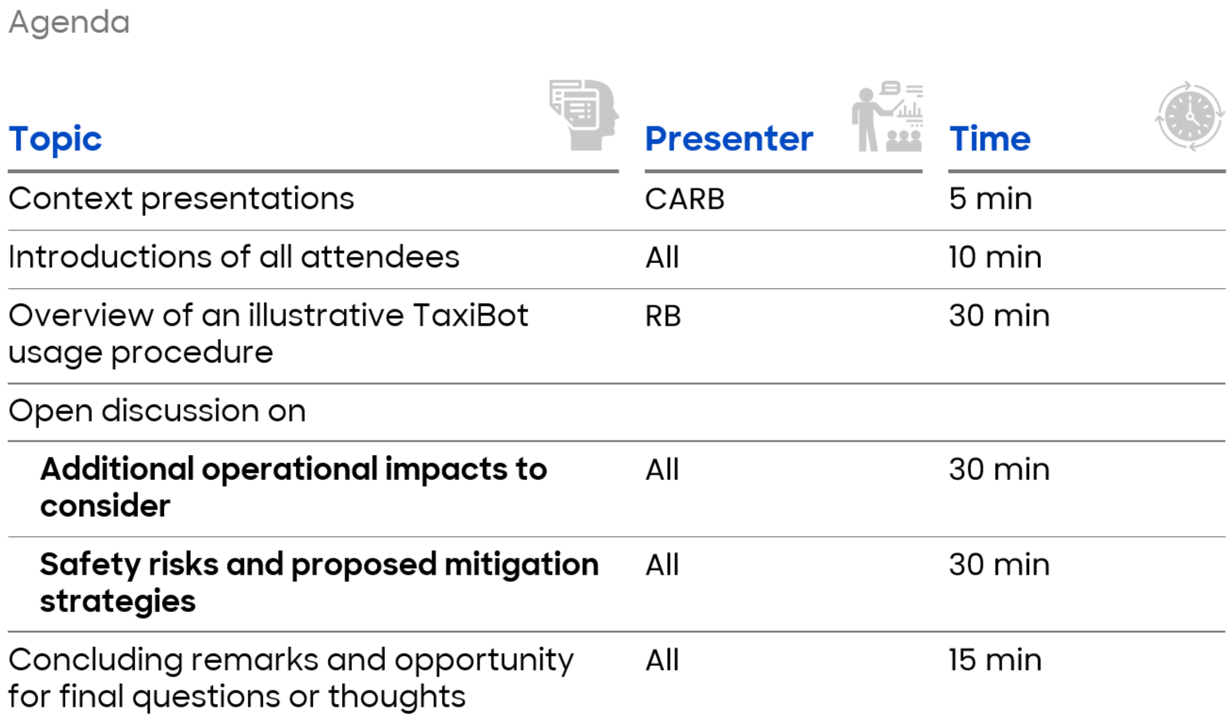
The SRM panel’s objective was to surface operational impacts, safety risks, and pragmatic mitigation measures associated with implementing ZE taxiing (TaxiBot-assisted taxi-out) at representative California airports for commercial operations, allowing to document feedback and address potential concerns raised by the FAA.

For this panel, a 2-hour format was retained with the following building blocks: context, introductions, the illustrative TaxiBot procedure, a 30-minute open discussion on operational impacts, a 30-minute risk/mitigation session, and closing remarks

Following the panel, participants were given a two-week window to submit additional comments, but no responses were received.

One key takeaway of the safety panel is that TaxiBot encountered only two operational issues at AMS, neither of which affected safety. No safety-related incidents were reported at New Delhi, Bengaluru, or Paris CDG airports.

Figure 12: SRM Panel agenda



Agenda

Topic	Presenter	Time
Context presentations	CARB	5 min
Introductions of all attendees	All	10 min
Overview of an illustrative TaxiBot usage procedure	RB	30 min
Open discussion on		
Additional operational impacts to consider	All	30 min
Safety risks and proposed mitigation strategies	All	30 min
Concluding remarks and opportunity for final questions or thoughts	All	15 min

4.2 Panel participants

The objective is to gather comprehensive feedback from stakeholders with direct implementation experience and those expressing interest or reservations to implement the solution:

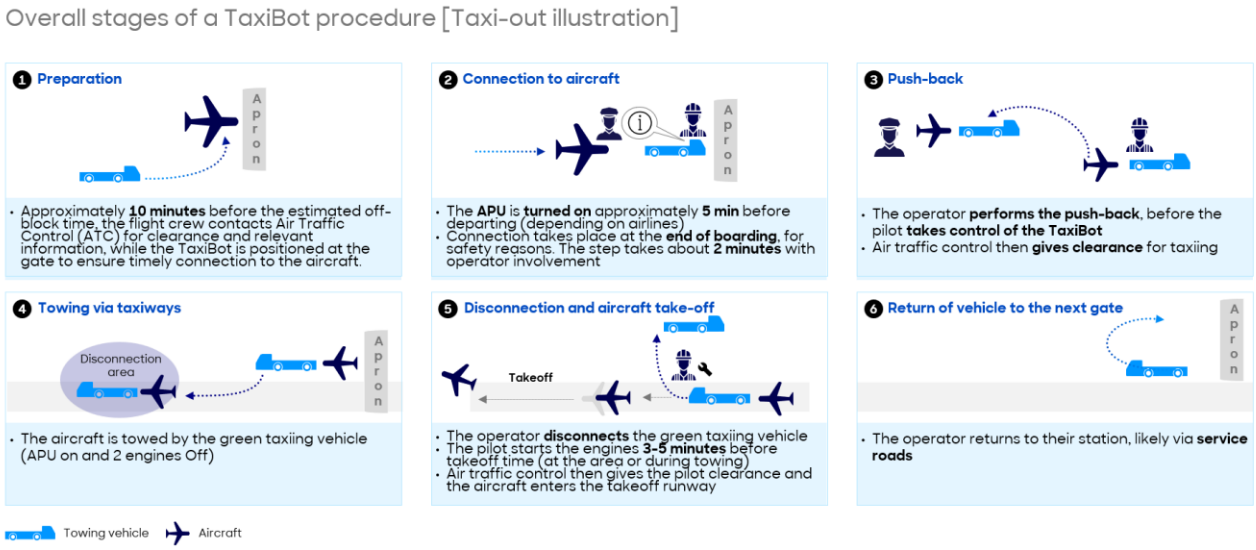
- Participants included representatives from CARB, FAA (member of the ATC at LAX), KLM Airlines, Delta Air Lines, Industry association A4A, LAX airport, SBP airport. Notably, A4A and LAX representatives demonstrated particularly strong involvement and active participation.

- Other guests who were either unavailable or declined to participate include AMS, JFK, SJC and LGB airports

4.3 Panel unfolding

The panel started with a review of step-by-step operational procedure (TaxiBot taxi-out) to anchor common understanding across participants, with a high-level version outlined below:

Figure 13: Overview of an illustrative TaxiBot procedure



Overall stages of a TaxiBot procedure [Taxi-out illustration]

❶ **Preparation**

- Approximately **10 minutes** before the estimated off-block time, the flight crew contacts Air Traffic Control (ATC) for clearance and relevant information, while the TaxiBot is positioned at the gate to ensure timely connection to the aircraft.

❷ **Connection to aircraft**

- The **APU** is **turned on** approximately **5 min** before departing (depending on airlines)
- Connection takes place at the **end of boarding**, for safety reasons. The step takes about **2 minutes** with operator involvement

❸ **Push-back**

- The operator **performs the push-back**, before the pilot **takes control of the TaxiBot**
- Air traffic control then **gives clearance** for taxiing

❹ **Towing via taxiways**

- The aircraft is towed by the green taxiing vehicle (APU on and 2 engines Off)

❺ **Disconnection and aircraft take-off**

- The operator **disconnects** the green taxiing vehicle
- The pilot starts the engines **3-5 minutes** before takeoff time (at the area or during towing)
- Air traffic control then gives the pilot clearance and the aircraft enters the takeoff runway

❻ **Return of vehicle to the next gate**

- The operator returns to their station, likely via **service roads**

A six-stage sequence for taxi-out operations was proposed, drawing in part from AMS airport procedures and validated by our KLM representative during the panel.

1. **Preparation** – ~10 minutes before off-block: flight crew contacts ATC for clearance and relevant information; TaxiBot positioned at gate
2. **Connection to aircraft** – Connection (~2 minutes) with operator involvement; APU typically activated ~5 minutes before departure (airline-dependent)
3. **Push-back** – Operator performs push-back; pilots assume control of TaxiBot; ATC issues taxi clearance
4. **Towing via taxiways** – Aircraft is towed (APU on, engines off); pilots steer via tiller/nose gear, managing speed via brakes in line with policy and conditions
5. **Disconnection & take-off** – At a designated disconnect area near runway: operator disconnects (~1 minute), engines start 3-5 minutes before take-off (at area or during towing, depending on procedures and clearance timing), ATC provides runway entry clearance
6. **Return to next gate** – Operator drives TaxiBot back via service roads, using bypass pads as needed

A review of airport set-up requirements allowed all stakeholders to understand the known needs and things to anticipate (refer to Table 2 of this document).

4.4 Key takeaways of the panel

In addition to the previously outlined operational impacts, a facilitation process enabled the identification of operational impacts and safety hazards, broken down by stage and stakeholder group, along with potential mitigation measures. This exercise was conducted jointly, leveraging Roland Berger's expertise–supported by interviews, desk research, and

Eurocontrol ConOps analysis—as well as illustrative examples from AMS airport, thanks to the active involvement of a KLM Airlines operations representative.

The KLM representative clarified that, across all 95 operations as of February 2026, there were two incidents in total: The first incident involved a nose overload caused by exceeding the recommended speed during a turn, resulting in a two-hour delay. This risk is expected to decrease with further training and experience. The other incident involved a diesel vehicle running out of fuel, which led to cancellations. Importantly, both incidents were operational rather than safety-related.

The operational impacts discussed are consistent with those identified in Tasks 1 and 2 of this report, underscoring the need for airports to proactively plan for infrastructure and operational requirements.

From a target perspective, the panel emphasized the need to discuss and evaluate the pilot's feasibility, noting that launching at a smaller airport could be appropriate—provided that taxi times are sufficiently long to justify the initiative.

Table 4: Operational impacts to anticipate

Step	ATC	Ground handlers	Airlines / cockpit crew
1. Preparation		Electrical infrastructure for charging electric vehicles must be assessed individually at each airport. Additionally, available space at the gates—for both the taxitow itself and charging facilities—was reported to be a potential issue	
6. Return of vehicle to the next gate		Service road width and configuration must be considered (e.g., At AMS, new terminal designs are being planned with appropriate service road dimensions in mind)	
All stages combined	Staffing requirements for the ATC may need to be reviewed to accommodate the additional workload required. Workload was found to be comparable at some airports (e.g., Delhi),	Vehicle ownership, operation, and maintenance will have to be determined by each airport's specific requirements (e.g., at AMS, future vehicles will be managed by ground handlers). The	Pilot training should extend beyond a 30-minute CBT, as more comprehensive instruction is likely necessary (incl. hands-on practice time) – particularly since airlines typically

	but significantly higher at others that are already highly constrained (e.g., CDG, although not thoroughly estimated). The impact varies based on airport congestion and the challenges of accommodating additional vehicles. A case-by-case analysis is necessary to accurately assess needs. Team structure could also be adjusted to co-locate pushback and towing teams.	business model may differ between pilot trials and full-scale implementation.	train pilots by aircraft model changes rather than home base, which requires large-scale training efforts (e.g., A4A mentioned that if TaxiBot is adopted for A320 aircraft at LAX, all airline pilots operating A320s nationwide would likely need to be trained, regardless of their home base, if current guidelines are applied) Practical, on-site training is also valuable for accelerating the learning curve as highlighted by KLM

Potential safety risks discussed reflect those already assessed at AMS airport, with mitigation measures implemented.

