

Report on Feasibility to Reduce Emissions During Aircraft Taxiing

Public presentation

June 2nd, 2026



Roland
Berger

We will provide an overview of the requirements and implications of Zero-Emission (ZE) aircraft taxiing in CA

Agenda

Topic



Time



Introduction and context

10 min

Assessment of available and emerging ZE technologies, and real-world applications

30 min

Typology of California airports

15 min

Trial Safety and Risk Management Panel

15 min

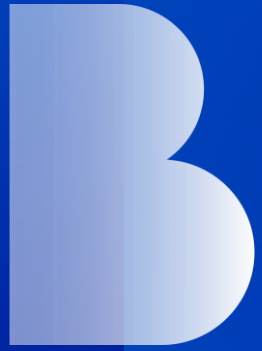
Cost-benefit assessment and implications

30 min

Concluding remarks and Q&A

20 min





A. Introduction of workshop presenters

This session is sponsored by a team from the California Air Resources Board and facilitated by the consulting firm Roland Berger



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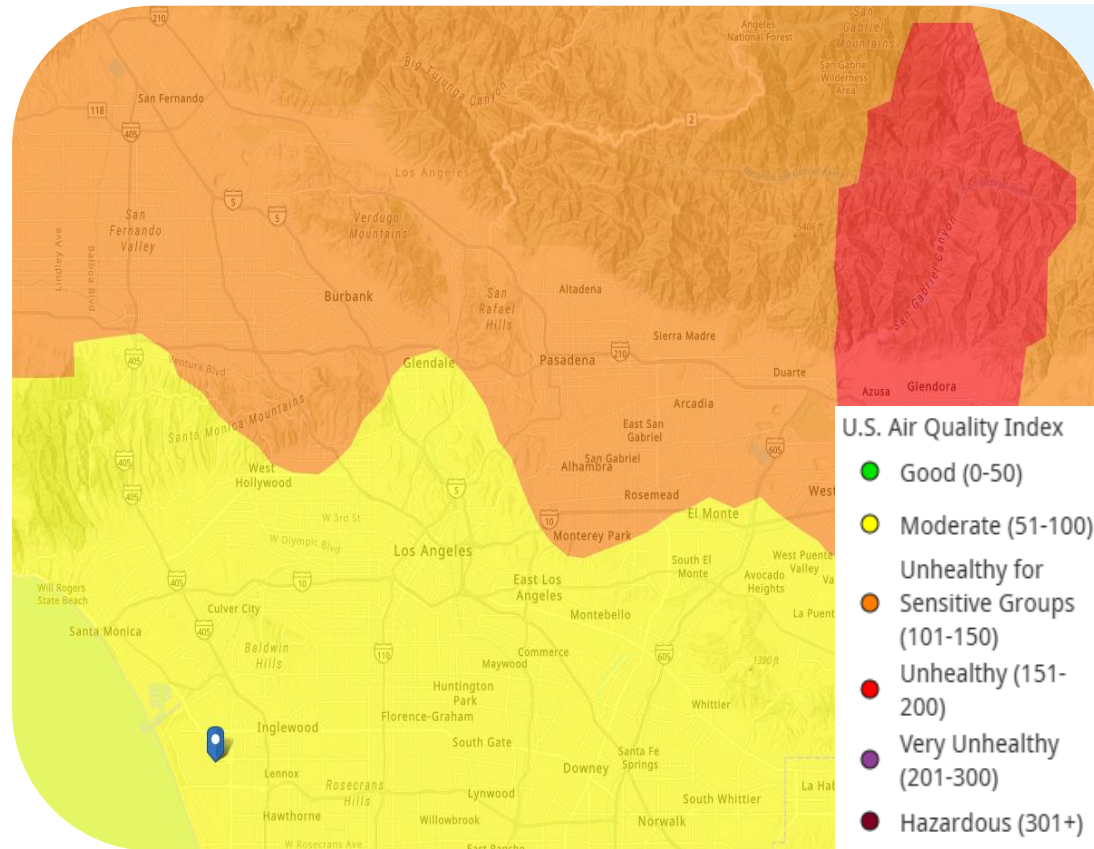
Roland Berger



B. Context of the study

Studies show elevated PM2.5 and NOx levels in areas near major airports, leading to increased respiratory concerns and air quality degradation

Map of air quality (PM2.5) at LAX, Emissions impact at major CA airports



Map of air quality (Ozone and PM (2.5 and 10)), Los Angeles International Airport, August 21 2024

Examples

Los Angeles International Airport (LAX)

- Studies show **elevated levels of ultra-fine particles (UFPs)** as far as **10 miles downwind**, particularly in communities such as Inglewood and El Segundo
- Research from UCLA found that **airplane emissions surpass freeway traffic** in terms of particle pollution near LAX

Sacramento International Airport (SMF)

- **Sacramento** ranks among U.S. cities with the **poorest air quality**, prompting **SMF to implement** measures aimed at reducing aviation-related emissions

Ontario International Airport (ONT)

- Residents in nearby cities have expressed **concerns about increased noise levels** due to the airport's operations, particularly because **ONT operates 24/7 with few noise abatement rules** compared to other Southern California airports

Airports across the world, like AMS, are implementing innovative solutions to improve air quality for their employees and surrounding communities

Amsterdam Airport Schiphol (AMS) – 100% electric taxiing by 2030



Electric taxiing at Amsterdam Airport

- Following a **study linking pollutants** (including NO_x, Particulate Matter) **emitted by aircraft engines** while idling/taxiing to **higher rates of cancer** amongst airport ground staff, Amsterdam Airport Schiphol (AMS) put in place a **new procedure requiring 100% electric taxiing by 2030** at a designated "Green Zone"
- AMS has implemented this as part of its broader goal to become an **emission-free airport**
- While not a formal law, this commitment is a **significant policy initiative supported by the Dutch Ministry of Infrastructure and Water Management** and various aviation partners

Travellers' increasing sensitivity to environmental considerations, alongside a general growth in regulatory oversight, puts pressure to curb air-travel emissions

Growing concerns about the environmental sustainability of air transport

Public awareness of the negative impact of aviation on atmospheric emissions

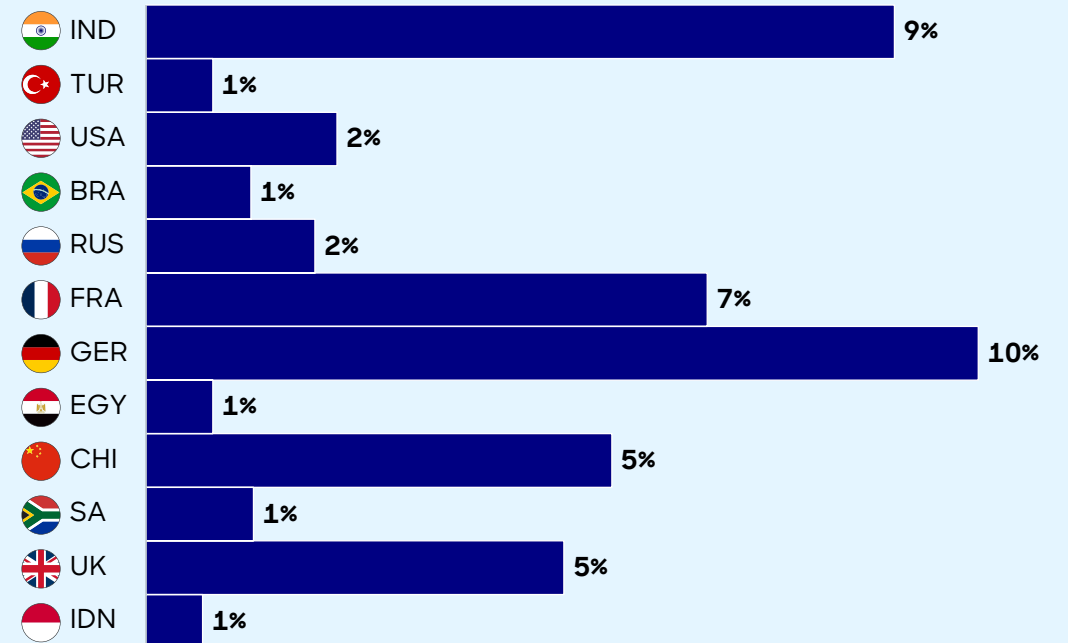
California announces SAF partnership to curb emissions

- CARB partnered with Airlines for America to boost the availability of SAFs, aiming for 200 million gallons by 2035
- This reflects public demand for cleaner air travel options and aligns with broader efforts to reduce aviation's carbon footprint