Table 5: Possible safety hazards and associated mitigation options

Step	**Potential safety hazards**	**Mitigation options**
1. Preparation	Procedures and safety measures vary based on towing/taxiing type	Ensure all operational stakeholders, including airside drivers and ground handling staff, are aware of the taxi mode being used, as this may have different implications for safety, capacity, and resources
2. Connection to aircraft	A single clearance for both pushback and taxiing could theoretically be issued if operational conditions permit	For safety reasons, this procedure should not be implemented in the near term. ATC will provide separate clearances for pushback and towing to ensure access to the disconnect area, as it may be occupied by another taxitow-equipped aircraft or an emergency vehicle

3. Push-back	Procedures and safety measures vary based on towing/taxiing type	In the event of an unplanned operational or planning change that prevents end-to-end low-emission taxiing operations, a taxitow may technically be used to perform only the pushback, using a dedicated Maintenance Towing mode. However, this mode follows a different operational procedure (bypass pin not installed) compared to a regular pushback vehicle (bypass pin installed), potentially increasing the risk of error. To maintain operational simplicity, procedural consistency, and clear expectations for flight crews, in the early stage of a ZE taxiing project, the taxitow is therefore not used for conventional pushback scenarios, and a regular pushback tug is preferred. Training of both pilots and operators is critical to ensure proper steps execution (no incidents reported by AMS airport)
4. Towing via taxiways	Potential vehicle failure or electric fire while towing an aircraft	Maintain an emergency pushback vehicle on standby at all times, ready to respond in the event of a major failure. At larger airports, establish a process to ensure the nearest available vehicle can intervene promptly
	Absence of communication between operator and ATC creating risk concerns	Operator does not steer, reducing need for ATC communication. However, communication can be established if needed, but may impact radio frequency load; airport discretion applies
	Crossing of an active runway	Follow standard procedures for taxiing aircraft; flight crew remains in contact with ATC at all times
	Lack of visibility for ATC vs. regular tow convoys	Equip the on-ground solution convoy (vehicle + aircraft) with the same or similar recognition lights as other taxiing aircraft to distinguish them from regular tow convoys

		Paint the taxitow a singular bright color to ensure visibility from all parties
5. Disconnection and aircraft take-off	Risks from jet blasts when engines are activated (either at the disconnect area or during taxiing) or other engine hazards	The operator in the vehicle, whether connected or disconnected from the aircraft, can monitor jet engine activation to ensure proper operation and communicate any observed hazards to the cockpit crew The operator can disconnect the vehicle within ~1 min. In an emergency (e.g., fire), the operator can disconnect and evacuate the area without needing to manually unplug, slightly accelerating disconnect
6. Return of vehicle to the next gate	Crossing with other vehicles could occur on the service roads	Emergency and firefighting vehicles responding to the runway should have priority. All other traffic, including taxitow must yield by moving to the nearest accessible bypass pad
	Vehicle failure after disconnect	The operator stays in contact with tow control by phone to address a potential failure and can also reach ATC or apron control in an emergency. Communication can occur in both directions
All stages combined	Pilot loses communication with ATC	The procedure is similar to operations without a taxitow. In an emergency, the operator can communicate with ATC, although this is not normally part of standard procedures
	ATC workload is a significant concern, as it is already deemed too high at certain airports	If separate, co-locate apron/push-back control with towing/taxiing control to manage all ground traffic (conventional taxi, taxitow, conventional tow) within the same organization. This enhances awareness of the traffic situation, reducing safety incidents and workload. Additional staffing may also be necessary for ATC to monitor taxitow pushback and taxiing and ensure that disconnect pads

	and queueing do not impede incoming/outgoing aircraft Each airport's specific layout and procedures must be evaluated to identify enablers for risk mitigation, potentially leading to increased ATC staffing, at least during the ramp-up phases

All identified concerns must be addressed with rigorous guidelines, close safety monitoring, comprehensive training for all pilots and operators, and a commitment to leaving nothing to chance. Safety should always be the top priority. A phased, trial-based approach is recommended to build operational experience, capture ad hoc scenarios, and develop targeted safety solutions.

5 Operational & infrastructure assessment of California airports

5.1 Background and objectives

To understand the feasibility of ZE taxiing at key airports, this section reviews the readiness to deploy ZE taxiing solutions based on the current infrastructure, operational constraints, and other technical constraints. These capabilities were compared to the requirements associated with the deployment of ZE taxiing covering different percentiles (25%, 50%, 75%, 100%) of the aircraft suitable for ZE taxiing ("ZE taxiing compatible") aircraft[4]. As a reminder, the selected technology to illustrate ZE taxiing was the TaxiBot.

The objective of the analysis is to identify any potential obstacles to the deployment of the solution across the different airports, then assess how they can be mitigated. Based on this assessment, a Flight Percentage with Minimum Infrastructure Modification (FP_{MIM}) was calculated to show the share of ZE taxiing compatible flights achievable with minimum infrastructure modifications (e.g., widening a service road when there are no adjacent buildings).

5.2 Methodology

5.2.1 Data sources

Our approach has been to rely on both public and airport data to understand current airport capabilities.

Leveraging public data, we considered the publications, reports, and masterplans of airports, as well as publicly available pictures and satellite views of the airport and its infrastructure. This allowed to identify the major infrastructure (e.g., key taxiways, service roads, etc.) and potentially limiting factors (e.g., absence of return service road from the runway).

Leveraging airport data, we reached out to the airports with data requests about the existing infrastructure and, when feasible, conducted interviews to confirm our findings.

The response rate from airports has been low, with only two airports (LAX and SBP) sharing some data. Consequently, the analysis relied more heavily on publicly available information. Where direct engagement with airports was not possible, operational challenges that may not be apparent in theoretical assessments could not be fully considered.

5.2.2 FP_{MIM}

To calculate the FP_{MIM}, infrastructure limitations to reaching 100% ZE taxiing for compatible flights are considered.

The first step is to calculate the baseline of all ZE taxiing compatible flights, based on aircraft compatibility. This baseline is composed of narrow-body aircraft from the following families: A320, A220, B737 and Embraer. These represent 79% of outbound movements across the 14 in-scope airports.

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[4] At present, TaxiBot is fully certified for the Boeing 737 and Airbus A320 families, which encompass the most widely used narrow-body aircraft in commercial aviation. The Airbus A321XLR is expected to receive certification by 2026, further expanding the A320 family's scope. Additionally, certification for the Embraer family and the Airbus A220 is anticipated by 2026, while the Boeing 737 Max is projected to be certified by the end of 2026. Major wide-body aircraft from the A330, A350, B777, and B787 families are expected to be certified by 2029, with the potential for extension to other aircraft models as required by airlines.

From this baseline, infrastructure incompatible with the deployment of ZE taxiing is assessed, based on criteria such as the absence of return service roads, their insufficient sturdiness, or insufficient width.

Overall, the formula used to calculate the FP_{MIM} at each airport is:

$$FP_{MIM} = \frac{\text{TaxiBot compatible baseline} - \text{Flights using incompatible infrastructure}}{\text{TaxiBot compatible baseline}}$$

Where, for each given airport:

$$\text{TaxiBot compatible baseline} = \sum_{\text{Airport}} \text{TaxiBot compatible flights}$$

Currently, ZE taxiing is restricted to taxi-out operations, therefore the analysis focuses on outbound flights only.

5.3 Current capability assessment

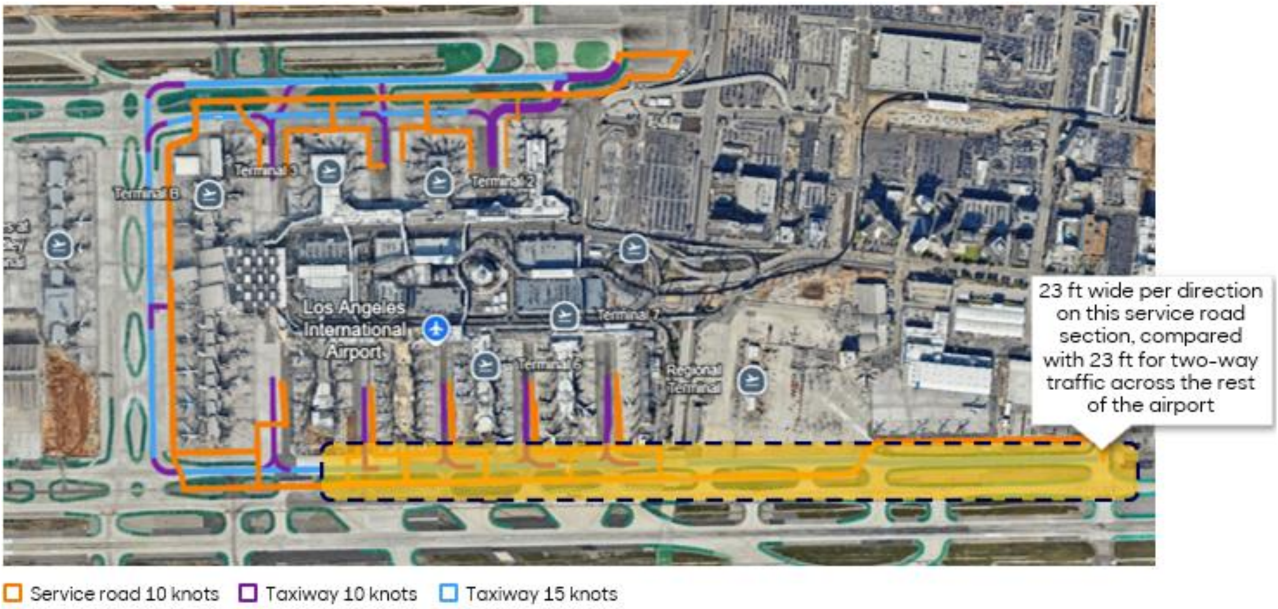
5.3.1 LAX

Overall, no major obstacle to 100% ZE taxiing has been identified for LAX (FP_{MIM} = 100%).

18 major routes cover approximately 90% of total LAX traffic, through runways 24L and 25R. These routes are the *de facto* standard routing for access from Terminals T1-T2-T3-B-T4-T5-T6-T7-T8. They all appear compatible with ZE taxiing based on their width, structure, and layout. They also appear to have access to service roads for the taxitow to return.

One further point of consideration for future studies is that the taxitow footprint exceeds the width of a single service road lane, implying that it would partially operate on the opposite lane when in motion. This configuration increases the complexity of bidirectional traffic management and vehicle crossings, and would require dedicated operational rules or infrastructure adaptations to ensure safe and efficient coexistence with other airside vehicles.

Figure 14: LAX Capability Assessment



23 ft wide per direction on this service road section, compared with 23 ft for two-way traffic across the rest of the airport

5.3.2 LGB

Overall, no blocker to 100% ZE taxiing was identified for LGB (FP_{MIM} = 100%).

2 major routes cover almost all of the traffic, through runways 30 and 12. Runways 26R/8L and 26L/8R are mainly used for General Aviation. Despite a complex operational flow with crossing runways, no material impact on ZE taxiing operation is expected given the airport's limited traffic. All taxiways appear compatible with ZE taxiing based on their width, structure, and layout. They also have access to service roads for the taxitows to return.

The study identified that the connection from the taxiway to the service road has ~120 ft to be paved to allow for ZE taxiing deployment, which adds to infrastructure deployment costs[5]. One further point of consideration for future studies is that the taxitow footprint exceeds the width of a single service road lane, implying that it would partially operate on the opposite lane when in motion. This configuration increases the complexity of bidirectional traffic management and vehicle crossings, and would require dedicated operational rules or infrastructure adaptations to ensure safe and efficient coexistence with other airside vehicles.

Figure 15: LGB Capability Assessment

5.3.3 SJC

One of SJC's runways is not compatible with ZE taxiing due to insufficient service road width, and limited space to expand the road (FP_{MIM} = 87%).

Runway 30R (~87 % of traffic[6]) presents no issues on the runway or service road: sufficient space is available, requiring only minor ground marking adjustments. Runway 12L is not compatible with ZE taxiing due to the insufficient width of the return service road. Fixed physical constraints on both sides (the airside wall and the road) limit the available width to approximately 10 ft in certain sections. Addressing this constraint would require to expand the road onto the airfield or the adjacent land plot (motorway), which would require on-site technical evaluation.

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[5] Included in the cost of infrastructure upgrade farther in the document.

[6] Division of the number of compatible take-offs from this runway by the number of compatible take-offs at the airport. Source: database of aircraft movements at key airports.

Figure 16: SJC Capability Assessment

Runway 12L represents a material issue for taxitow return operations (redline), as the return service road is narrow. Fixed physical constraints on both sides (the airside wall and the road) limit the available width to approximately 10 ft in certain sections. Addressing this constraint would require a detailed feasibility assessment to widen the road, potentially involving significant capital investments

🟧 Service road 10 knots 🟪 Taxiway 10 knots 🟦 Taxiway 15 knots

5.3.4 SBP

One of SBP’s runway is not compatible with ZE taxiing due to insufficient service road width, and limited space to expand the road (FP_{MIM} = 86%).

Runway 29 (~86 % of traffic) does not appear to present any incompatibility on the runway or service road. Partial use of the opposite service road lane and temporary exit/re-entry of the airport to access the service road can be an operational complexity to manage, but is not deemed a blocking point due to the limited airport traffic. Runway 11 (14% of traffic) is not accessible due to insufficient return service road width: at its end, the access road is below taxiway level; raising it would require changes to an adjacent third-party retaining wall. The access roads are also unpaved.

One further point of consideration for future studies is that the width of a taxitow (~3.7 m) may exceed the width of a single service road lane at SBP (~2.7m), implying that it would partially operate on the opposite lane when in motion. While this configuration increases the complexity of bidirectional traffic management, this is not expected to be a major hurdle for SBP given the low volume of traffic and the limited existing traffic complexity (i.e., traffic in the other direction might need to stop to let the ZE taxitow solution pass).

Figure 17: SBP Capability Assessment

At the 11 end, the access road is below taxiway level; raising it would require changes to an adjacent third-party retaining wall. The access roads are also unpaved

☐ Service road 10 knots ☐ Taxiway 10 knots ☐ Taxiway 15 knots

5.4 Total flights and FP_{MIM} by airport

The below table summarizes airport traffic and constraints for ZE taxiing.

Table 6: FP_{MIM} for key airports

Airport	Movements out (2024)	Incompatible aircraft	Incompatible infra	Compatible flights	FP_{MIM}	% of tot. flights
LAX	257 278	54 824	0	202 454	100%	79%
LGB	17 650	53	0	17 597	100%	99%
SJC	53 378	752	6 754	45 872	87%	86%
SBP	5 516	753	646	4 117	86%	75%

5.5 Capability gaps and modifications

Considering aircraft compatibility fixed, infrastructure and operational modifications can allow to reach the highest number of ZE taxiing compatible flights. The table below summarizes current limitations and possible mitigations at all 4 airports.