Alaska Air, Delta lawsuit over Seattle airport pollution

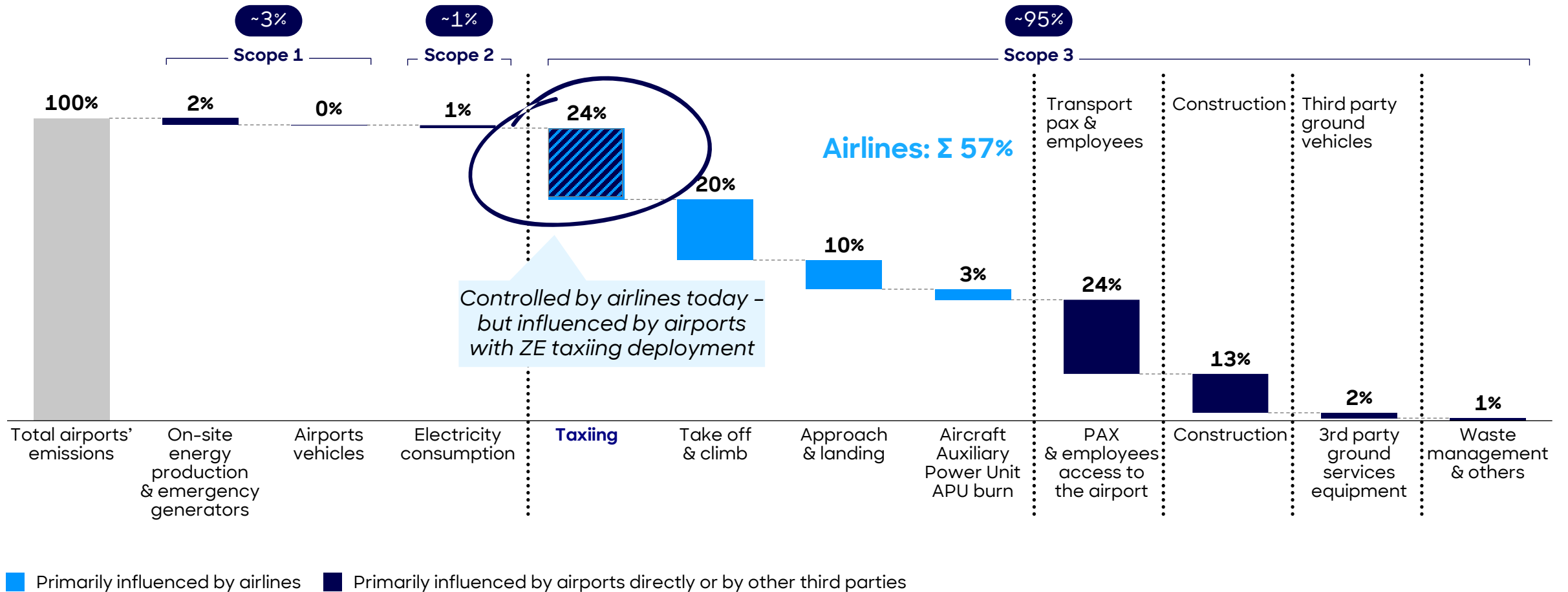
- A lawsuit proceeded against Alaska Air, Delta, and Port of Seattle, alleging aircraft emissions from Seattle-Tacoma Airport cause toxic pollution
- Emissions disproportionately harm low-income and minority residents in a five-mile "Contamination Zone"

Share of surveyed population stating they want to travel less for environmental reasons



Aircraft taxiing represents c. 1/4th of airport emissions, which airports can influence notably via zero-emission taxiing solutions

Airport emissions by emission source - CO₂_{eq} [Example of a large international hub; %]



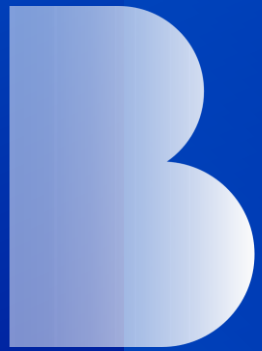
In this context, Roland Berger was contracted to evaluate the high-level feasibility and cost of deploying ZE taxiing solutions in California

Scope of work

Objectives

Carried out based on data collected in Q3/Q4 2025

- **Evaluate the feasibility** of implementing ZE taxiing for commercial aircraft at **select California airports**
 - Analyze **current and emerging ZE technologies**, airport operations, and infrastructure
 - Identify **persona airports** informing the model of ZE taxiing phase in
 - Conduct a Risk and Safety Management (RSM) panel to **address safety concerns**
 - Model **operational constraints** and **expected cost-benefits**
- **Task 1.** Assessment of available and emerging ZE technologies
 - **Task 2.** Analysis of real-world applications of ZE Taxiing
 - **Task 3.** Selection of relevant California airports
 - **Task 4.** Trial Safety and Risk Management panel
 - **Task 5.** Operational and infrastructure assessment of select California airports
 - **Task 6.** Modeling of ZE taxiing at selected airports
 - **Task 7.** Cost benefit analysis
 - **Public presentation**



C. Assessment of ZE taxiing technologies

To tackle taxiing emissions, low-emission taxiing solutions are emerging, both on ground (TaxiBot, EcoTug) and on-board (WheelTug, low-emission Taxi)

Examples of low-emission taxiing solutions

TaxiBot



- A semi-robotic towing vehicle that the cockpit crew controls directly after the pushback is completed by the operator.
- 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.

 On-ground
Targets ground handlers or airlines

 On-board
Targets airlines or aircraft manufacturers

EcoTug procedure



- The 'Aircraft Extended Towing Procedure' (AETP) uses Trepel's TLTV Charger 380-Electro to tow wide-body aircraft with a driver and an operator. It builds on the dispatch towing process, used only in rare failures or emergencies, and is not yet certified for widespread use.

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.








Zero Engine Taxi



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,







































On-ground solutions are in lab testing with no passenger demos, while EcoTug has been demonstrated once and TaxiBot is in use at multiple airports

Comparison of the four sustainable taxiing solutions (1/3)

	TaxiBot  	EcoTug 	WheelTug (WT) 	Zero Engine Taxi 
Development 	<ul style="list-style-type: none"> Developed by IAI, manufactured by TLD (prototype in 2011), sales by Smart Airport Systems 	<ul style="list-style-type: none"> Uses a towbarless pushback by Trepel, a German GSE manufacturer 	<ul style="list-style-type: none"> Designs and manufactures electric systems at its Baltimore assembly line 	<ul style="list-style-type: none"> Launched in 2021 as a spin-off of Safran's eTaxi project (now solely meant for new generation new aircraft), supported by a former L3 VP
Tests & demonstrations 	<ul style="list-style-type: none"> Currently deployed at airports in Amsterdam, New Delhi and Bengaluru (see following pages) 	<ul style="list-style-type: none"> 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 and denial from the French civil aviation authority, the DGAC (Direction Générale de l'Aviation Civile) 	<ul style="list-style-type: none"> Testing at Memphis International Airport used an AlbaStar 737-800 (no passengers). A two-year Mumbai Airport study showed a 2-3 flight/day increase per gate (from 8 avg.). No further in-service aircraft demos planned. Over 25 airlines have expressed interest in 2,600+ WheelTug systems (e.g., Vueling, AlbaStar 2022). 	<ul style="list-style-type: none"> 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

Onboard solutions remove the need for a pushback tug and minimize infrastructure upgrades, while TaxiBot allows for the highest taxiing speeds

Comparison of the four sustainable taxiing solutions (2/3)







	TaxiBot 	EcoTug 	WheelTug (WT) 	Zero Engine Taxi 
Control of the aircraft	 Cockpit crew	 Tug operator	 Cockpit crew	 Cockpit crew
Speed	 23 knots	 17 knots ¹⁾	 7 knots ¹⁾ - Recommended for use in with one engine after leaving gate area	 16 knots ¹⁾
Aircraft wear	 May require more frequent brake manifolds replacement for Airbus	 Prolonged use could subject aircraft to high forces, potentially causing damage ¹⁾ - Risk yet to be evaluated	None known	None known
(Un)coupling	 Requires dedicated area and associated procedure	 Requires dedicated area and associated procedure	 Not required	 Not required
Installation	 Requires modifications for Airbus aircraft. Can be installed overnight	 No modification needed	 Requires 2 overnights. No APU modification	 Requires 2 overnights. No APU modification
Tow-vehicle size	 29.5 ft length x 13.1 ft width	 23.0 ft length x 13.1 ft width	 Not applicable	 Not applicable
In-flight wight	 None	 None	 200 kg - 440 lbs ²⁾	 Up to 140 kg - 300 lbs ²⁾
Required operators	 Requires 1 tug operator for the trip (~45 min for a large hub)	 Requires 2 tug operators for the trip (~45 min for a large hub)	 None	 None
Maneuverability	 Similar to current pushbacks	 Similar to current pushback tugs	 Enhanced (wheelback or turn up to 78 degrees vs 45 degrees of aircraft)	 Similar to current aircraft taxiing

Impact:  Positive  Neutral  Slightly negative  Negative

1) Drawbacks mentioned by AMS as the main reasons for which they do not plan to proceed with the solution , 2) No fuel trade-off considered in this assessment

The solutions are primarily designed for narrow-body aircraft, with TaxiBot being the only certified. On-board systems use the Auxiliary Power Unit (APU)

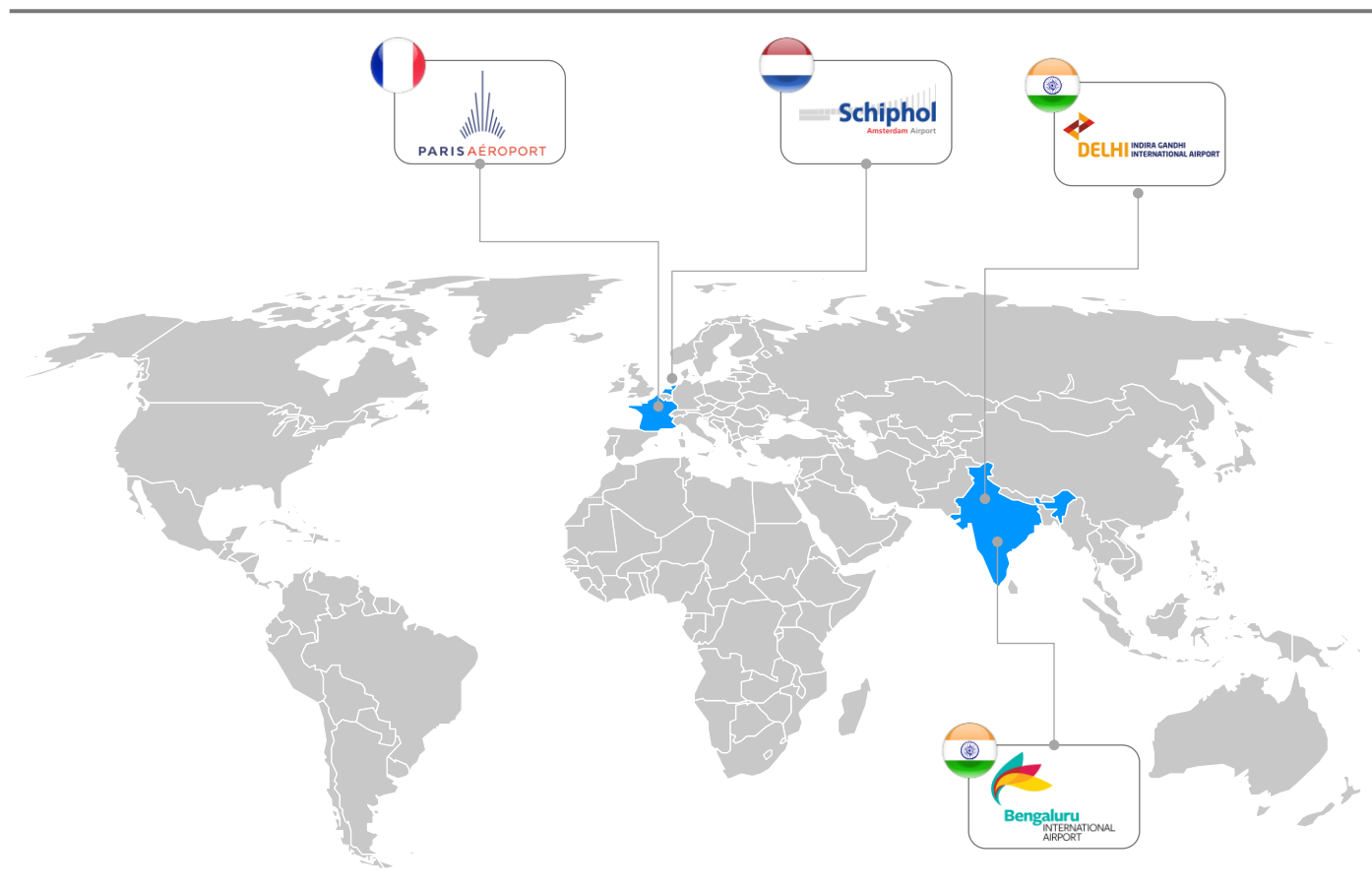
Comparison of the four sustainable taxiing solutions (3/3)