Table 7: SBP Capability Assessment

Criteria	LAX	LGB	SJC	SBP
Limiting infrastructure	• Narrow SRs that would not fit 2 heavy vehicles at 24L (23ft wide vs. 13ft for TB) – not directly impacting FP_{MIM}	• No bi-directional flow for large vehicles on return service roads	• Narrow return service road on 12L, making taxitow return impossible • No bi-directional flow for large vehicles on return service roads	• Lower elevation at SR 11 making it incompatible with ZE taxiing • Ground work needed for a small portion of the SR 29

Criteria	LAX	LGB	SJC	SBP
Operational constraints	- Authorization to cross non movement zone to reach SR at 24L & 25 R – *not directly impacting FP_{MIM}*	- Operational complexity due to X-shaped runways – *not directly impacting FP_{MIM}*	- n.a.	- Mid-field take-off currently not authorized and requires FAA approval
	Modifications to ATC & pilot checklist to ensure proper recognition of Taxiied aircraft3)			
ZE taxiing compatible movements (FP_{MIM})	**202k** 100%	**18k** 100%	**46k** 87%	**4k** 86%
Infrastructure modifications	- Concreting of unused land to be used for storing taxitow, otherwise storage airside - Space at gate must be verified on site as Google Earth analysis does not allow to conclude - Adaptation of maintenance infrastructure	- Sufficient available surface areas, either already paved or readily suitable for paving	- Existing paved areas seem to offer flexibility for reallocation, including potential use for ZE taxiing	- Paving return service road 29 and storage space - Space at gate must be verified on site as Google Earth analysis does not allow to conclude - Adaptation of maintenance infra
Operation modifications	- Authorization from FAA & ATC to cross non movement area on few meters to joint SR - Authorization for bypass use	- n.a.	- n.a.	- Authorization for mid field take-off and/or by-pass utilization

6 Modeling of ZE Taxiing at selected airports

6.1 Background and objectives

Building on the analysis of key airports, a simulation model for ZE taxiing was developed, incorporating data points including runway layouts, real-world flight data, and ZE unit specifications.

The objective is to understand the requirements to the deployment of ZE taxiing covering tranches (25%, 50%, 75%, 100%) of the ZE taxiing compatible movements out in order to assess and test the associated operational constraints. The key outputs of this model are:

- The number of taxitow
- The electrical load required for optimized recharging
- The average utilization time
- The confirmation of any infrastructure or operational bottlenecks that could limit airport efficiency

6.2 Methodology

6.2.1 Overarching structure

The methodology aims to size the minimum number of taxitows required, and to derive both the number of flights effectively using ZE taxiing and the resulting capacity impact.

It follows 3 sequential steps:

1. **ZE taxiing hourly capacity calculation (by route and terminal group)**

The number of roundtrips per hour that a ZE taxiing can perform between a terminal and a runway is computed based on a full operational cycle time, including:

- Idle time at gate (informed by current deployment case studies)
- Terminal-to-runway travel time (derived from the max between the distance and average speed and current taxi time)
- Decoupling time net of time saved at gate
- Return trip
- Operational availability factor (including criteria such as electric charging, planned maintenance, etc.)

This defines the hourly productivity of a taxitow for each route, with taxitows mutualized within a group of terminals. LAX is divided into 3 groups; SJC, SBP and LGB have only 1 group.

2. **Theoretical addressable demand**

Starting from the total number of movements per hour, successive filters are applied for:

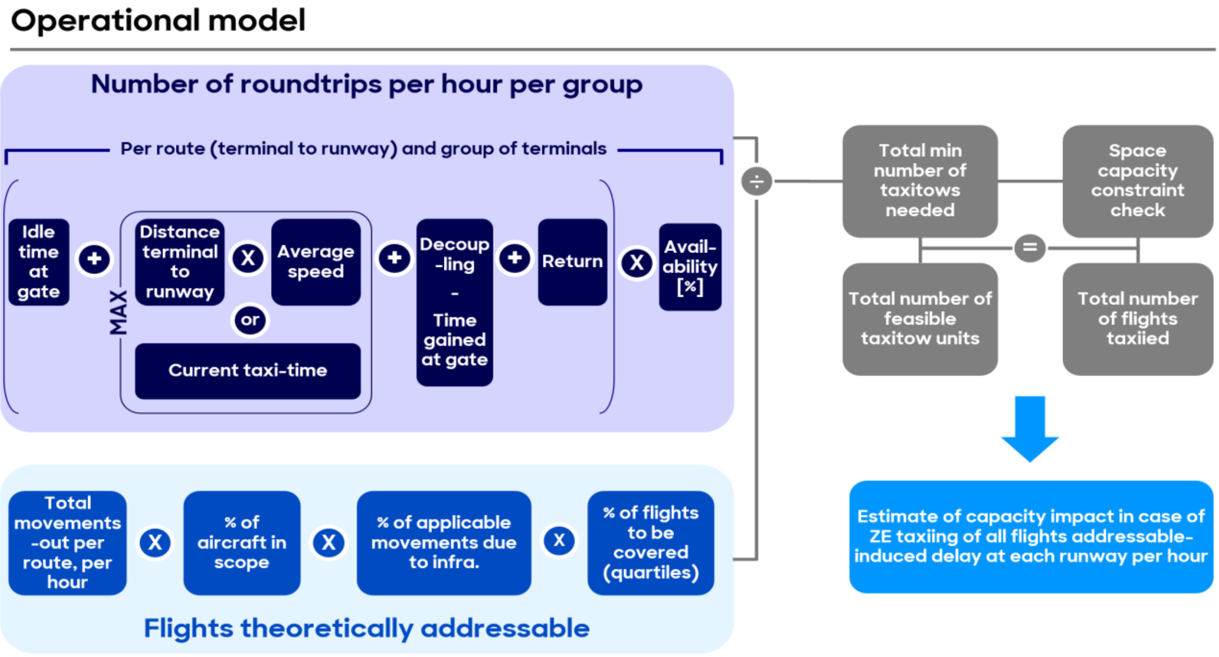
- The share of ZE taxiing-compatible aircraft
- Infrastructure applicability (service roads available, charging and standby space available, road width, material, and whether these are compatible with taxitow traffic)
- Targeted coverage level (quartiles: 25%, 50%, 75%, 100%)

This results in the number of flights theoretically addressable by taxitow per hour.

3. Fleet sizing

By comparing addressable demand with available taxitow fleet capacity, the model determines the minimum number of taxitows required to achieve the targeted coverage level based on peak-hour analysis. It then derives the actual number of flights using ZE taxiing, enabling an estimate of runway capacity impact, including ZE-taxiing-induced delays or time savings per runway and per hour, through a congestion analysis.

Figure 18: High-level overview of model flow



6.2.2 Main principles

The model relies on a set of principles and key hypotheses listed below:

- Only routes with a large share of movements out are considered, as deploying ZE taxiing equipment to routes (from gate / embarking point to runway) that are almost never utilized would lead to critically underutilized equipment which is not deemed realistic
- Taxitows are centrally dispatched and shared across routes within a group of terminals (3 groups for LAX, 1 group for the other airports)
- Share of taxitows compatible aircraft deemed stable over time
- Potential delay caused by decoupling step is compensated by time gained at gate, since taxiing can be performed immediately after pushback tractor. However, this gain is set at 0 in our base case scenario
- Return routes are based on an outside-in analysis and speed is estimated stable at 10 knots
- Runway capacity is modeled via minimum headway constraints: the model assumes that taxied planes maintain between themselves the minimum distance to ensure smooth and safe operations. We do not expect ZE taxiing to modify these parameters when compared to current operations

- ZE-taxiing-induced delay only applies to ZE-taxiing-enabled flights - flights that are not compatible may absorb or propagate delay but do not generate additional delay[7]

6.2.3 Identification of the flights compatible with ZE taxiing

Flight-level operational data are sourced from CH Aviation, which provides detailed information on aircraft type, and airport operations. This database was also selected as it allows a robust identification of aircraft eligibility for ZE taxiing operations, which is a prerequisite for accurate demand sizing and fleet compatibility assessment.

The scope of the analysis is deliberately restricted to commercial narrow-body aircraft: in practice, this includes the A220 family, the Airbus A318/A319/A320/A321 families (including NEO and Sharklets variants), the Boeing 737 family (Classic, NG and MAX variants), as well as Embraer E-Jets (E170/175/190/195, including E2 variants). These aircraft types constitute the core addressable taxitow fleet and represent the majority of movements on the airports under study.

Wide-body aircraft (e.g. A330, A340, A350, A380, B747, B767, B777, B787), long-haul freighters, regional turboprops, business jets, military aircraft, helicopters, and general aviation are explicitly excluded from scope, as they are either not technically compatible with ZE taxiing operations, not representative of the targeted operational use cases, or marginal in terms of ZE taxiing deployment potential. Military flights and special-purpose aircraft are also excluded.

This scope definition ensures that the modeling focuses on high-frequency, operationally relevant movements, while remaining fully consistent with the technical constraints of the ZE taxiing system and the objective of maximizing operational and environmental impact.

6.2.4 Reminder on ZE specifications used for the model

Given that the objective of this study is ZE taxiing, and considering the manufacturer's focus on producing zero-emission models going forward, only battery-electric models were considered in the modeling[8].

Table 8: Technical specifications of the TaxiBot

Parameter	Value
Dimensions	13.5 ft (width) × 29.5 ft (length) × 6.6 ft (height)
Weight	55.1 k lbs
Top speed	23 knots
Operational range	Operational range: ~8 hours per full charge
Battery capacity	2 LIP (Lion Iron Phosphate) battery packs, 210 kWh each (total: 420 kWh)
Charging	CCS Type 2 – up to 2 × 100 kW (200 kW total)

6.2.5 Additional input sources

To ensure simulations are grounded in real-world data, a movement database encompassing our four airports is used, capturing flight times, aircraft types, gates, and the specific taxiways

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[7] It is important to note that ZE taxiing is not expected to create delays. If a taxied flight is delayed, only the flight immediately behind can bypass while the first aircraft is decoupling. Other flights remain in the taxiway queue

[8] While the model has the capability to allocate a share to hybrid models, this option was set to zero in the base case scenario

and runways utilized. This database provides input on where specific flights (with aircraft types) landed, which taxiway was used, terminal, and gate - grounding the analysis in empirical data.

The data was cross-referenced with a second database covering taxi-outs at each airports over the past 20 years, allowing to cross-reference any yearly trend observed. This exercise allowed to create a standard day for the sake of the analysis, representing the average traffic at each hour across the year[9]. Data from TaxiBot's OEM (TLD SAS) is also incorporated to reflect the solution's operational parameters, such as acceleration, speed, braking distance, energy consumption, and battery characteristics.

Taxiing time assumptions are mainly derived from CH Aviation, as this source provides the necessary level of detail on taxiing times by terminal-runway pair, which is essential for modeling taxitow routing and productivity at a granular level. CH Aviation compiles airport layout information, operational procedures, and observed movement data to estimate taxiing distances and times for each route. In contrast, other aviation databases typically offer only airport-wide average taxi-out times, which do not capture the route-specific operational variations needed for this analysis.

To maintain alignment with the broader modeling framework, the airport-level average taxi-out time is taken from the reference sources mentioned above. To integrate both data levels, route-specific deviations (terminal-to-runway) are calculated using CH Aviation data and applied to the airport-level average taxi-out time. This method maintains consistency with the overall average taxi-out time assumption while enabling the route-level detail required for accurate taxitow cycle-time and capacity modeling.

In addition, the modeling approach is informed by the academic paper *"Design the Allocation of External Alternative Aircraft Taxiing Systems at Airports"* (2022-Airport-Operation-and-Maintenance_First_Zhang.pdf), which compares centralized and decentralized allocation strategies. The paper shows that when average taxi-out time is the critical performance metric, a partially centralized (group-based) allocation delivers the best performance, while a fully centralized approach minimizes average waiting time for tugs.

Given that the primary objective of this analysis is to maximize emissions reductions, taxi-out time is retained as the key performance driver. Accordingly, a group-based (partially centralized) allocation logic is retained, whereby taxitows are mutualized across terminal groups rather than dedicated to individual terminals. This approach assumes maximized utilization, limited idle time, and improved overall system efficiency[10].

In practice, this leads to the definition of three taxitow groups for LAX, reflecting its terminal layout and traffic scale, and a single taxitow group for each of SJC, SBP, and LGB.

6.3 Model output

Overall, deploying ZE taxiing at large airports, such as LAX, requires dozens of taxitows, while only a few (as little as 1) allow to cover up to 100% of compatible take offs for smaller airports. Due to the high requirements to cover the peak, there is typically a gap between 75% and 100% coverage, whereas a steadier taxitow increment is associated with the coverage of tranches from 25% to 75%. For example, at LAX, 32 taxitows are required to reach 100% ZE Taxiing, vs 16 for 75%, or 5 for 25%.

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[9] Data from 2024, with one database allowing to cross-reference year trends from 2004 to 2024

[10] While the impact of taxitow on other GSE traffic was not modeled, previous deployment cases at AMS and CDG show limited impact on GSE congestion

To ensure adequate charging for a taxitow, the required number of charging stations and the corresponding power load (in kW) are calculated. This represents a maximum loading scenario, in which peak operations are sustained while a subset of taxitows is charging, with charging time embedded in the utilization cycle. Electrical load is assessed assuming simultaneous operation of all chargers, which is typically expected to happen when other airport systems' energy consumption is lower (e.g., during the night). This approach also assumes that the full fleet of taxitows has already been acquired; the figures reflect the end-state system rather than initial deployment, therefore, in practice, airports will be able to ramp up gradually over several years.

The results of the model are summarized below.

Figure 19: Modeling of ZE taxiing - key outputs by penetration quartile

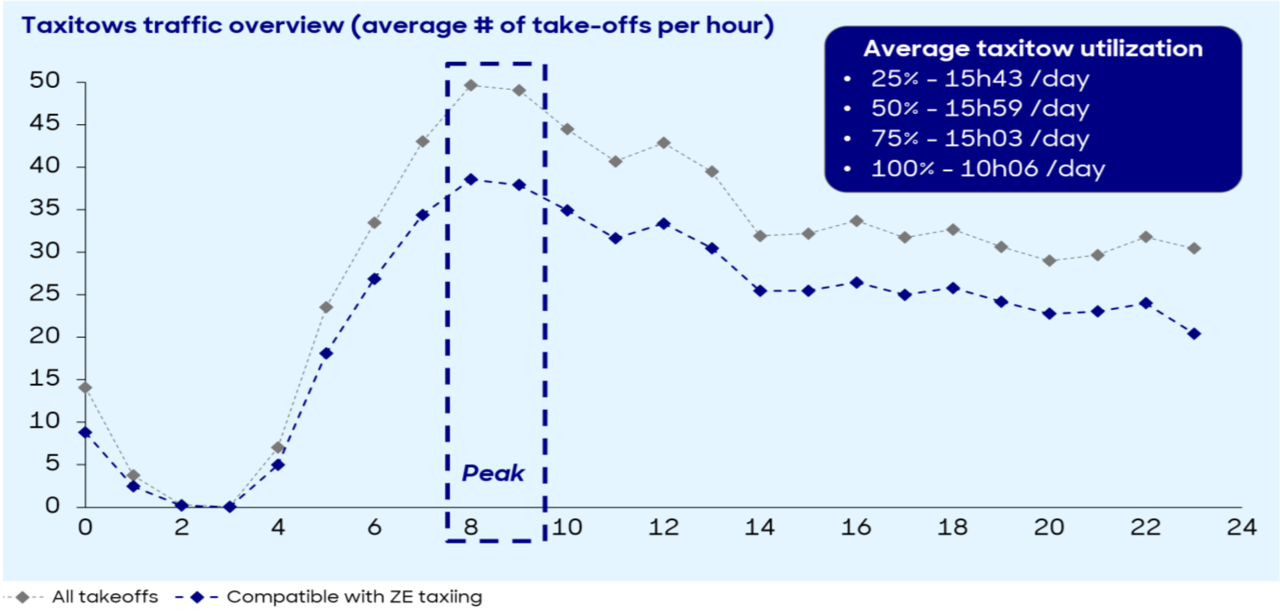
1) ZE taxiing penetration is pro-rated to FP_{MIM}; 2) Maximum power draw from the charging stations at the moment they are all utilized

6.3.1 LAX

Los Angeles International Airport is one of the busiest US airports, with consistently high utilization of all runway and taxiways throughout the day, except between midnight and 5:00 am. The peak is reached around 8:00 am, when up to 49 flights (ZE taxiing compatible or non-ZE taxiing compatible) take-off during the hour.

Such a high number of take-offs guarantees a high utilization of the taxitow. Respectively 5, 10, and 16 taxitows are needed for 25%, 50%, and 75% ZE taxiing at LAX, with equivalent utilization, between 15 and 16 hours per day. 32 taxitows are needed to reach 100% ZE taxiing, due to the requirements to cover the morning peak, but this dilutes the general utilization of a taxitow across the day (from 15 to 10 hours, on average, per day).

Figure 20: LAX airport traffic overview [average number of take-offs per hour]



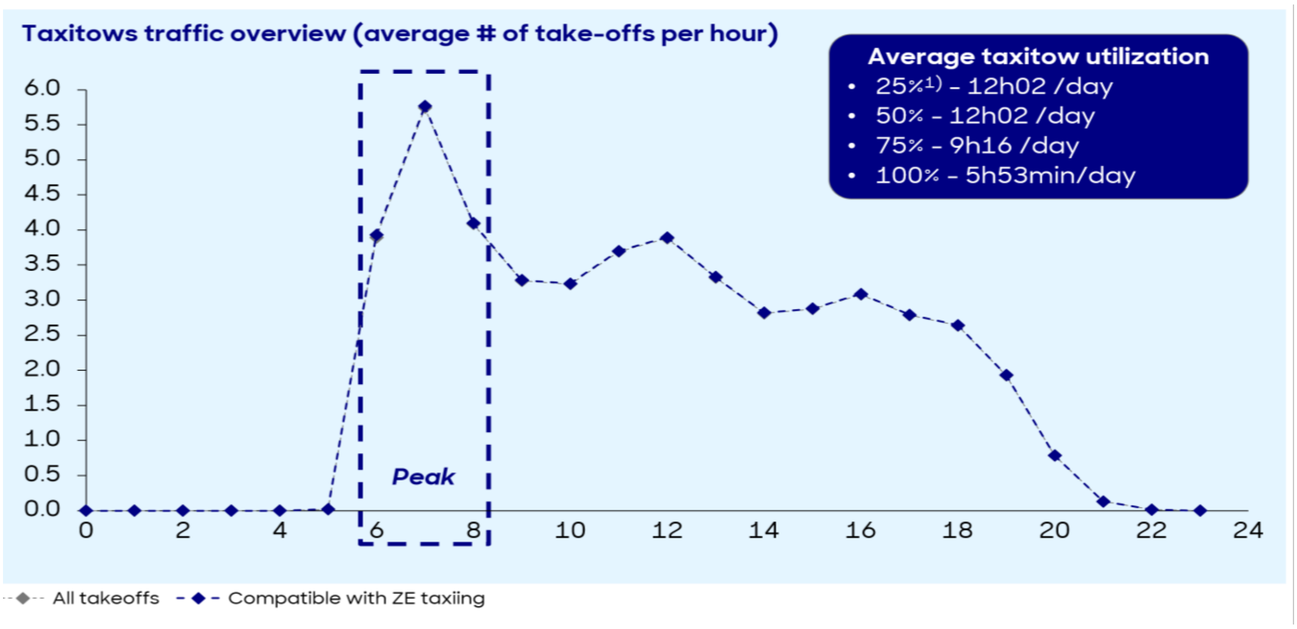
6.3.2 LGB

Long Beach Airport has an average of approximately 3.5 flights per hour between 6:00 am and 7:00 pm, and virtually no flights between 8:00 pm and 5:00 am. Moreover, the traffic peaks around 7:00 am with 6 flights, which is ~70% higher than the traffic for the rest of the day.

1 taxitow is sufficient to cover up to 50% of the ZE-taxiing-compatible take offs, with an average utilization of 12h per day. Covering 75% of compatible outbound flights requires an additional taxitow, and dilutes utilization to 9 hours and 16 minutes, on average per day. Lastly, to cover the morning peak and reach 100% ZE taxiing, a total of 4 taxitows are necessary, while the vehicles would be used no more than 6 hours on average during the day.

As per the analysis, one 200 kW charging station is sufficient to cover all configurations.

Figure 21: LGB airport traffic overview [average number of take-offs per hour]



1) Actually representing 50% of flights, as 1 taxitow can cover 50% of addressable flights

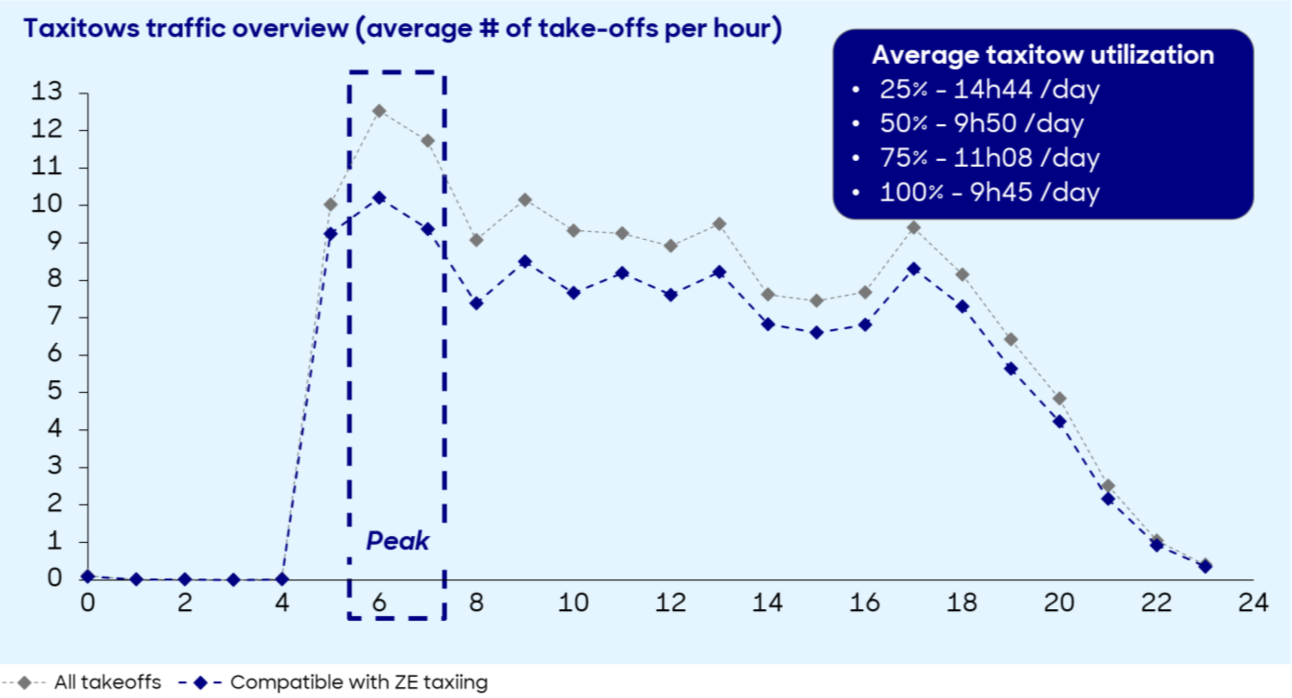
6.3.3 SJC

San Jose Mineta International Airport handles an average of 10 flights per hour from 5:00 am to 6:00 pm. Flight activity decreases in the evening and at night, with about 5 flights at 8:00 pm and no flights scheduled between midnight and 4:00 am. The busiest period is around 6:00 am, with approximately 13 flights.

A single taxitow can serve 25% of compatible take-offs[11], operating on average for 14 hours and 44 minutes per day. To reach 50% coverage, two more taxitows are needed; however, this reduces average utilization per unit, as two taxitows alone do not quite reach the 50% threshold, making a third necessary to exceed it. Four taxitows can cover 75% of eligible flights, while six are required to achieve 100% coverage.

A 200 kW charging station is sufficient to meet the energy needs of ZE taxiing for up to 75% zero-emission taxiing. To reach 100% zero-emission taxiing, an additional 100 kW of charging capacity is required.

Figure 22: SJC airport traffic overview [average number of take-offs per hour]



6.3.4 SBP

SLO County Airport rarely has more than 2 departing flights per hour. 1 taxitow fully covers all ZE taxiing compatible flights, to reach the 100% ZE taxiing target. Due to the limited number of flights, the average taxitow utilization is less than 5 hours per day however, therefore the taxitow remains idle approximately 80% of the time.

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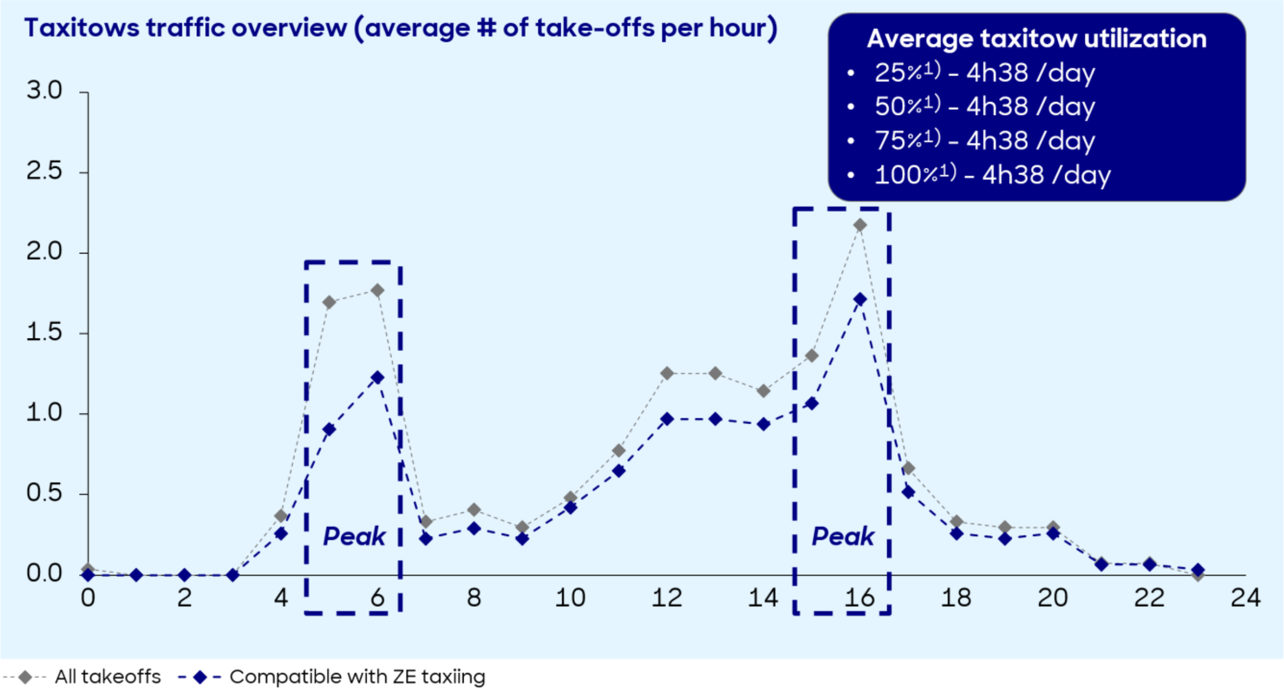
[11] Since the FP_{MIM} is lower than 100%, the tranches are such that that 100% represents the number of flights associated with the Max FP_{MIM}

Figure 23: SBP airport traffic overview [average number of take-offs per hour]



1) 1) Actually representing 100% of flights, as 1 taxitow can cover 100% of addressable flights

7 Cost-benefit analysis

7.1 Background and objectives

The objective of this analysis is to compare the total costs of ZE taxiing to the total expected benefits of the solution, based on different quartiles of penetration. This analysis is conducted for the 4 key airports (LAX, LGB, SJC, and SBP), covering, among other cost elements: capital, infrastructure, operational, construction, and fuel costs/savings.

Based on this analysis, the statewide cost & benefits at the scale of California is estimated, leveraging the results of the ZE taxiing analysis, and previous comparisons between airports.