	TaxiBot 	EcoTug 	WheelTug (WT) 	Zero Engine Taxi 
Certification 	<ul style="list-style-type: none"> ✓ Certified by EASA and FAA for narrow-body aircraft as a priority. This includes the following families: B737 (excl. Max) and A320 -Certification for A220 family and B737 Max expected by Q2/Q3 2026, Embrarer by May 15th • Airport-deployment approval from the FAA is pending 	<ul style="list-style-type: none"> ✗ The procedure known as dispatch towing is certified by EASA for use, but not approved by airports for regular taxiing • Only applicable to WB Boeing aircraft. No dispatch towing for Airbus NB aircraft 	<ul style="list-style-type: none"> ✗ Currently certified, but the company reports that their Certification Plan has been FAA-accepted • The company aims to achieve certification by end of 2027, via a Supplemental Type Certificate (STC), starting with 737NG • FAA DERs¹⁾ have been involved in observing lab tests and analyzing results 	<ul style="list-style-type: none"> ✗ Currently certified, but the company reports that their Certification Plan has been FAA-accepted • The company partnered with StandardAero to guide them through regulatory approval (STC), involving 10 DERs¹⁾ • Development supported by \$5.6 m FAA grant
Powertrain 	<ul style="list-style-type: none"> • Available in a hybrid diesel powertrain • Electric model set to launch in Q2 2026 • Uncertain timeline for hydrogen models (2030+) 	<ul style="list-style-type: none"> • Available in diesel, hybrid, and electric models, with a hydrogen model currently under development, though no timeline has been announced 	<ul style="list-style-type: none"> • Electric system powered by the APU 	<ul style="list-style-type: none"> • Electric system powered by the APU

1) Designated Engineering Representatives

TaxiBot is the only solution currently deployed for commercial flights at several airports, allowing for large-scale testing

Mapping of global TaxiBot deployments



India New **Delhi (DEL)** and **Bengaluru (BLR)** airports began using TaxiBots in 2018, with 2 units at DEL and 1 at BLR, **completing over 2,500 trips**. Operations are paused after Celebi reportedly lost its license, with resumption pending. TaxiBots operated efficiently with minimal impact, but no large-scale deployment or new purchases are planned



Netherlands **Amsterdam Airport (AMS)** **acquired 2 TaxiBots** in 2020 and started a Proof of Concept for commercial flights in April 2024, completing **~130 trips by May 2026**. Supported by regulators, airlines, and air traffic control, AMS has a detailed operational plan. The airport plans to **expand to 46 vehicles by 2031**, incl. electric models. TaxiBots mainly operate on the Polderbaan runway, available about 40% of the time

France Paris: Charles de Gaulle Airport (CDG) **leased 1 TaxiBot in 2023/2024 for testing**, with no confirmed plans for wider use. Airlines and ground handlers worry about delays and costs; air traffic control is concerned about staffing for safe operations

Note: Currently, TaxiBot usage is limited to taxi-out missions. The taxi-in process benefits from momentum and is primarily conducted using only one engine, which minimizes the potential advantages of utilizing TaxiBot.

Using taxitows requires infrastructure works and presents operational challenges (ATC, airlines, ground operators), but mitigation solutions exist

Feedback from real-world application of ZE Taxiing (1/3)



	Operational challenge	Mitigation solutions
Infrastructure 	<ul style="list-style-type: none"> A dedicated decoupling zone must be established near the runways to enable the taxitow operator to disconnect the vehicle from the aircraft 	<ul style="list-style-type: none"> CDG utilized the de-icing zone when it is not in use (over 90% of the time). AMS has a designated holding pad adjacent to the Polderbaan runway (previous de-icing area)
	<ul style="list-style-type: none"> Service roads need to be adequately wide to accommodate larger vehicles 	<ul style="list-style-type: none"> AMS, DEL, BLR, and CDG have performed little to no infrastructure improvements to widen service roads; however, some areas remain inaccessible
	<ul style="list-style-type: none"> Apron space must be sufficient to prevent collisions or congestion while maneuvering large vehicles 	<ul style="list-style-type: none"> CDG airport has implemented light modifications to accommodate larger vehicles
	<ul style="list-style-type: none"> Large vehicles necessitate substantial storage space in dedicated hangars 	<ul style="list-style-type: none"> Dedicated areas will likely be needed in the future. The final decision will also depend on whether the taxitows are intended to replace existing pushback tugs or come in addition
	<ul style="list-style-type: none"> Adequate energy supply and charging infrastructure are essential for electric models 	<ul style="list-style-type: none"> 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 and slower overnight charging
Air Traffic Control (ATC) 	<ul style="list-style-type: none"> The change in procedures may increase workload for ATC teams 	<ul style="list-style-type: none"> This can possibly be offset by optimized procedures, especially if the aircraft taxis immediately after pushback, which would help reduce congestion at the gates

Note: mentions regarding CDG relate to the POC conducted by the airport in late 2023/early 2024

Source: Interviews, desk research, Eurocontrol ConOps

Using taxitows requires infrastructure works and presents operational challenges (ATC, airlines, ground operators), but mitigation solutions exist

Feedback from real-world application of ZE Taxiing (2/3)

	Operational challenge	Mitigation solutions
<p>Airline Operations</p> 	<ul style="list-style-type: none"> • Taxiing with a taxitow is slower than non-towed aircraft and introduces a decoupling step and potential detour, potentially impacting efficiency and • Pilot training is necessary, which can incur costs and may hinder large-scale readiness, complicating taxitow operations planning • Airbus aircraft must undergo modifications to connect with the taxitow • In addition, usage is expected to increase wear on brake manifolds, which are typically rarely replaced during the aircraft's lifespan 	<ul style="list-style-type: none"> • Repeated operations are expected to enhance the learning curve. Currently, the decoupling duration is c.1.5 minutes, with a target of 1 minute. Both Indian airports no longer report time loss, due to saved time from immediate towing after push-back • Current training duration is less than 30 minutes in AMS, resulting in minimal disruption to training programs, allowing for the rapid onboarding of a large number of pilots • However, for the initial phase, taxitow usage may be restricted to home carriers, as not all pilots at a national or global level will receive training • Aircraft modification costs are relatively low (~USD 17.4 k), performed overnight • 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
<p>Ground Handler Operations</p> 	<ul style="list-style-type: none"> • The operation of the taxitow 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 	<ul style="list-style-type: none"> • A gradual ramp-up in adoption could facilitate the recruitment and training of sufficient operators. Training for operators is estimated to take 2-3 hours, depending on their prior experience level, and utilizes a simulator to keep costs low

Note: mentions regarding CDG relate to the POC conducted by the airport in late 2023/early 2024

Source: Interviews, desk research, Eurocontrol ConOps

Using taxitows requires infrastructure works and presents operational challenges (ATC, airlines, ground operators), but mitigation solutions exist

Feedback from real-world application of ZE Taxiing (3/3)

Operational challenge

Mitigation solutions

Ground Handler Operations

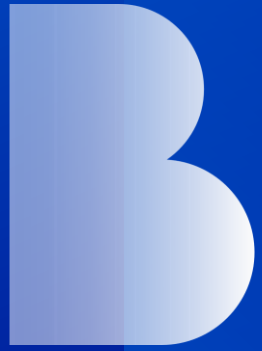


- The purchase, leasing, and operation of the equipment involve **relatively high costs**

- Currently, these costs are **borne by AMS and CDG airports during trial phases**. In the future, an additional usage fee for the taxitow is likely to be implemented (e.g., cost per minute for airlines, with the generated revenue shared between the operator and the airport)

- **Maintenance is critical for effective deployment** and longevity of the vehicle (and its batteries), but it is considered relatively complex for taxitows and requires a high level of expertise