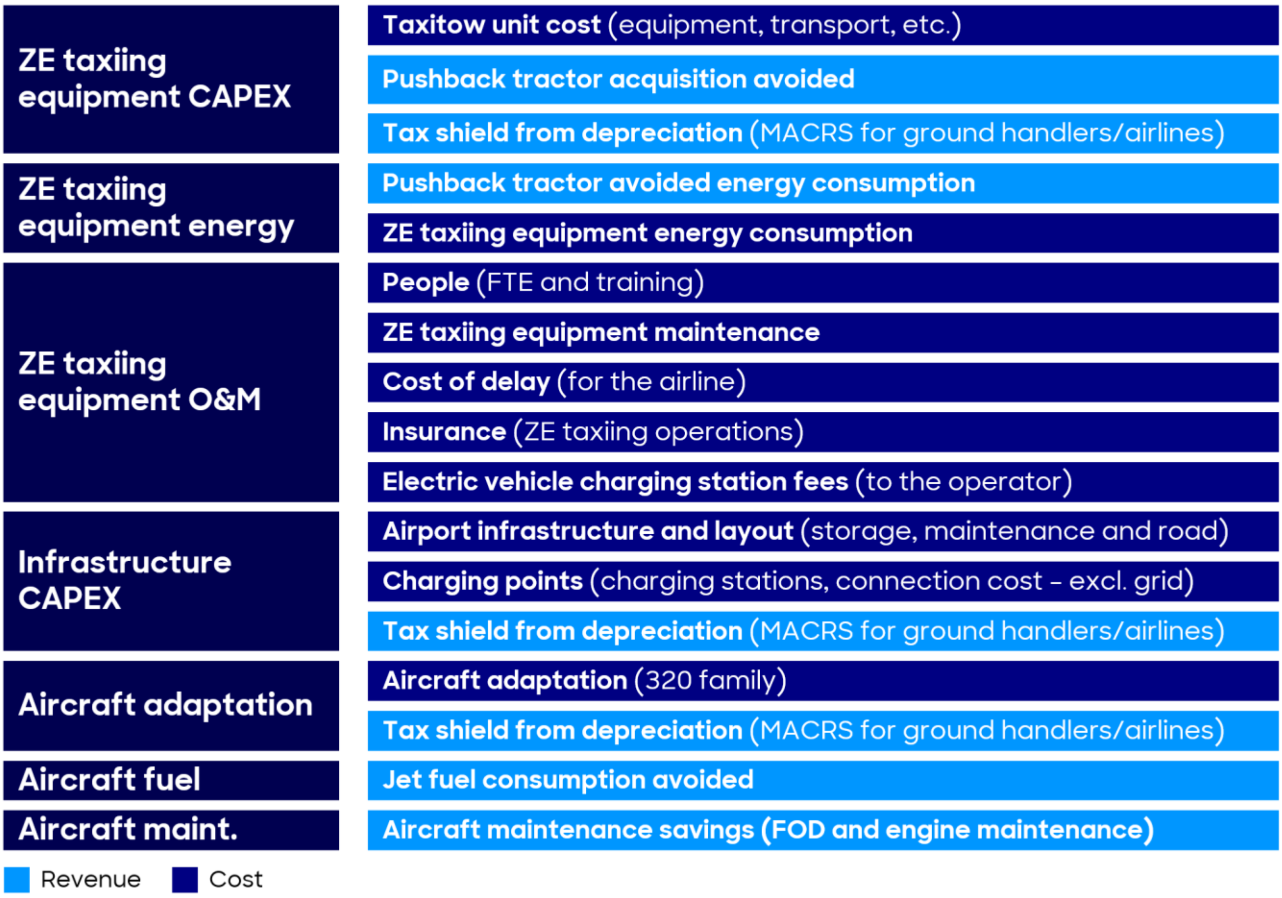
7.2 Methodology

7.2.1 Overarching structure and cost elements

A robust model was built to quantify the end-to-end economic impact of deploying ZE taxiing at different airports (airlines, airports, ground handlers). This model calculates the Total Cost of Ownership (TCO) of deploying the solution over its lifetime, and compares it to the expected economic benefits.

This model adds the key costs of ZE taxiing deployment and subtracts the direct savings that it generates. The different costs and revenues included in each bucket are detailed below.

Figure 24: Overview of key cost elements (Costs are indicated in dark blue, savings in light blue)



ZE taxiing equipment CAPEX	**Taxitow unit cost** (equipment, transport, etc.)	■
	Pushback tractor acquisition avoided	🟦
	Tax shield from depreciation (MACRS for ground handlers/airlines)	🟦
ZE taxiing equipment energy	**Pushback tractor avoided energy consumption**	🟦
	ZE taxiing equipment energy consumption	■
ZE taxiing equipment O&M	**People** (FTE and training)	■
	ZE taxiing equipment maintenance	■
	Cost of delay (for the airline)	■
	Insurance (ZE taxiing operations)	■
	Electric vehicle charging station fees (to the operator)	■
Infrastructure CAPEX	**Airport infrastructure and layout** (storage, maintenance and road)	■
	Charging points (charging stations, connection cost - excl. grid)	■
	Tax shield from depreciation (MACRS for ground handlers/airlines)	🟦
Aircraft adaptation	**Aircraft adaptation** (320 family)	■
	Tax shield from depreciation (MACRS for ground handlers/airlines)	🟦
Aircraft fuel	**Jet fuel consumption avoided**	🟦
Aircraft maint.	**Aircraft maintenance savings (FOD and engine maintenance)**	🟦

🟦 Revenue ■ Cost

The cost-benefit calculation is performed at the level of the persona airport, allowing to obtain a detailed view of each airport group's economic case attractiveness. The results at the level of the airport group are then extrapolated proportionately to the number of movements out to reach a state-level view of all initial 14 representative airports. While this approach gives an order of magnitude of the cost-benefits of the deployment in California, it does not capture individual cost drivers at each airport.

7.2.2 Key input

Figure 25: Details of key assumptions

Category	Key assumption	Value	Simplified comment
Financial parameters	Weighted average cost of capital	6.3%	Assumed blended rate
Financial parameters	Payback period	15 years	Standard horizon for airport equipment
Taxation	Corporate tax rate	29.84%	Combined federal and California tax rate
Taxitow equipment	Lifetime of an electric Taxitow	15 years	Same assumption across all airports
Taxitow equipment	Acquistion cost per electric Taxitow	2.30 million USD	Initial price, indexed with inflation
Taxitow equipment	Transport cost per Taxitow	0.05 million USD	Manufacturer estimate
Taxitow lifecycle	Dismantling cost	Not included	Assumed offset by residual value
Conventional equipment	Cost per pushback tractor	0.35 million USD	Ground handler benchmark
Productivity	Taxitows equivalent to one pushback tractor	5 to 7	Depends on airport configuration
Labor	Full-time employee requirement per Taxitow	1.0 full-time employee	Manufacturer data
Labor	Hourly rate of a pushback operator	50 USD/hour	Benchmark including overhead
Training	Pushback-operator training cost	Included in Taxitow sales	No separate cost assumed
Training	Pilot training	Included into their continuous training cost (the training need is minimal)	
Delay	Cost per minute of delay	100 USD/minute	Airline benchmark used in the model
Maintenance	Maintenance cost for electric Taxitow	0.54 USD/minute	Includes battery replacement, equipment, and labor
Maintenance savings	Maintenance cost for pushback tractor	0.06 USD/minute	Benchmark updated to current prices
Insurance	Annual insurance cost as share of capital expenditure	3%	Heavy mobile equipment benchmark
Charging infrastructure	Management fee per charger	400 USD per charger	Benchmark assumption

Charging infrastructure	Transaction fee per charger	0.0134 USD/kilowatt	Benchmark assumption
Infrastructure	Storage infrastructure cost	100 USD/square meter	Pavement-only assumption
Charging infrastructure	Cost per 200-kilowatt charger	120,000 USD	Includes equipment and installation
Battery	Battery replacement interval	22,500 hours	One replacement assumed over Taxitow life
Battery	Battery replacement labor cost	Included in maintenance package	No separate capital expenditure assumed
Battery	Battery pack replacement cost	Included in maintenance package	No separate capital expenditure assumed
Aircraft adaptation	Aircraft connection add-on cost	0.02 million USD per aircraft	Manufacturer data
Aircraft adaptation	Aircraft manifold add-on cost	0 USD in base case	Replacement not assumed in the base case
Fuel	Fuel burn per minute, excluding auxiliary power unit	4.58 to 6.49 kilograms/minute	Depends on airport aircraft mix
Fuel	Auxiliary power unit fuel burn per minute	1.83 kilograms/minute	Common benchmark assumption
Fuel	Share of taxiing with auxiliary power unit on	25%	Benchmark assumption
Fuel	Fuel burn with two engines and auxiliary power unit off	8.33 to 11.81 kilograms/minute	Depends on airport aircraft mix

All costs included in the model cover the full economic perimeter of airlines, airports and ground handlers. A 6.3% WACC (Weighted Average Cost of Capital) is assumed, reflecting the low-risk profile of a U.S. public airport with stable, regulated cash flows and strong public backing. This assumption is consistent with observed peer benchmarks for regulated airport infrastructure (5–7%) and with observed investment-grade USD bond yield levels.

All ZE-taxiing-related CAPEX is assumed to be incurred upfront in year 0 (2026), with operations modeled over a 15-year lifetime, in line with constructor data. This includes both taxitow acquisition and aircraft adaptation. Traffic is held flat at year-0 levels, and the share of ZE-taxiing-compatible flights is assumed to remain stable over time, in order to isolate the intrinsic economics of ZE taxiing deployment.

The A320 family requires aircraft adaptation to enable ZE taxiing operations. For the same reasons, 100% of relevant aircraft are assumed to be modified at year 0[12], allowing ZE taxiing usage across all penetration scenarios (25%, 50%, 75% and 100%) without constraining aircraft rotations or daily allocation.

All CAPEX is assumed to be fully equity-funded (no debt). Potential tax savings from depreciation for ground handlers and airlines are treated as a sensitivity only and are therefore excluded from the base case.

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[12] Connection costs to use pilot-controlled ZE taxitow solution, estimated at USD 16,000 per aircraft

Pilot and ground handler training costs are set to zero, as ZE-taxiing-related training represents only a few hours embedded in existing recurrent training programs and is considered negligible at the scale of the model.

Insurance costs for ZE taxiing assets are assumed at 3% of CAPEX, in line with standard benchmarks for heavy mobile equipment. Maintenance is assumed to be contracted with the constructor and modeled as a usage-based cost per operating hour, including, for electric taxitows, battery replacement over the asset lifetime.

Any additional electrical CAPEX directly associated with ZE taxiing operations is considered negligible, as the model already includes the full turnkey cost of chargers—covering the power cabinet, dispenser, and installation. While grid-level upgrades may be required[13], these are not included in the analysis.

7.2.3 Disclaimers

The model is built using the best available data, ensuring consistency and comparability across airports. In the absence of direct costing data from the airport, an outside-in perspective adopted, relying on publicly available data and benchmarks with other airports of similar size.

The analysis is based on current traffic levels, providing a stable and conservative baseline to isolate operational and capacity effects. The quartiles of ZE taxiing reflect therefore quartiles of today’s traffic, not future traffic. Results can be re-scaled under traffic growth scenarios to assess additional taxitow needs over time.

Aircraft upgrade costs are deemed incompressible, this is to say that the costs to upgrade all ZE-taxiing compatible aircraft at an airport are incurred irrespectively of the quartile of penetration considered. This is because aircraft availability and operational requirements are inherently uncertain and evolve over time: airlines must preserve the option to taxi any compatible aircraft on any given day, as delays, aircraft rotations, maintenance events, or last-minute fleet substitutions can occur. In addition, flight schedules, routes, and operating hours change structurally over the years, making it impractical to restrict upgrades to a fixed subset of aircraft. As a result, to ensure operational robustness and long-term flexibility, the full population of ZE-taxiing-compatible aircraft must be upgraded upfront, regardless of the effective utilization rate in the early phases of deployment.

The taxitow fleet and required aircraft modifications are assumed to be fully implemented at the outset (Year 0), creating a full-potential reference scenario for Total Cost of Ownership calculations. This approach does not account for gradual operational ramp-up or phased deployment (such as spreading taxitow purchases over several years or adjusting the number of modified aircraft by quartile, which could improve TCO). This conservative assumption frontloads all deployment costs, whereas in practice these costs would be distributed over time.

ZE taxiing utilization and charging are modeled at a system-average level, not through taxitow-by-taxitow simulation. Asset-level modelling would allow refined analysis of charging queues, battery state-of-charge and peak-load conditions.

Infrastructure feasibility is assessed based on current layouts and visible constraints, using an outside-in screening approach. Cost estimates are indicative and high-level, sufficient for

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[13] The deployment of ZE taxitow charging stations is not expected to require interconnection upgrades beyond current plans. For example, the maximum power draw for taxitow charging at LAX (at full deployment, full maturity, and all charging stations being utilized simultaneously) would represent no more than 0.5% of the interconnection capacity. This peak draw from taxitow charging would take place during the night, when the activity and power draw from the airport is the lowest. During peak activity, ZE taxitows would rely on their batteries.

comparative analysis but not for detailed engineering decisions. More precise feasibility and cost estimates would require on-site assessments, and airport-led validation.

7.3 Model output

At the level of the 14 airports considered, deploying ZE taxiing delivers economic benefits at both 75% and 100% zero-emission taxiing penetration. Most net economic gains are generated by Group 1 airports and, for Group 3, at 75% penetration over the solution's lifetime, offsetting net economic costs incurred at Group 2 and 4 airports.

Initial deployment costs are substantial but are gradually offset by savings in fuel and engine time. The estimated payback period for Group 1 and 3 airports ranges from 5 to 9 years, highlighting the need for a long-term perspective to justify the upfront investment.

7.3.1 LAX

Due to its high annual number of movements and high runway utilization throughout the day, Los Angeles International Airport presents the strongest business case for ZE taxiing.

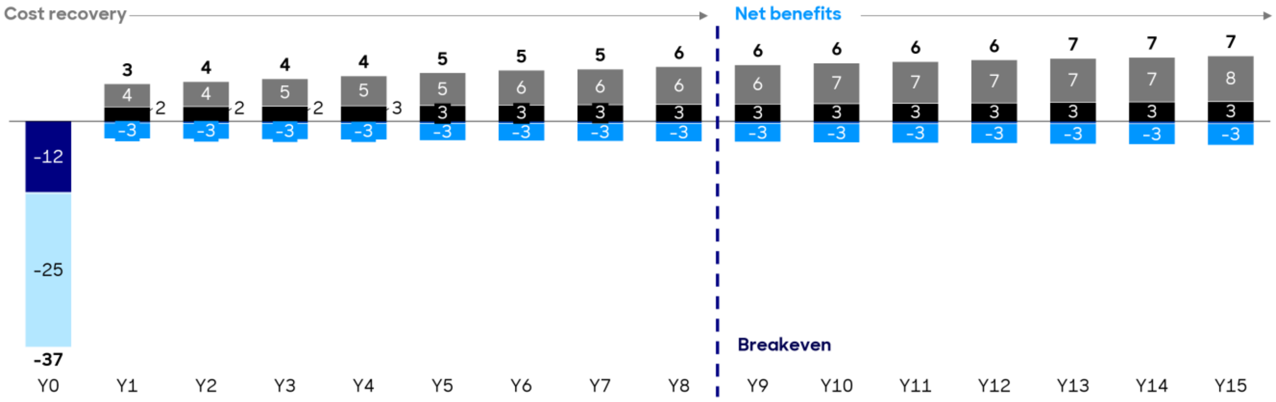
For instance, at 25% penetration, ZE taxiing would create net benefits of USD 11.8 m over the asset lifetime (NPV, constant 2025 dollar value), or USD 44.3 m (flat). This requires an upfront investment of USD 37.5 m, associated with the acquisition of 5 taxitows, upgrade of the infrastructure, and adaptations of the aircraft. Yearly fuel savings average USD 6 m, and yearly maintenance savings reach USD 2.8 m. Operational costs of the solution are USD 3.3 m per year.

See below for a detailed view of all quartiles:

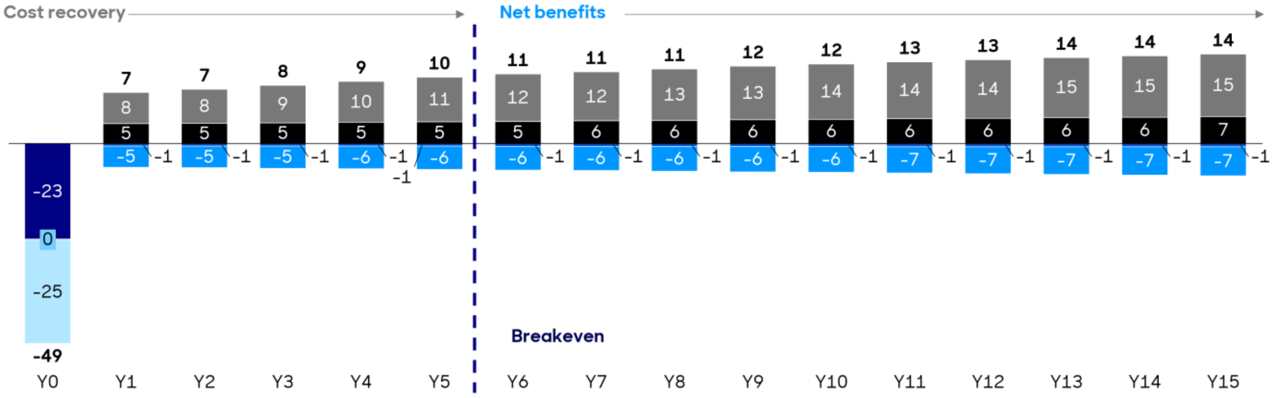
Table 9: Key cost-benefits results for LAX

Parameter	25%	50%	75%	100%
# of taxitows	5	10	16	32
Net-benefits (NPV, USD m)	+12	+51	+85	+91
Net-benefits (flat, USD m)	+44	+117	+184	+219
Internal Rate of Return - IRR (%)	10%	18%	21%	16%
Y0 deployment costs (USD m)	38	50	64	103
Yearly fuel savings (USD m)	6	12	18	25
Yearly maintenance savings (USD m)	3	6	9	12
Operational costs (USD m)	3	7	10	15

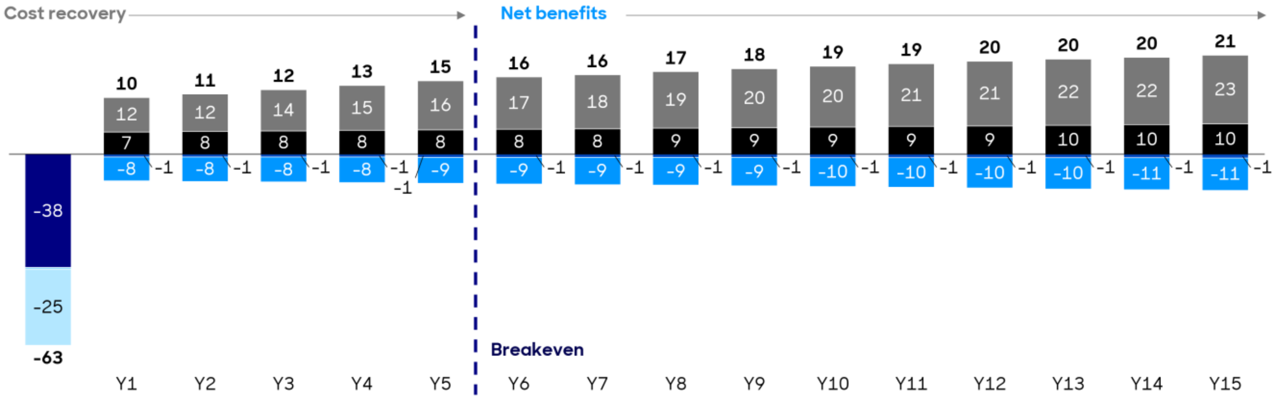
Lifetime costs (flat) by cost category - *25% penetration [USD m]*

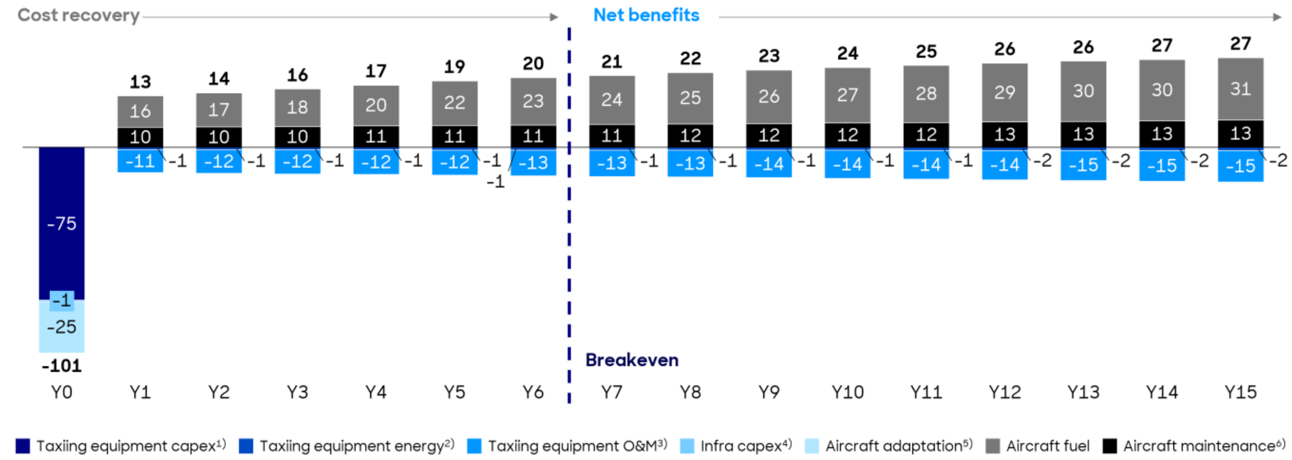


Lifetime costs (flat) by cost category - *50% penetration [USD m]*



Lifetime costs (flat) by cost category - *75% penetration [USD m]*





Lifetime benefits (flat) by cost category - *100% penetration [USD m]*

1) Taxiing equipment acquisition (option to model financing costs and tax-efficient depreciation; base case assumes zero debt); resale of existing tugs; 2) Taxiing equipment electricity consumption (no diesel modelled in the base case) and electricity/diesel savings from reduced pushback operations; 3) Including operator salaries, trainings (assumed to be 0 in the model), maintenance, insurance costs; 4) Storage area, service road, and full turnkey cost of 200 kW equipment (power cabinet, dispenser and installation), excluding grid connection; 5) Connection costs on '320 family'; 6) Based on saved engine time and FOD maintenance avoided

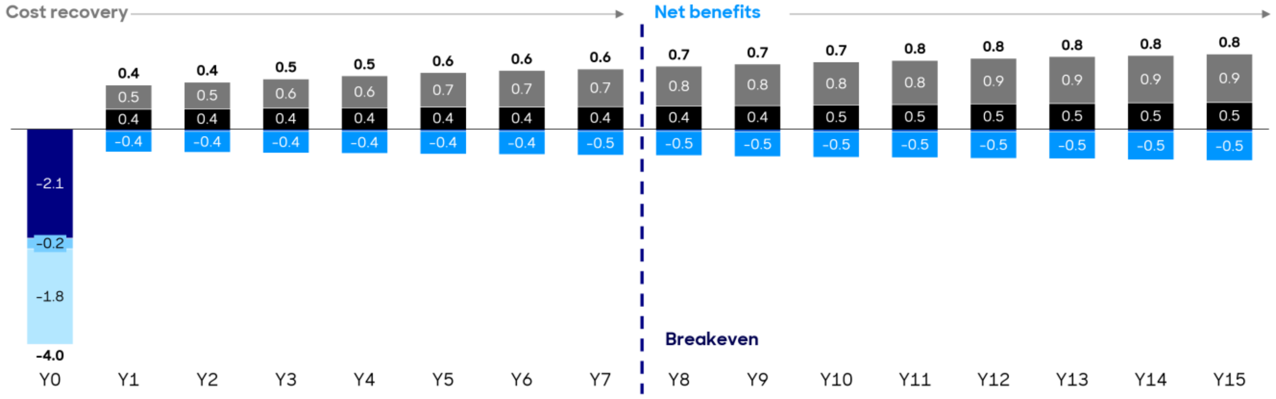
7.3.2 LGB

Long Beach Airport has a less consistent traffic than Los Angeles, and a high traffic peak in the morning that is costly to cover fully with taxitows. Indeed, covering the peak requires twice as many taxitows as the 75% penetration case, which dilutes the general utilization per unit. This makes the economics of covering this peak net-negative in NPV, but net positive if the time-value of money is not considered.

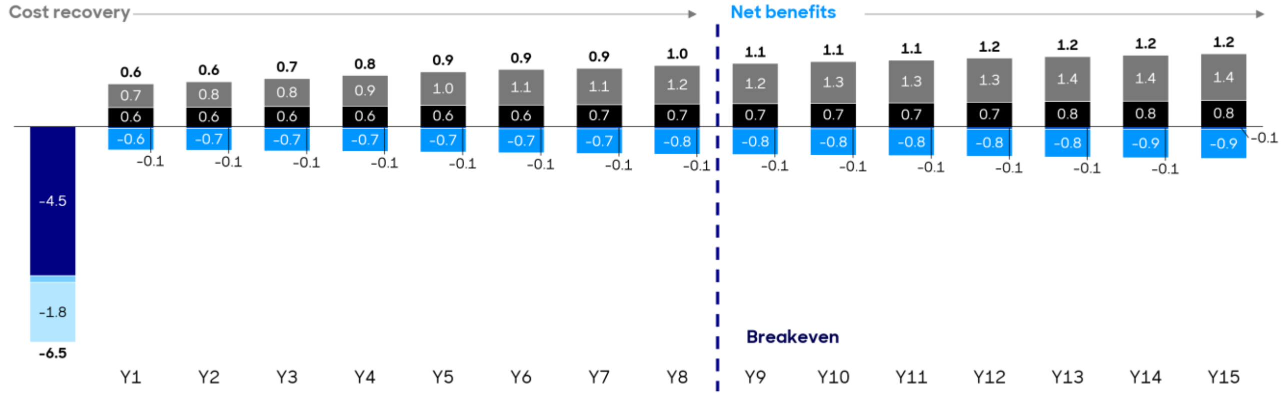
Table 10: Key cost-benefits results for LGB

Parameter	25%	50%	75%	100%
# of taxitows	*1 taxitow allows to cover 50% of flights*	1	2	4
Net-benefits (NPV, USD m)		+1.8	+2.2	-1.5
Net-benefits (flat, USD m)		+5.7	+8.0	+5.1
Internal Rate of Return – IRR (%)		12%	10%	4%
Y0 deployment costs (USD m)		4.4	6.8	11.7
Yearly fuel savings (USD m)		0.7	1.1	1.4
Yearly maintenance savings (USD m)		0.4	0.7	0.9
Operational costs (USD m)		0.5	0.8	1.2