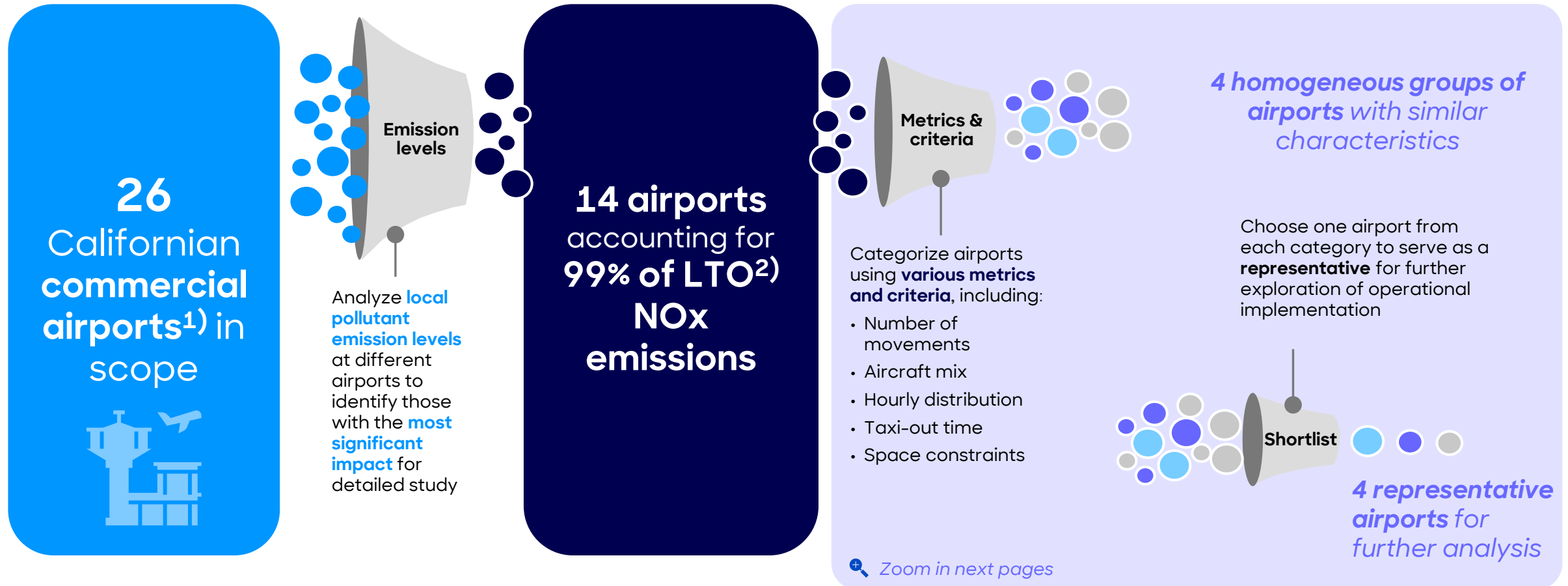
- Maintenance could be initially conducted by the OEM (TLD SAS). A **dedicated team would need to be established** with low turnover to ensure continuous training and gradually take over maintenance responsibilities within 1-2 years



D. Grouping of California airports

Our approach is to focus the analysis on airports contributing most to NOx emissions – identifying archetypes that can inform our models

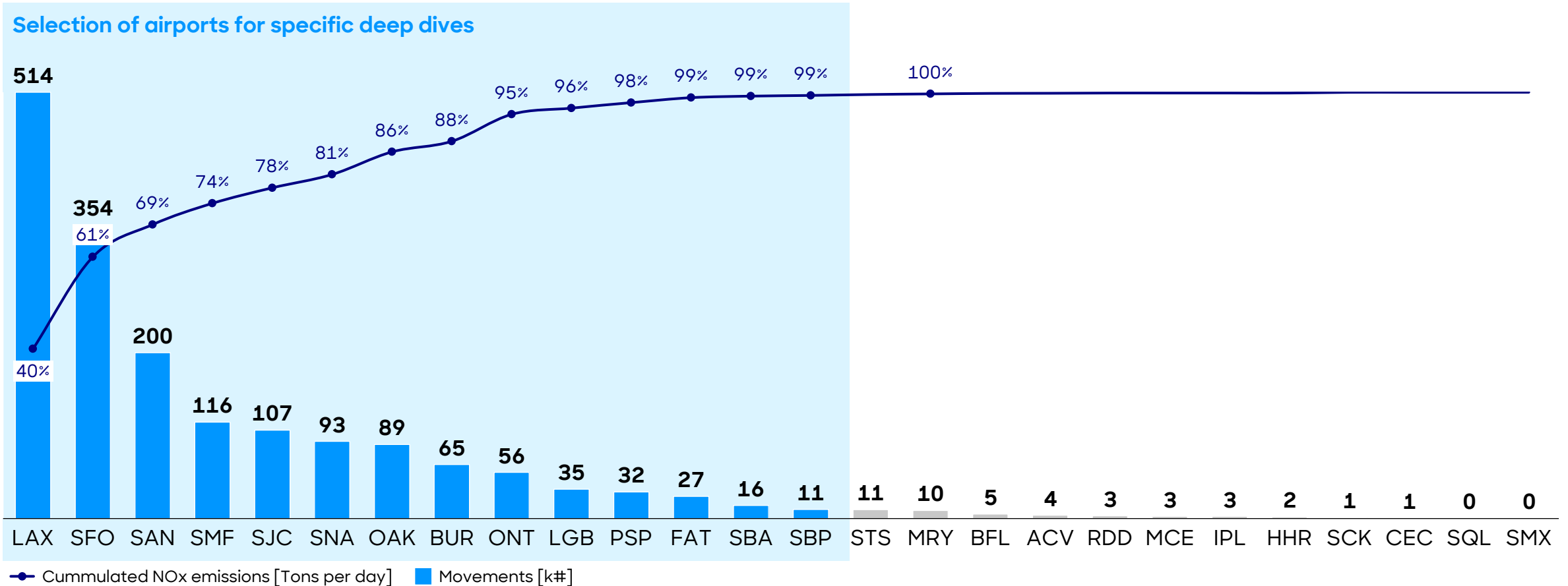
Airports selection funnel



1) Excluding general aviation, reliever airports, military and public-use airports; 2) Landing and Take-Off cycles

The 14 largest commercial airports in CA, ranked by movements, are responsible for over 99% of aircraft NOx emissions. These airports are our primary focus






LTO¹⁾ NOx emissions by Californian airports and yearly passenger movements [2024]



1) Landing and Take-Off cycles

We categorized airports using key metrics relevant to ZE taxiing operations, thereby grouping them based on similarities

Key metrics used for airport grouping

Metric / criteria	Definition and rationale	Source
 <p>1. Number of movements</p>	<p>Number of annual commercial flights out</p>	<p>Industry leading base</p>
 <p>2. Aircraft mix</p>	<p>Mix of annual commercial flights out, categorized by type of aircraft, assessing the applicability of ZE taxiing</p>	<p>Industry leading base</p>
 <p>3. Hourly distribution</p>	<p>Number of movements out per hour per day, impacting the number of ZE taxiing equipment needed to cover all flights, as well as their utilization rate</p>	<p>Industry leading base</p>
 <p>4. Taxi-out time</p>	<p>Affects jet fuel consumption and emission savings, impacted by distance from terminals to runway and airport congestion (navigation complexity, access to runways, etc.)</p>	<p>Industry leading base, CA airports</p>
 <p>5. Space constraints</p>	<p>Availability of disconnection zones, condition and layout of service roads informing ease of the return of vehicles</p>	<p>Outside-in view, airports</p>

When looking into infrastructure, airports can be categorized into a fourth group characterized by higher complexity due to space constraints

Metric 5 – High-level space constraints

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 ZE taxiing 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 ZE taxiing flow	Group 2
SNA*	Group 2	Easy/Moderate	R.20R offers ZE taxiing 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 ZE-taxiing compatible, 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 ZE taxiing return routes	Group 3
FAT*	Group 3	Moderate	22-foot service roads accessible but limit two-way taxitow flow; mid-runway takeoffs need FAA approval	Group 3
SBA	Group 3	Complex	SBA’s tight layout and X-shaped runways complicate ZE taxiing operations, risking congestion and delays	Group 4
SBP*	Group 3	Complex	Narrow gravel roads and elevation differences near Runway 11 hinder ZE taxiing operations without reconstruction	Group 4

Easy Moderate Complex

The assessment led to categorize the 14 airports into 4 groups, with LAX, SJC, LGB, and SBP selected as “persona” airports to anchor the models

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

Grouping

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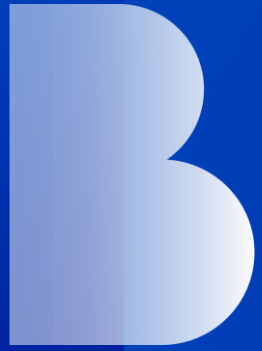
LAX, SFO	SAN, SJC, SNA, OAK, ONT, BUR	PSP, FAT, LGB	SMF, SBA, SBP
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LAX

SJC

LGB

SBP



E. Trial Safety and Risk Management (SRM) Panel

Drawing on the experiences of other airports, the following potential safety risks and mitigation options have been identified (1/2)

Possible safety hazards and associated mitigation options (1/2)

	Potential safety risks	Mitigation options
1 Preparation	Procedures and safety measures vary based on towing/taxiing type	<ul style="list-style-type: none"> 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	<ul style="list-style-type: none"> 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	<ul style="list-style-type: none"> In the event of a planning change, 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, in the early stage of a ZE taxiing project, the taxitow is therefore not used for conventional pushback scenarios. 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	<ul style="list-style-type: none"> Keep an emergency vehicle on standby at all times, ready to intervene in case of failure
	Absence of communication between operator and ATC creating risk concerns	<ul style="list-style-type: none"> Operator does not steer, reducing need for ATC communication. However, communication can be established in emergency situations, but may impact radio frequency load; airport discretion applies
	Crossing of an active runway	<ul style="list-style-type: none"> 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	<ul style="list-style-type: none"> 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

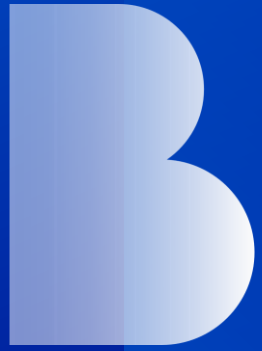
Note: possible positive safety risks include the absence of jet blasts close to aircraft stands, and the reduction is FOD risks

Drawing on the experiences of other airports, the following potential safety risks and mitigation options have been identified (2/2)

Possible safety hazards and associated mitigation options (2/2)

	Potential safety risks	Mitigation options
5	<p>Disconnection and aircraft take-off</p> <p>Risks from jet blasts when engines are activated (either at the disconnect area or during taxiing)</p>	<ul style="list-style-type: none"> The operator in the vehicle, whether connected or disconnected from the aircraft, can monitor 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, the operator can disconnect and evacuate the area without needing to manually unplug, slightly accelerating disconnect
6	<p>Return of vehicle to the next gate</p> <p>Crossing with other vehicles could occur on the service roads</p> <p>Vehicle failure after disconnect</p>	<ul style="list-style-type: none"> Emergency and firefighting vehicles responding to the runway should have priority. All other traffic, including taxitows must yield by moving to the nearest accessible bypass pad 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
	<p>All stages combined</p> <p>Pilot loses communication with ATC</p> <p>ATC workload is a significant concern, as it is already deemed too high at most airports</p>	<ul style="list-style-type: none"> 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. 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 <ul style="list-style-type: none"> - 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

Note: possible positive safety risks include the absence of jet blasts close to aircraft stands, and the reduction is FOD risks



F. Cost-benefit assessment and implications

79% of aircraft in CA are compatible with ZE taxiing. We then considered the constraints at airports to determine the # of compatible take offs (86% FP_{MIM})

Infrastructure and operation requirements

Criteria	LAX	LGB	SJC	SBP
Limiting infrastructure	<ul style="list-style-type: none"> Narrow service roads that would not fit 2 heavy vehicles at 24L (23ft wide vs. 13ft for ZE taxiing equipment) - <i>not directly impacting FP_{ci}</i> 	<ul style="list-style-type: none"> No bi-directional flow for large vehicles on return service roads 	<ul style="list-style-type: none"> Narrow return service road on 12L, making taxitow return impossible No bi-directional flow for large vehicles on return service roads 	<ul style="list-style-type: none"> Lower elevation at SR 11, making it impossible to use for ZE taxiing Ground work needed for a small portion of the SR 29
Limiting operational constraints	<ul style="list-style-type: none"> Authorization to cross non movement zone to reach SR at 24L & 25 R - <i>not directly impacting FP_{MIM}</i> 	<ul style="list-style-type: none"> Operational complexity due to X-shaped runways - <i>not directly impacting FP_{MIM}</i> 	<ul style="list-style-type: none"> n.a. 	<ul style="list-style-type: none"> Mid-field take-off currently not authorized and should be validated by FAA
Modifications to ATC and pilot checklist to ensure proper recognition of taxied aircraft ³⁾				
Compatible take-offs (FP_{MIM}⁴⁾	<div style="border: 1px solid black; border-radius: 50%; padding: 5px; display: inline-block;">202k</div> <div style="border: 1px solid gray; border-radius: 50%; padding: 2px; display: inline-block;">100%</div>	<div style="border: 1px solid black; border-radius: 50%; padding: 5px; display: inline-block;">18k</div> <div style="border: 1px solid gray; border-radius: 50%; padding: 2px; display: inline-block;">100%</div>	<div style="border: 1px solid black; border-radius: 50%; padding: 5px; display: inline-block;">46k</div> <div style="border: 1px solid gray; border-radius: 50%; padding: 2px; display: inline-block;">87%</div>	<div style="border: 1px solid black; border-radius: 50%; padding: 5px; display: inline-block;">4k</div> <div style="border: 1px solid gray; border-radius: 50%; padding: 2px; display: inline-block;">86%</div>
Infrastructure modifications	<ul style="list-style-type: none"> Paving of unused land to be used for storing ZE taxiing equipment, otherwise storage airside Space at gate must be verified on site Adaptation of maintenance infra. 	<ul style="list-style-type: none"> Paved area to be potentially reallocated or available area to be paved 	<ul style="list-style-type: none"> Paved area to be reallocated - possibility of dedicating it to ZE taxiing 	<ul style="list-style-type: none"> Paving return service road 29 and storage space Space at gate must be verified on site Adaptation of maintenance infra.
Operation modifications	<ul style="list-style-type: none"> Authorization from FAA and ATC to cross non movement area on few meters to joint SR Authorization for bypass use 	<ul style="list-style-type: none"> n.a. 	<ul style="list-style-type: none"> n.a. 	<ul style="list-style-type: none"> Authorization for mid field take-off and/or by-pass utilization
Average taxi-time [min]	<div style="border: 1px solid gray; border-radius: 50%; padding: 5px; display: inline-block;">15.3</div>	<div style="border: 1px solid gray; border-radius: 50%; padding: 5px; display: inline-block;">11.6</div>	<div style="border: 1px solid gray; border-radius: 50%; padding: 5px; display: inline-block;">11.0</div>	<div style="border: 1px solid gray; border-radius: 50%; padding: 5px; display: inline-block;">9.0</div>

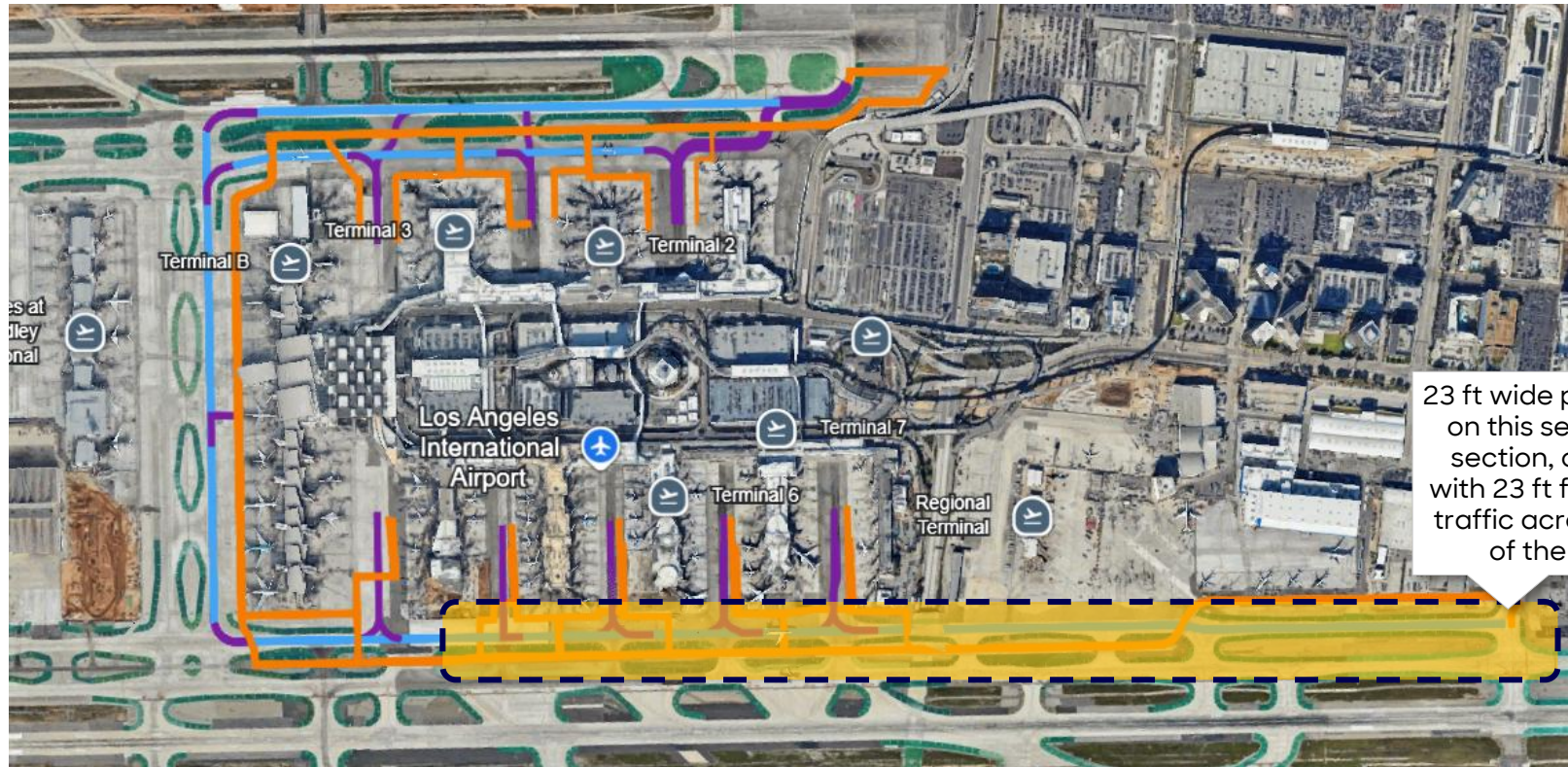
Obstacles have been identified to the full deployment of the ZE taxiing solution on SJC and SBP due constrained service roads¹⁾ Minor auxiliary taxiways are recommended to be excluded for pragmatic, efficient ZE taxiing use²⁾

1) Outside-in perspective due to the lack of access to non-public data; 2) Some flight routings on secondary taxiways that would not be optimal for aircraft towing procedure; 3) To be further assessed during safety panel; 4) Flight Percentage with Minimal Infrastructure Modification expressed as % of compatible flights (i.e., out of 79% of all flights)

For example, at LAX there are no red flags about ZE taxiing feasibility across the core 18 routes