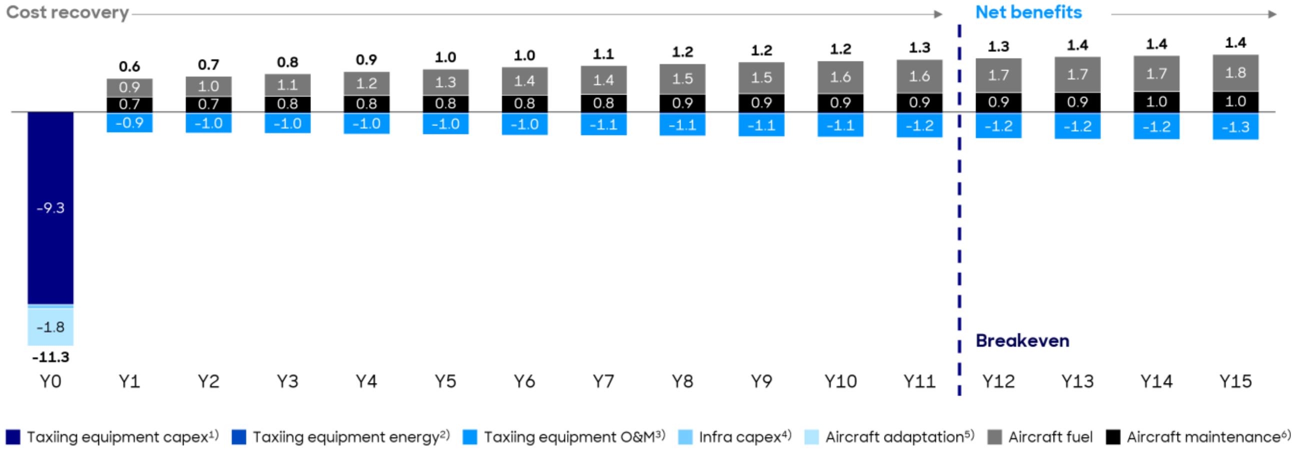
Lifetime costs (flat) by cost category – *50% penetration [USD m]*



Lifetime costs (flat) by cost category – *75% penetration [USD m]*



Lifetime benefits (flat) by cost category – *100% penetration [USD m]*



1) Taxiing equipment acquisition (option to model financing costs and tax-efficient depreciation; base case assumes zero debt); resale of existing tugs; 2) Taxiing equipment electricity consumption (no diesel modelled in the base case) and electricity/diesel savings from reduced pushback operations; 3) Including operator salaries, trainings (assumed to be 0 in the model), maintenance, insurance costs; 4) Storage area, service road, and full turnkey cost of 200 kW equipment (power cabinet, dispenser and installation), excluding grid connection; 5) Connection costs on '320 family'; 6) Based on saved engine time and FOD maintenance avoided

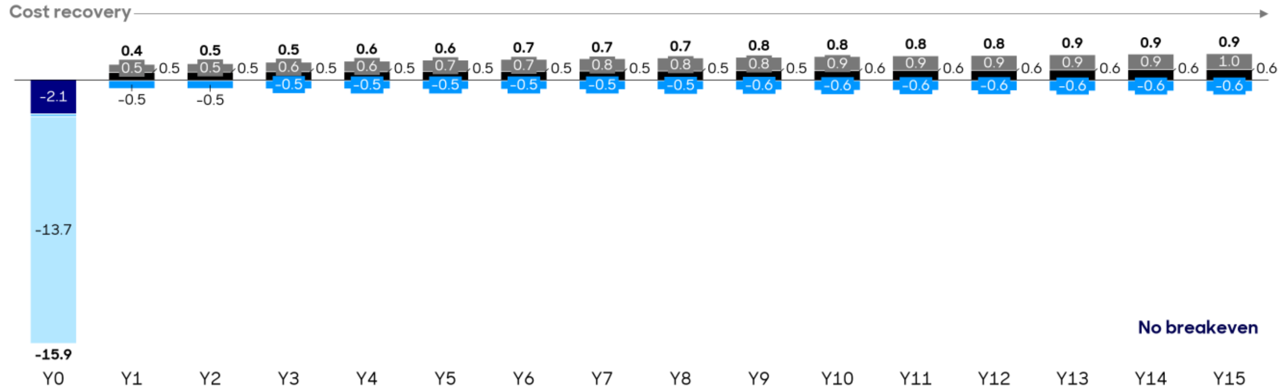
7.3.3 SJC

On a NPV-basis, ZE taxiing does not create net-benefits for all quartiles of ZE taxiing at SJC. However, the solution has a positive IRR, associated with positive net benefits if the time-value of money is not considered, at 75% and 100% ZE taxiing. This is because the upfront flat cost of adapting the airplanes and the infrastructure is high, but the traffic peak is comparatively easier to cover than for an airport like LGB.

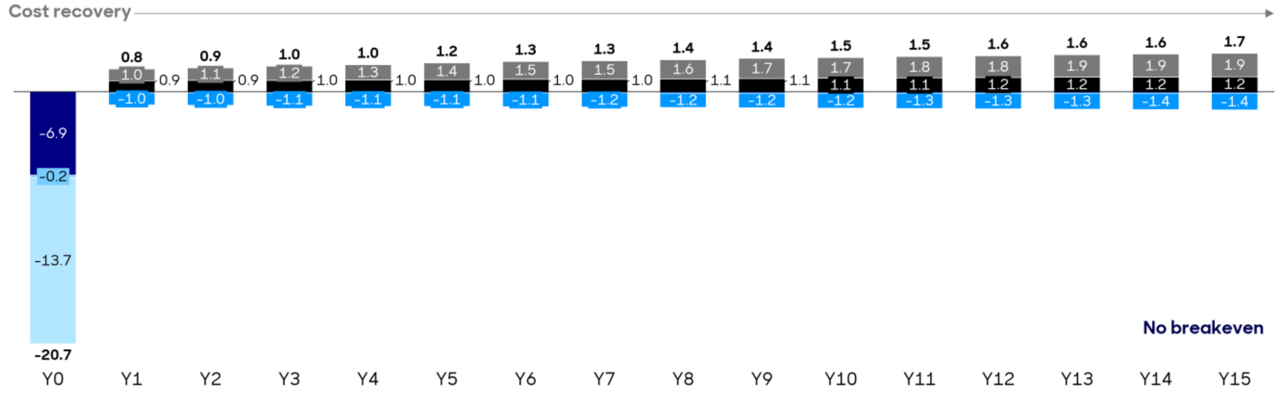
Table 11: Key cost-benefits results for SJC

Parameter	25%	50%	75%	100%
# of taxitows	1	3	4	6
Net-benefits (NPV, USD m)	-9.6	-9.0	-5.1	-4.9
Net-benefits (flat, USD m)	-5.5	-1.2	+6.9	+10.5
Internal Rate of Return - IRR (%)	-4%	-1%	3%	4%
Y0 deployment costs (USD m)	16.3	21.1	23.5	28.3
Yearly fuel savings (USD m)	0.8	1.5	2.3	3.0
Yearly maintenance savings (USD m)	0.5	1.1	1.6	2.1
Operational costs (USD m)	0.6	1.3	2.0	2.6

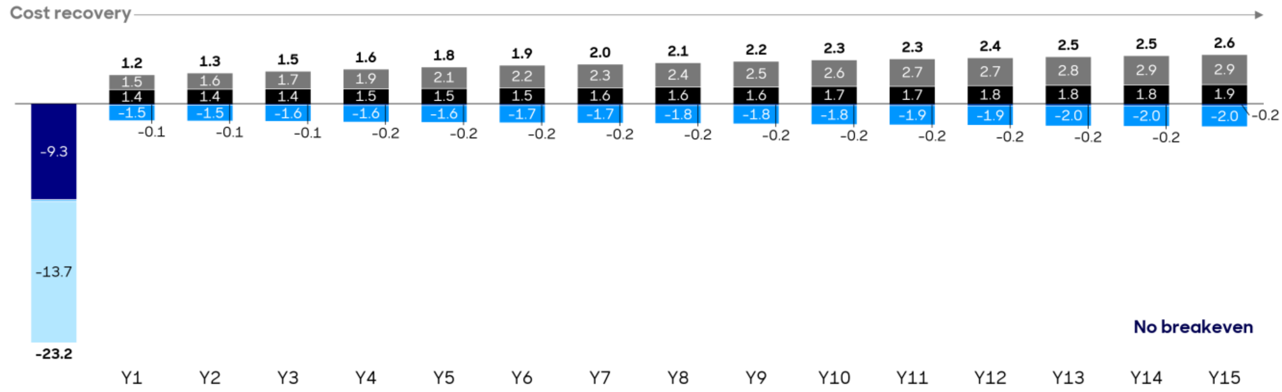
Lifetime costs (flat) by cost category - *25% penetration [USD m]*



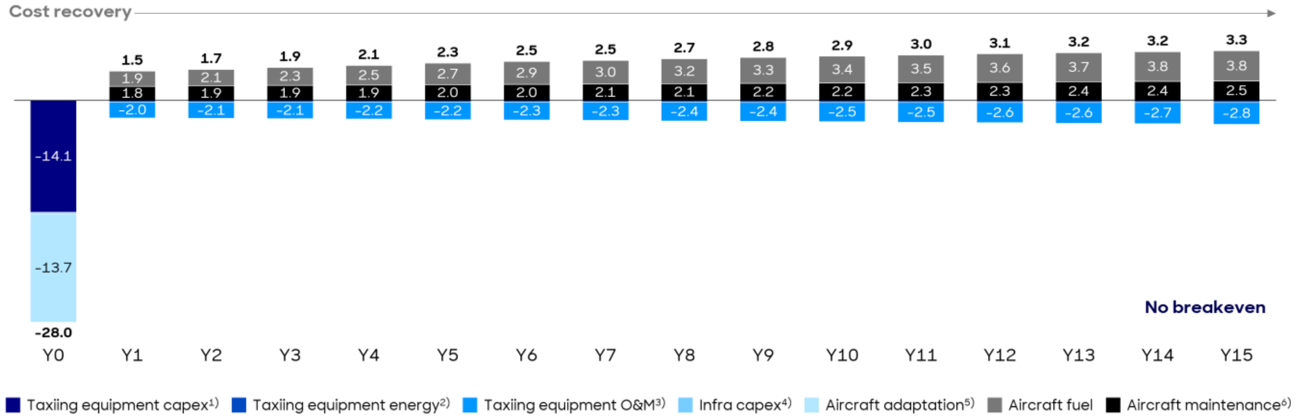
Lifetime costs (flat) by cost category - *50% penetration [USD m]*



Lifetime costs (flat) by cost category - *75% penetration [USD m]*



Lifetime benefits (flat) by cost category - *100% penetration [USD m]*



1) Taxiing equipment acquisition (option to model financing costs and tax-efficient depreciation; base case assumes zero debt); resale of existing tugs; 2) Taxiing equipment electricity consumption (no diesel modelled in the base case) and electricity/diesel savings from reduced pushback operations; 3) Including operator salaries, trainings (assumed to be 0 in the model), maintenance, insurance costs; 4) Storage area, service road, and full turnkey cost of 200 kW equipment (power cabinet, dispenser and installation), excluding grid connection; 5) Connection costs on '320 family'; 6) Based on saved engine time and FOD maintenance avoided

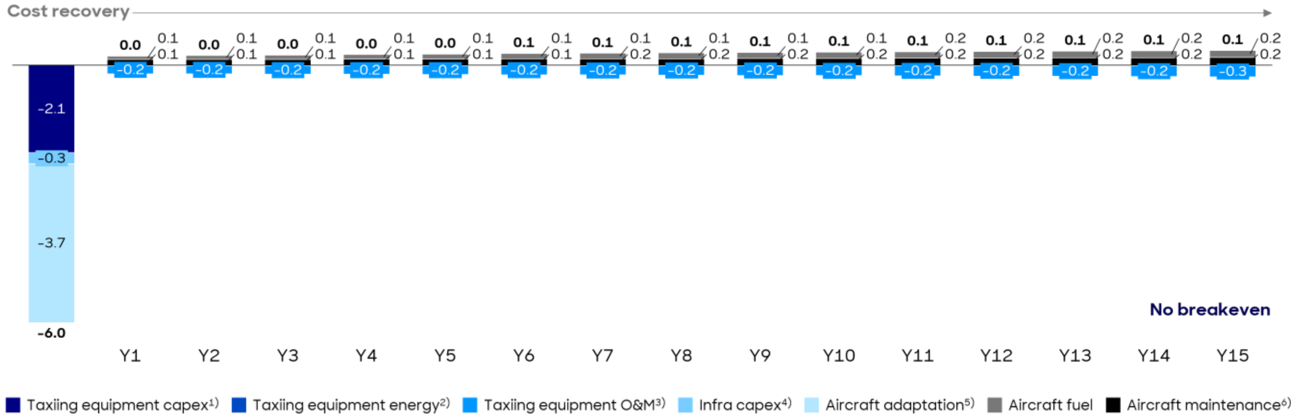
7.3.4 SBP

Deploying 1 taxitow at LGB allows to cover all of the compatible flights at the airport. This is associated with net costs of USD (-) 5.6 m over the asset lifetime (NPV), or USD (-) 5.2 m (flat). This requires an upfront investment of USD 6.4 m, associated with the acquisition of the taxitow, upgrade of the infrastructure, and the upgrade of the aircraft. Yearly fuel savings average USD 0.1 m per year, and yearly maintenance savings are USD 0.2 m. Operational costs of the solution are USD 0.2 m per year. Overall, the ROI of deploying one taxitow is -17%.