Capability assessment - LAX

Detailed capabilities



■ Service road 10 knots
 ■ Taxiway 10 knots
 ■ Taxiway 15 knots

Route analysis

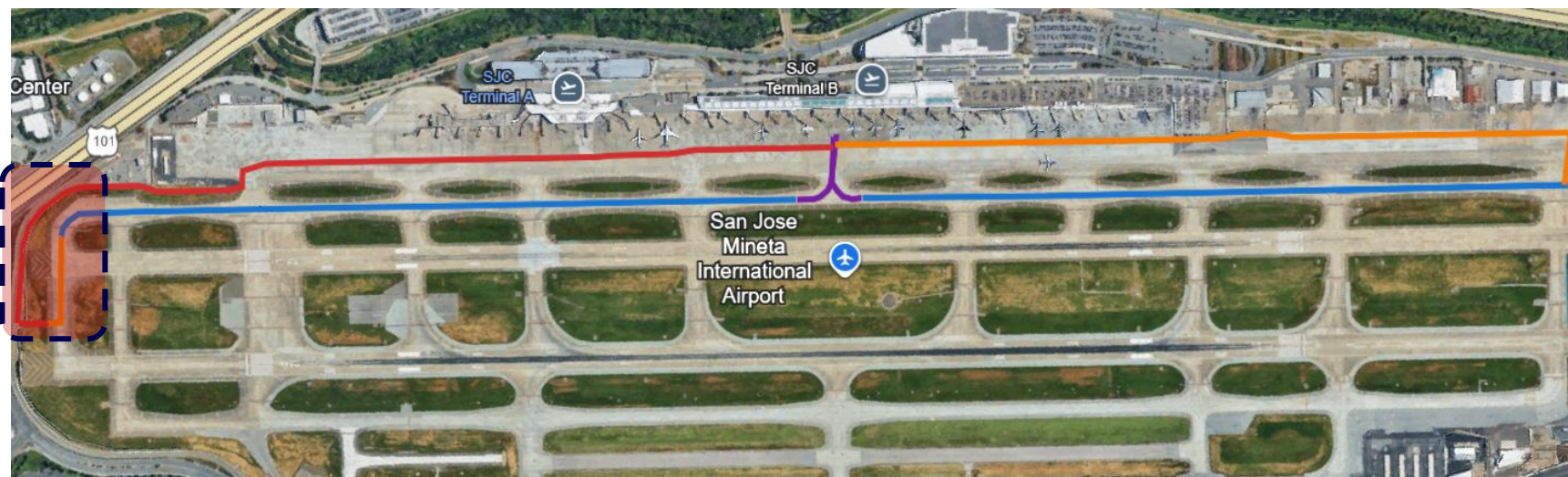
- Runways **24L** and **25R** concentrate ~90 % of total traffic
- De facto standard routing for access from Terminals **T1-T2-T3-B-T4-T5-T6-T7-T8**
- Structurally, **no major issues are identified**
- Operational challenges need to be confirmed with additional data access, as some sections of the service road may currently prevent 2 taxitows from crossing

FP_{MIM}: 100%

Conversely, at SJC, runway 12L is not ZE taxiing-compatible due to narrow service roads for the return

Capability assessment – SJC

Detailed capabilities



Runway 12L represents a material issue for taxiway 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

1) Outside-in

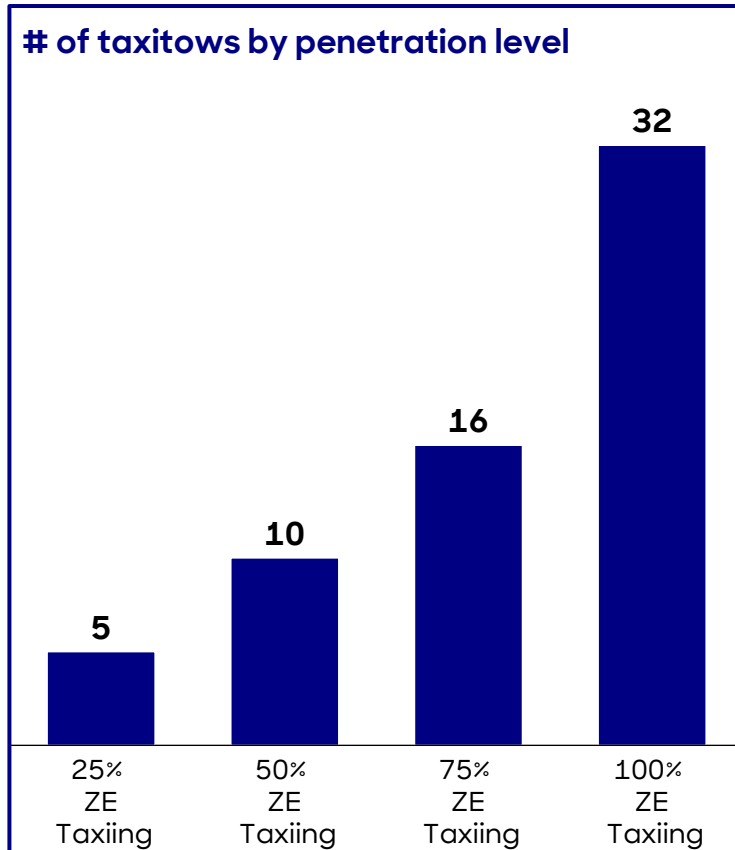
Route analysis

- **Runway 30R** (~87 % of traffic) presents no issues on the runway or service road, as sufficient space is available, requiring only minor ground marking adjustments
- **Runway 12L** is not accessible due to insufficient width¹⁾
- **Terminals A and B** were analyzed as a single departure point using a shared barycenter, given the greater length of Terminal B

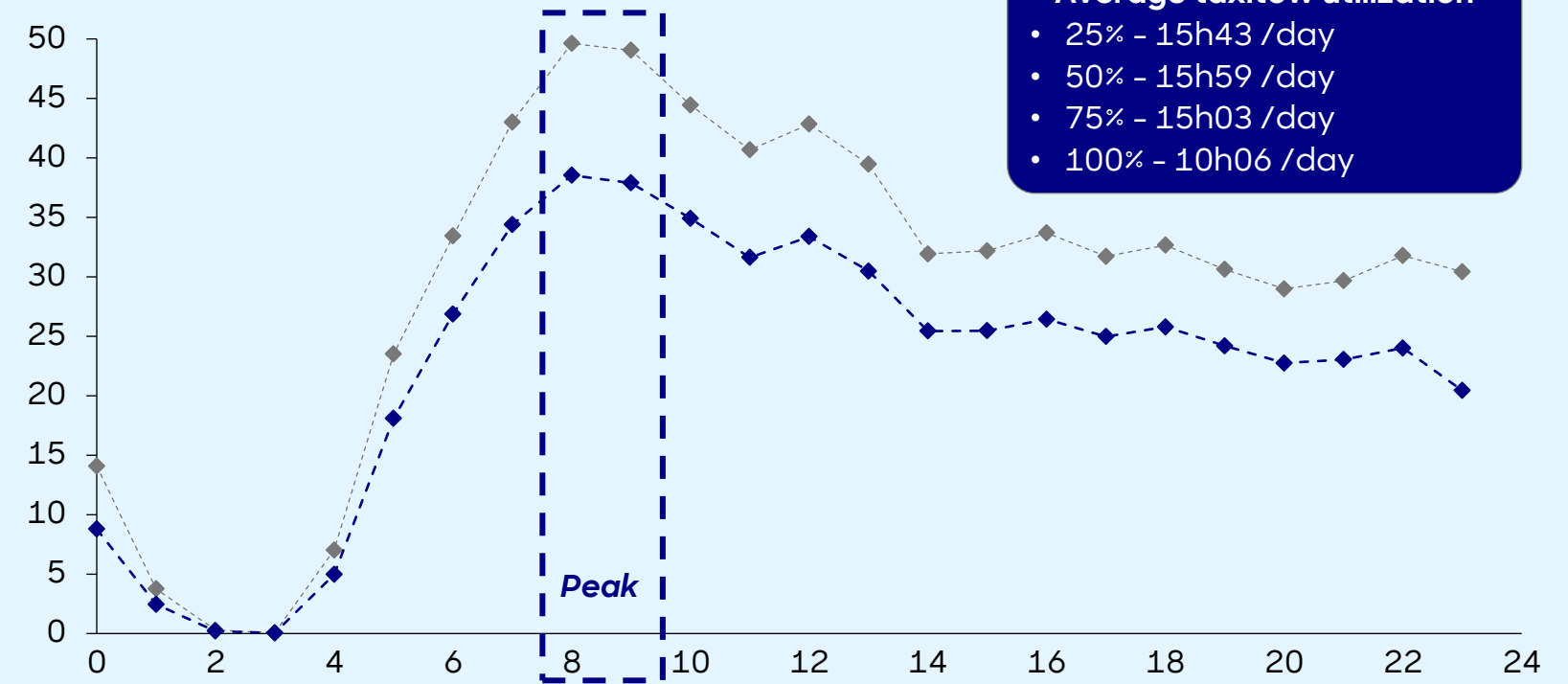
FP_{MIM}: 87%

We modeled the # of ZE taxiing equipment needed to handle the compatible take-offs at each airport - accounting for peak traffic dynamics

ZE taxiing - LAX



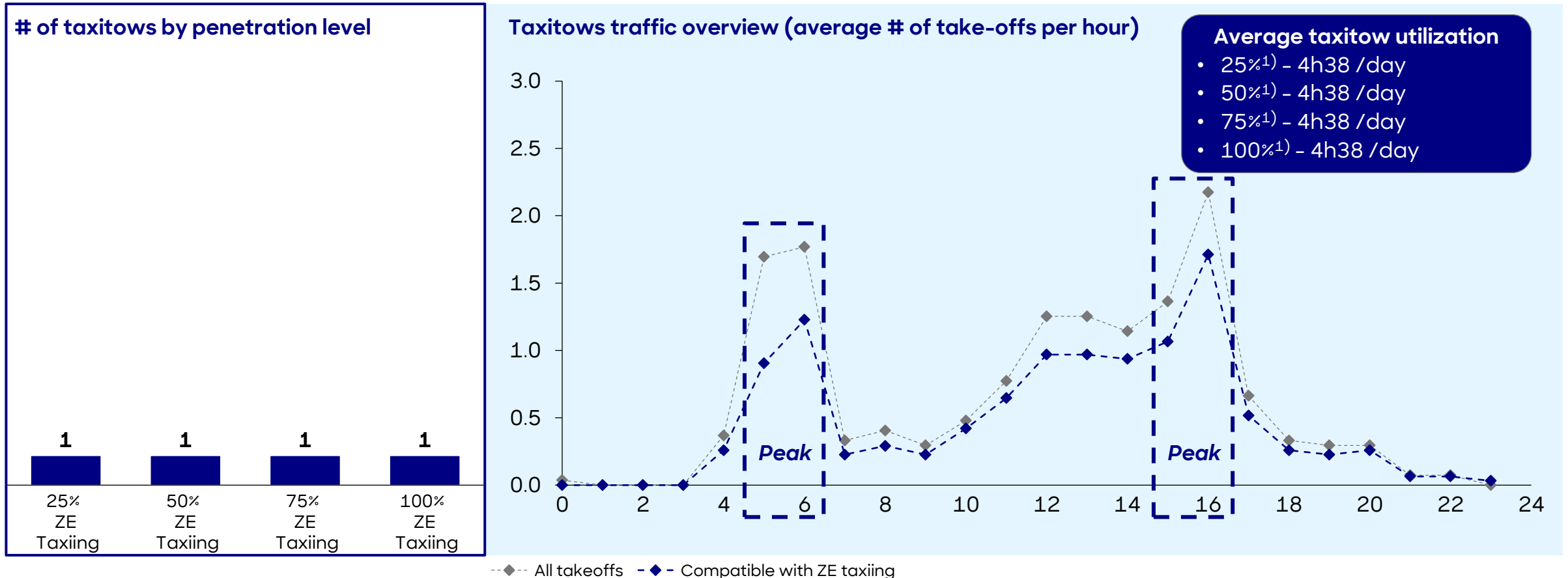
Taxitows traffic overview (average # of take-offs per hour)



--◆-- All takeoffs -◆- Compatible with ZE taxiing

At airports with limited traffic, one taxitow is enough to handle all ZE-taxiing-compatible flights

ZE taxiing - SBP

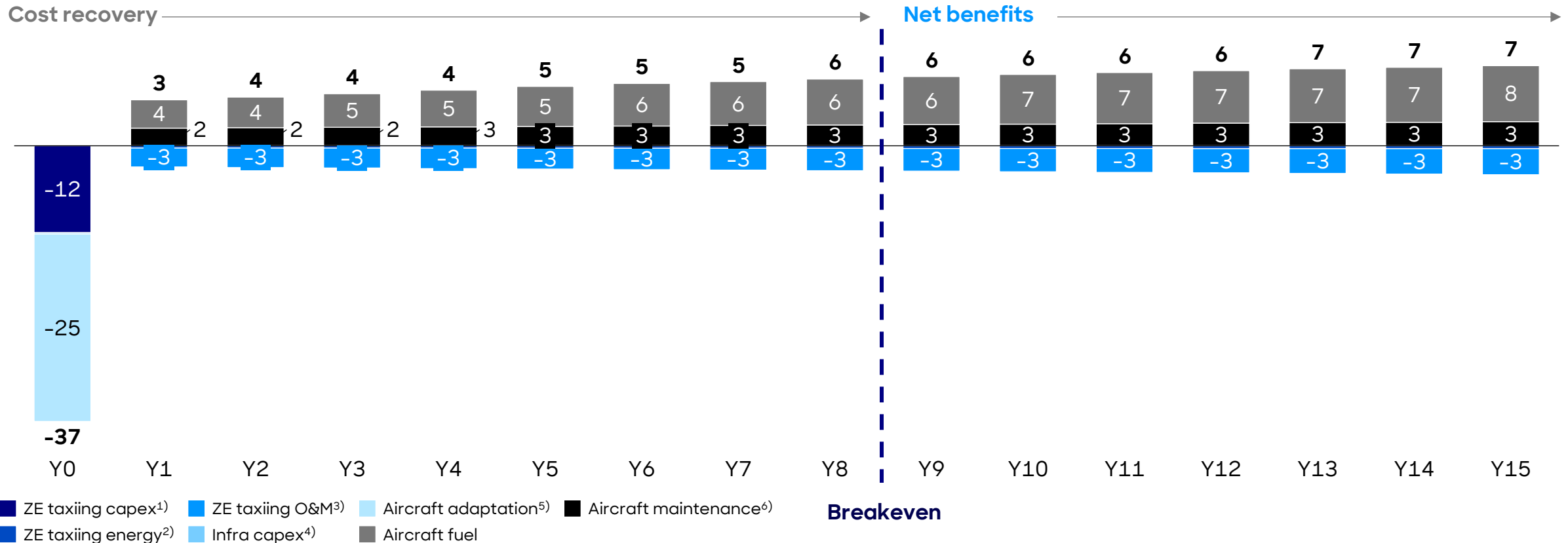


1) Actually representing 100% of flights, as 1 Taxitow can cover 100% of addressable flights

Upfront investment in the equipment and infrastructure modification is offset across project lifetime by fuel and engine-time savings

Cost-benefit analysis – LAX, 25% penetration

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

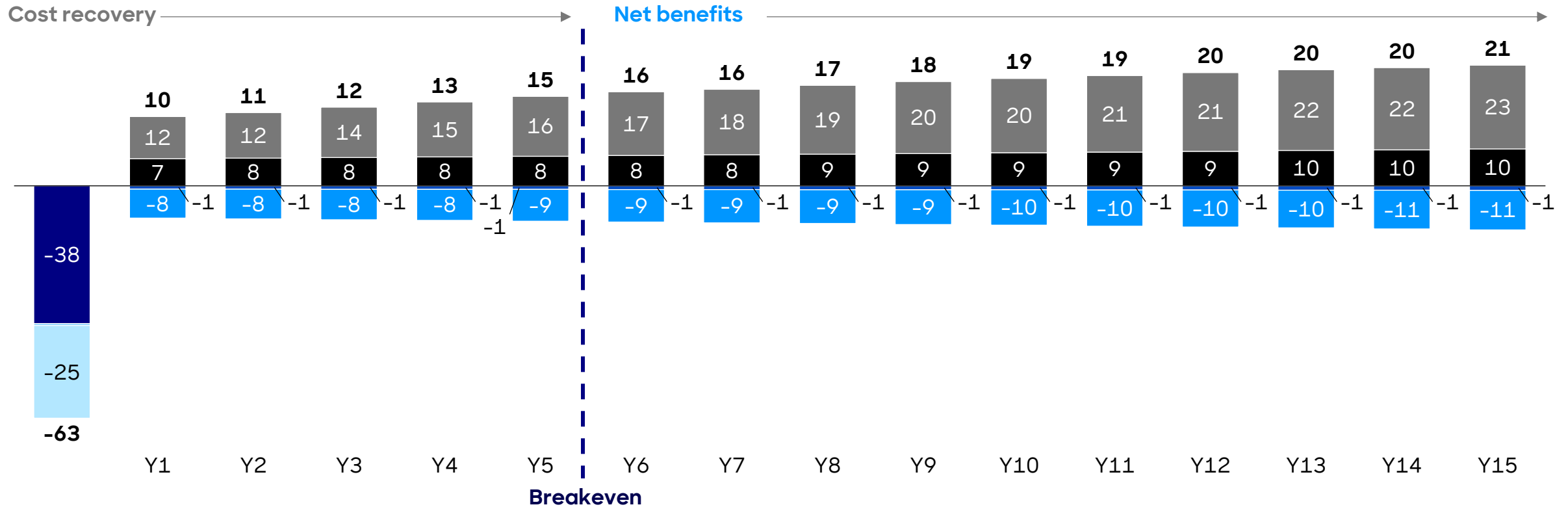


1) Acquisition (option to model financing costs and tax-efficient depreciation; base case assumes zero debt); resale of existing tugs; 2) Electricity consumption (no diesel modelled in the base case) and electricity/diesel savings from reduced pushback operations; 3) Including operator salaries, trainings (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

The economic case becomes more attractive at higher penetration levels, justifying the upfront investment to adapt service roads and aircraft

Cost-benefit analysis – LAX, 75% penetration

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



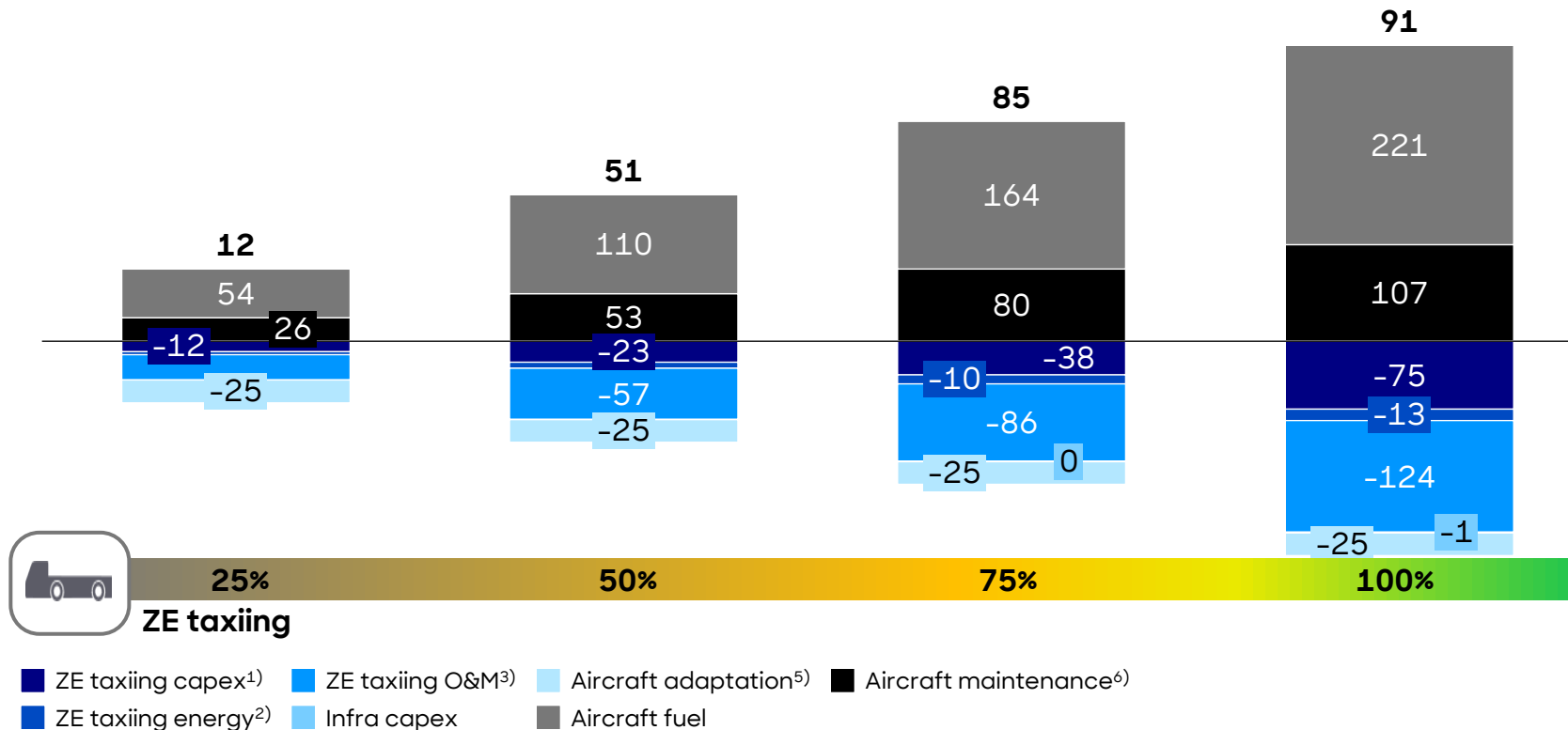
■ ZE taxiing capex¹⁾ ■ ZE taxiing energy²⁾ ■ ZE taxiing O&M³⁾ ■ Infra capex⁴⁾ ■ Aircraft adaptation⁵⁾ ■ Aircraft fuel ■ Aircraft maintenance⁶⁾