Table 12: Key cost-benefits results for SBP

Parameter	**25%**	**50%**	**75%**	**100%**
# of taxitow	*1 taxitow allows to cover 100% of flights*			1
Net-benefits (NPV, USD m)				-5.6
Net-benefits (flat, USD m)				-5.2
Internal Rate of Return - IRR (%)				-17%
Y0 deployment costs (USD m)				6.4
Yearly fuel savings (USD m)				0.1
Yearly maintenance savings (USD m)				0.1
Operational costs (USD m)				0.2

Lifetime costs (flat) by cost category - *100% penetration [USD m]*



1) Taxiing equipment acquisition (option to model financing costs and tax-efficient depreciation; base case assumes zero debt); resale of existing tugs; 2) Taxiing equipment electricity consumption (no diesel modelled in the base case) and electricity/diesel savings from reduced pushback operations; 3) Including operator salaries, trainings (assumed to be 0 in the model), maintenance, insurance costs; 4) Storage area, service road, and full turnkey cost of 200 kW equipment (power cabinet, dispenser and installation), excluding grid connection; 5) Connection costs on '320 family'; 6) Based on saved engine time and FOD maintenance avoided

7.3.5 California-State

The cost-benefit analysis is conducted at airport level, providing a detailed assessment of the cost/benefit attractiveness for each airport group. These group-level results are then proportionally extrapolated based on the number of movements to generate a state-level perspective for the initial set of 14 representative airports.

At the scale of all Californian airports considered[14], ZE taxiing deployment could save up to 16 million gallons of jet fuel annually, resulting in net savings of approximately USD 50 m over the solution's lifetime with maximum zero-emission taxiing. Achieving full zero-emission taxiing across all airports considered in California would require an estimated 114 taxitows, representing a total investment of USD 460 m, including aircraft modifications and necessary infrastructure upgrades.

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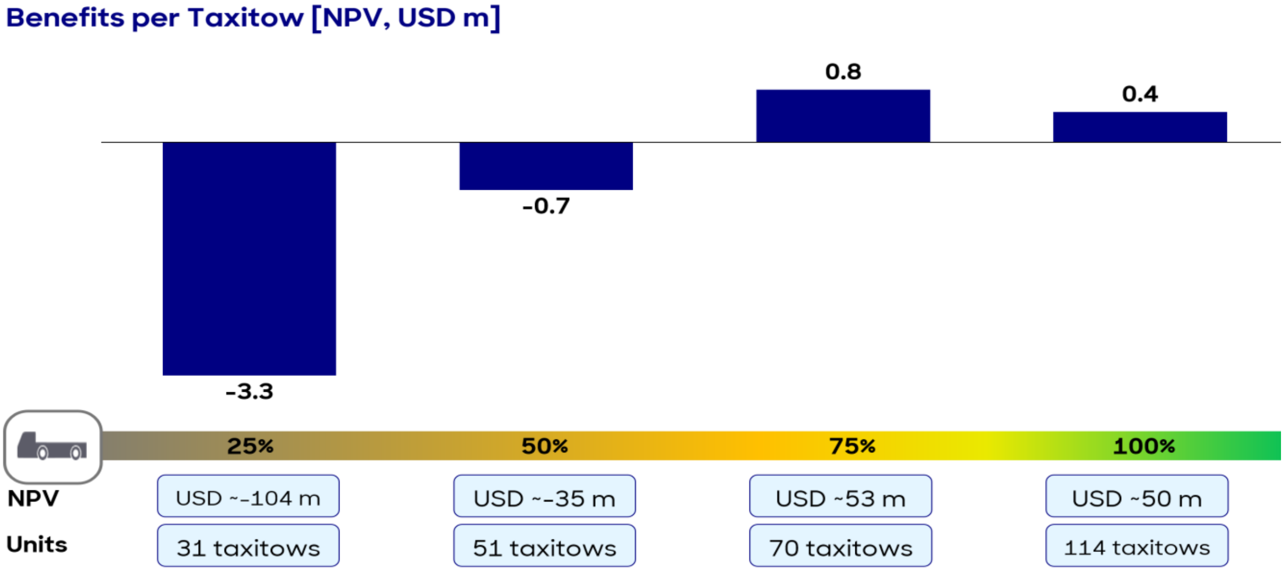
[14] 14 airports representing 99% of NOx emissions from airports in California (figure 2)

Figure 26: Benefits per taxitow by penetration quartile [all 14 airports considered]



	25%	50%	75%	100%
NPV	USD ~-104 m	USD ~-35 m	USD ~53 m	USD ~50 m
Units	31 taxitows	51 taxitows	70 taxitows	114 taxitows

The most cost-effective penetration level is 75%, generating USD 53 m in net benefits over the assets lifetime. This is mainly because only 70 taxitows are required—about 40% fewer than in the 100% penetration scenario, and utilization reaches an efficient absorption of fixed and operational costs. Full adoption remains value accretive at the unit level, delivering USD 0.4 m NPV per taxitow over asset lifetime, which would be justified by system-level emission savings rather than pure ROI on taxitow unit.

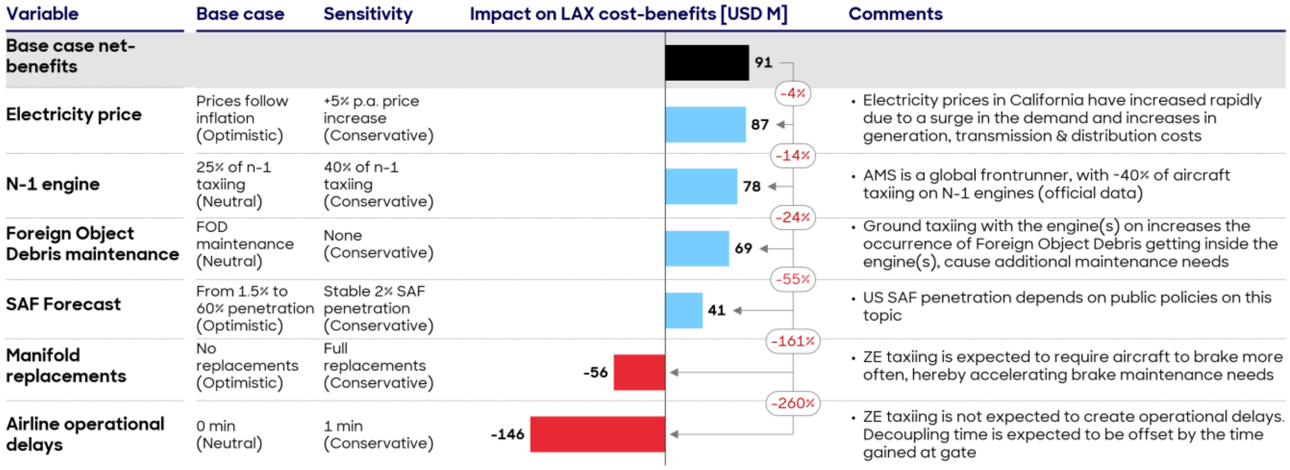
At 25% and 50% ZE taxiing penetration, the deployment does not yield net economic benefits on an NPV basis, as the costs incurred at group 2 and 4 airports are not offset by the fuel savings achieved at group 1 and 3 airports.

7.4 Sensitivities

Several sensitivity analyses were conducted to assess the impact of changes in key model inputs. Among the factors with a negative effect on the cost-benefit model, operating delays and the requirement to replace aircraft manifolds have the greatest impact. In contrast, debt financing and the ability to recover taxitow depreciation significantly improve the economic outcome. Higher fuel prices also enhance the attractiveness of the solution.

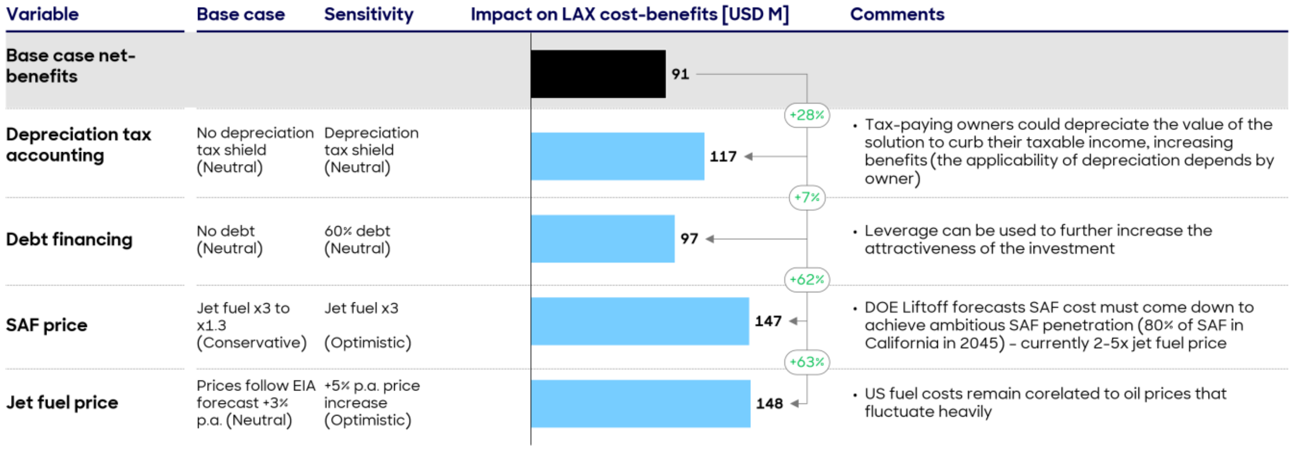
Selected results from these sensitivity analyses are presented below, using the LAX 100% penetration scenario as an example.

Figure 27: 100% LAX case - Sensitivities negatively impacting the business case



Variable	Base case	Sensitivity	Impact on LAX cost-benefits [USD M]	Comments
Base case net-benefits			91	
Electricity price	Prices follow inflation (Optimistic)	+5% p.a. price increase (Conservative)	-4% 87	• Electricity prices in California have increased rapidly due to a surge in the demand and increases in generation, transmission & distribution costs
N-1 engine	25% of n-1 taxiing (Neutral)	40% of n-1 taxiing (Conservative)	-14% 78	• AMS is a global frontrunner, with ~40% of aircraft taxiing on N-1 engines (official data)
Foreign Object Debris maintenance	FOD maintenance (Neutral)	None (Conservative)	-24% 69	• Ground taxiing with the engine(s) on increases the occurrence of Foreign Object Debris getting inside the engine(s), cause additional maintenance needs
SAF Forecast	From 1.5% to 60% penetration (Optimistic)	Stable 2% SAF penetration (Conservative)	-55% 41	• US SAF penetration depends on public policies on this topic
Manifold replacements	No replacements (Optimistic)	Full replacements (Conservative)	-161% -56	• ZE taxiing is expected to require aircraft to brake more often, hereby accelerating brake maintenance needs
Airline operational delays	0 min (Neutral)	1 min (Conservative)	-260% -146	• ZE taxiing is not expected to create operational delays. Decoupling time is expected to be offset by the time gained at gate

Figure 28: 100% LAX case - Sensitivities positively impacting the business case



Variable	Base case	Sensitivity	Impact on LAX cost-benefits [USD M]	Comments
Base case net-benefits			91	
Depreciation tax accounting	No depreciation tax shield (Neutral)	Depreciation tax shield (Neutral)	+28% 117	• Tax-paying owners could depreciate the value of the solution to curb their taxable income, increasing benefits (the applicability of depreciation depends by owner)
Debt financing	No debt (Neutral)	60% debt (Neutral)	+7% 97	• Leverage can be used to further increase the attractiveness of the investment
SAF price	Jet fuel x3 to x1.3 (Conservative)	Jet fuel x3 (Optimistic)	+62% 147	• DOE Liftoff forecasts SAF cost must come down to achieve ambitious SAF penetration (80% of SAF in California in 2045) – currently 2-5x jet fuel price
Jet fuel price	Prices follow EIA forecast +3% p.a. (Neutral)	+5% p.a. price increase (Optimistic)	+63% 148	• US fuel costs remain corelated to oil prices that fluctuate heavily

7.5 Conclusions

Zero-emission taxiing using on-ground solutions is operationally feasible at major California airports, with limited infrastructure constraints. At LAX and LGB, no material airside blockers are identified (FP_{MIM} = 100%), while constraints at secondary airports (SJC, SBP) are localized and linked to service-road configurations rather than runway or gate availability. Overall, space availability does not appear to be a limiting factor to cover up to 75% of the flights compatible with taxitows, and can be a localized constraints to reach 100% coverage at non-major airports.

From an outside-in perspective, energy charging and load capacity requirements are not expected to be major deployment constraints. Energy demand from charging remains limited during the day, with peak consumption happening at night when other airport systems consume less energy. Charging time is embedded within the taxitow utilization cycle, enabling peak operations to be sustained without operational disruption.

Reaching full (100%) coverage requires adding taxitows primarily to absorb short peak periods, rather than to support day-to-day operations. As a result, average utilization declines materially compared with intermediate penetration levels (~75%).

From an economic perspective, the value concentrates at large hubs while medium-sized airports typically show a lower daily utilization of taxitows, leading to less fuel savings and lower economic value. LAX exhibits a robust and resilient business case across all penetration levels, supported by sustained traffic and high taxitow fleet utilization. At medium-sized airports, outcomes are more sensitive to sizing and cost structure. The deployment of the solution creates net-positive economic benefits at LGB, contingent on a low cost of capital. The business case for SJC is challenging despite higher traffic volumes (vs. LGB), primarily due to higher aircraft-related CAPEX. These airports operate close to the breakeven line, making optimization levers - such as fleet sizing, penetration targets, and potentially cross-airport CAPEX mutualization[15] critical to achieving net positive economic benefits. At small airports such as SBP, low utilization structurally limits the economic attractiveness, despite technical feasibility and limited infrastructure requirements.

At the state level, zero-emission taxiing delivers meaningful fuel and emissions reductions. Yet, the full deployment of the solution is less economically optimal than 75% coverage due to the logistical constraints of covering the traffic peaks. In contrast, a 75% penetration of the solution appears to minimize deployment costs while capturing the majority of operational and environmental benefits.

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[15] Aircraft adaptation costs are currently treated on a stand-alone, per-airport basis. Synergies across airports are expected in practice (i.e., for airplanes that fly to multiple CA airports), which would reduce this cost should the solution be deployed at CA-level