1) Acquisition (option to model financing costs and tax-efficient depreciation; base case assumes zero debt); resale of existing tugs; 2) 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

Overall, ZE taxiing can create USD 12-91 m of value (NPV) at an airport like LAX- owing to fuel and maintenance savings from avoided engine hours

Cost-benefit analysis - LAX

Lifetime costs [NPV, USD m] By share of taxied flights and cost category



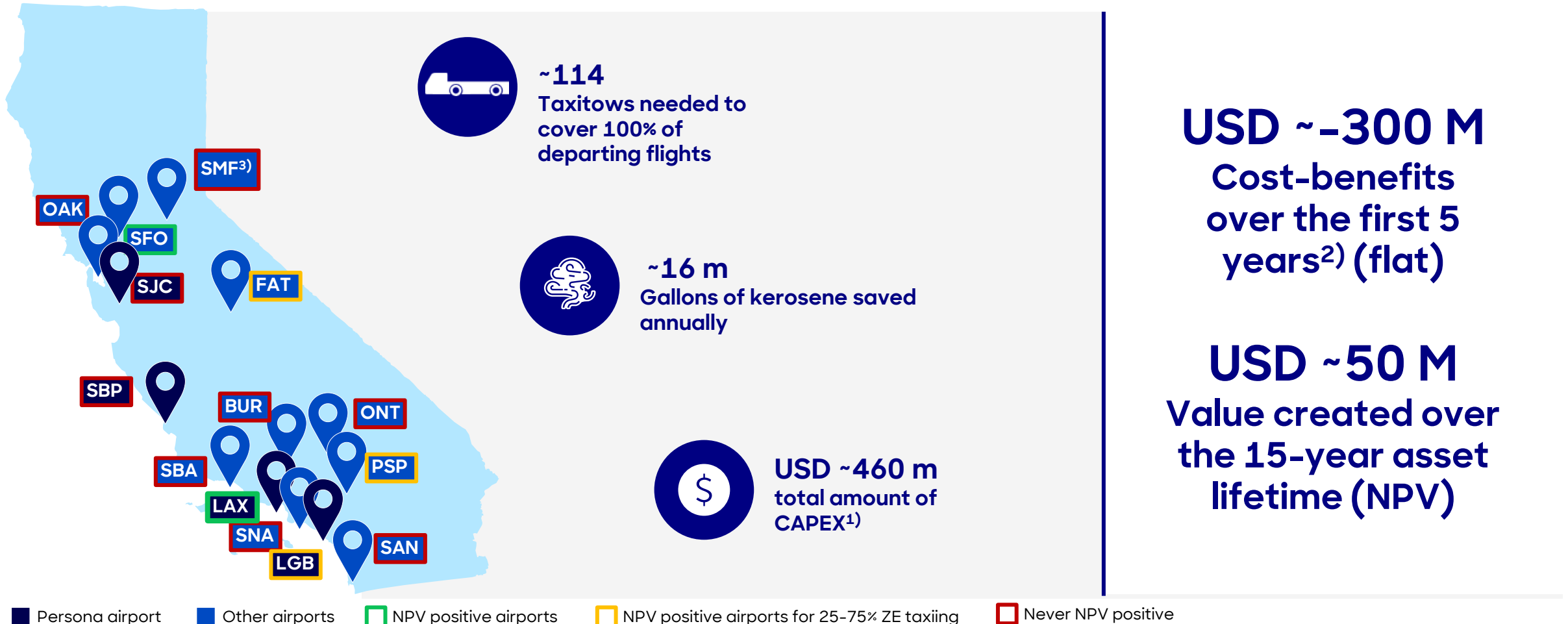
Comments

- **The economic case is fundamentally fuel-driven and scale-led**, with fuel savings as the dominant value driver, maintenance as a stable secondary upside, and ZE taxiing equipment costs largely fixed and absorbed beyond ~50% adoption
- **Value creation accelerates with scale**, as fixed and semi-fixed costs are diluted while operational savings continue to compound
- **Higher adoption systematically improves system-level economics**, with no value inflection or downside observed up to full deployment
- **Full adoption maximizes economic and CO₂ impact**, despite diminishing marginal returns at the unit level due to lower per-unit utilization

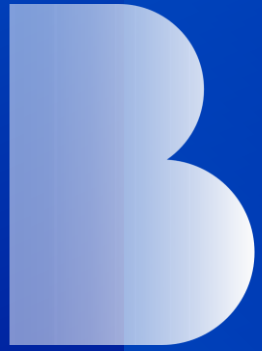
1) Including acquisition and financing costs, and factoring in tax-efficient depreciation and resale of existing tugs; 2) Used electricity; 3) Including operator salaries, maintenance, insurance costs; 5) Including front wheel adaptation costs on '320 family'; 6) Based on saved engine time

Overall, ZE taxing could save 16 m gal of jet fuel yearly and create ~USD 50 M net benefits in CA - although the economic case is not NPV-positive at all airports

Cost-benefit analysis - 14 CA airports (100% penetration case)



1) Total CAPEX : ZE taxiing equipment purchase, infrastructure investment, aircraft adaptation ; 2) 2026-2030, including 2026 as a first year of investment; 3) SMF is included in Group 4 (complex cases) with comparatively smaller airports, but ZE taxiing implementation is expected to be particularly complex there due to infrastructure constraints. A specific study with further access to data is recommended



G. Concluding remarks and Q&A

For a successful deployment of ZE taxiing, it is key to align interest between stakeholders and maximize both economic & environmental benefits

Implications and open points for further study

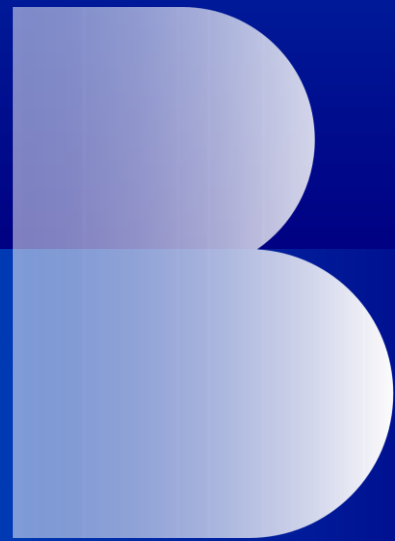
Questions	Conclusions from the study	Further points to investigate
Where is ZE taxiing deployment most feasible?	<ul style="list-style-type: none"> • Economic viability is concentrated in large airports, where fuel and maintenance savings outweigh CAPEX • At smaller airports, lower traffic, shorter taxi times and smaller aircraft limit savings and do not offset investment costs 	<ul style="list-style-type: none"> • Smaller airports should be considered as pilots rather than standalone economic cases
What can be done for the 20% flights non-compatible?	<ul style="list-style-type: none"> • Residual share of flights remains structurally non-compatible, due to Aircraft incompatibility, focus on narrow body, infrastructure constraints, operational limitations on specific routes, etc. • Focusing ZE taxiing deployment with these constraints captures a large share of achievable fuel and CO₂ savings 	<ul style="list-style-type: none"> • Complementary decarbonization levers for flights not covered with: <ul style="list-style-type: none"> - Onboard solution (e.g., electrical wheel) - Operational levers (e.g., single engine taxiing) - Fuel and energy levels (e.g., SAF) - System level decarb. (e.g., CCS)
What should be the targeted level of ZE taxiing?	<ul style="list-style-type: none"> • Full decarbonation requires a large fleet of ZE taxiing equipment, leading to low utilization and weaker economics • At large airports (e.g. LAX), the economically optimal penetration lies around 50-75%, maximizing impact and savings per taxitow • Economic case at 100% penetration in CA remains NPV positive 	<ul style="list-style-type: none"> • Target decarbonization ambition (100% vs. impact per USD) • Minimum acceptable utilization level for ZE taxiing and dedicated teams • Complementary levers beyond ZE taxiing
How can the situation be a win for all stakeholders	<ul style="list-style-type: none"> • Deploying ZE Taxiing technologies in CA airports will require a well-designed economic and incentives mechanism to account for the fact that different actors bear CAPEX investment (e.g., airports) vs benefit from OPEX savings (e.g., airlines) 	<ul style="list-style-type: none"> • Target governance model (airport-led, airline-led, third-party or public-driven) • Cost and value allocation mechanisms across airports, airlines and ground handlers

Questions & Answers

Q&A



Thank you for joining this session



Roland
Berger