Scope of Work

Feasibility study of zero emission taxiing of aircraft at CA airports

Background

California Air Resources Board (CARB) has successfully implemented regulations over past decades that have substantially decreased criteria pollutants and greenhouse gas emissions in California. Despite these monumental successes, more emission reductions are necessary throughout the State. One specific region of concern, the South Coast Air Basin, has been classified as an extreme nonattainment area for the 1997 8-hour ozone National Ambient Air Quality Standard.[1] Furthermore, as CARB implements the new 0.9 $\mu g/m^3$ PM standard, many regions in central and northern California are expected to fall out of attainment. Addressing nonattainment of these air quality standards will require reducing NOx, Hydrocarbon, and Particulate Matter (PM) pollutants.

CARB's most recent regulations focus on the implementation of Zero Emission (ZE) technologies to drive down emissions for many mobile source sectors. Aviation remains a sector that is predicted to have growing emissions in future years. Statewide NOx emissions from aviation are expected to increase from 49 tons per day in 2020 to 69 tons per day in 2037, with almost three quarters of that NOx coming from commercial aviation.[2] Mitigating emissions from commercial aviation could help many regions of California reach attainment of air quality standards, as major airports are located throughout the state.

One strategy to reduce emissions at airports is incorporating ZE taxiing of commercial aircraft. Fortunately, there are market-ready technologies that can greatly reduce or eliminate emissions during taxiing. Additionally, due to the inefficient fuel consumption of traditional taxiing, a transition to ZE taxiing may financially benefit airlines and airports by minimizing fuel use. This further increases the viability of ZE taxiing as an effective approach to reduce NOx emissions.

Purpose and objectives:

The contractor will assess the feasibility of implementing zero-emission taxiing for commercial aircraft at select California airports. This will include an assessment of available and emerging ZE technologies, modeling and analysis of present-day operations and infrastructure of select California airports. The contractor will determine what modifications to operations and infrastructure, or additional resources will be necessary to implement ZE taxiing such that there are no negative impacts on the efficiency of the airport, or the route or service of an airline. A Risk and Safety Management panel will be organized to identify and mitigate safety risks associated with ZE taxiing. Finally, a cost-benefit analysis will be performed to provide insight into operationally and technically feasible ZE taxiing application approaches for California airports and airlines.

Tasks to be accomplished

1. Assessment of available and emerging ZE technologies

The contractor will assess the current technologies that could be used to to enable ZE taxing between airport gates and runways.

There are generally two ZE technologies for taxiing aircraft: External tug units, which pull or push the aircraft, and internal electrification units, which use onboard power from the aircraft to power its wheels. An example of external tugs are the eTT Series from EagleTugs[3], while examples of internal electrification would include eTaxi by Safran Group[4] or WheelTug[5]. The most commercially applicable tug available today is SAS Taxibot[6], which only offers a diesel-hybrid powered unit, but is expected to release all-electric and hydrogen fuel-cell units in the future. The contractor should compile all such technologies as well as any that don't fit in the categories listed here that utilize electrification or hydrogen fuel-cell to power the taxiing of aircraft to and from the runway.

The contractor should address the following questions for each commercially available ZE technology:

- What is the technology readiness level (TRL) of each ZE technology as determined by an established metric, such as ISO 16290:2013?[7]
- If the ZE technology has a TRL index of 9, will the company be capable of producing enough units at a rate to supply all California airports with commercial air traffic over a 5-year time frame?
- If units are not already in use in the state of California, will any additional testing, certification, or modifications of ZE technologies be necessary to guarantee compliance with state and federal regulation code for operating on CA airport aprons, taxiways, and runways?
- For electric tugs: How far can tugs drive with and without aircraft in tow on one charge? What is the recharge or refuel time for the units? What is the acceleration rate, deacceleration rates and maximum speed while tugging and not tugging aircraft? How long does it take for the tug to connect and disconnect from aircraft?

- For onboard electrification or similar: to what extent will the aircraft manufacturers need to be involved in implementing these technologies? Can a commercial airline retrofit in-use aircraft with these devices, or can they only be implemented during the initial construction of the aircraft?

Additionally, any emerging technologies for taxiing aircraft not yet on the market should be documented. Determine the timeframes in which the emerging technologies (TRL index < 9) are expected to become commercially available (TRL index = 9), and what hindrances they may encounter in reaching wider market availability.

The contractor is also expected to perform a literature review to summarize any existing research that has examined the use, efficiency, cost-effectiveness, environmental impact, or operational challenges of ZE technologies used for taxiing aircraft.

2. Analyze real-world applications of ZE aircraft taxiing

The contractor will examine implementation of ZE taxiing underway in Europe and other parts of the world and determine how benefits and challenges experienced in those areas would translate to CA airports.

One initial example in Europe, SESAR, specifically a program called HERON, is projected to carry out 20 demonstrations from around 2022 – 2025 to investigate elements of sustainable taxiing with zero-emission technologies, sustainable taxiing operation for wide-body aircraft, and green taxiing management tools. The contractor should analyze tests and demonstrations performed by HERON to determine if lessons-learned from the project would be relevant to CA airports.

There are at least three examples of the SAS Taxibot being deployed for commercial flights:

- A multi-airline demonstration project in 2020 at Amsterdam Schiphol Airport.[8]
- Lufthansa flights at Frankfort Airport in 2015.[9]
- Air India flights at Bengaluru and Delhi airports in 2023.[10]

In addition, as of July 2024, South Coast AQMD is pursuing a demonstration for zero-emission taxiing at Ontario International Airport in Southern California. The details of this demonstration are not yet set, but contractor should investigate this demonstration if it occurs within the timeframe of the contract.

The contractor should review the zero-emission taxiing deployments listed above, as well as any other examples they can find. Through researching available documents and contacting airlines and airports involved, the contractor should address the following questions for each deployment:

- What fraction of the airport/airline flights of the were taxied with ZE technologies? What specific ZE technology units were used?
- Was ZE taxiing performed for *both* departing and arriving flights? If not, why?
- What challenges were encountered? In what ways, if any, did the ZE technologies units underperform or fail to meet expectations?
- What specific operational changes were made to enable use of the ZE technologies? Did these operational changes result in any changes to the level of service that the airline was able to provide to its customers?
- What, if any, infrastructure adjustments were made to allow for ZE technologies use?
- Was ZE taxiing use limited to low flight-load time periods, such as off-peak hours? If so, what operational or infrastructure limitations prevented airports from performing ZE taxiing during high flight-loads?
- It is likely that all Taxi-bots deployed were powered by diesel-hybrid engines. If so, what additional challenges would be encountered at these airports if they replaced the diesel-hybrid units with electric or hydrogen fuel-cell units?

3. Selection of California airports

CARB and the contractor will mutually choose a group of example airports (4-5) to represent a variety of sizes, configurations, operational strategies, and specific zero-emission technology applications. For example, a possible combination might be Los Angeles International Airport, Sacramento International Airport, Ontario International Airport, and Redding Municipal Airport. The primary goal in selecting the set of airports is that every commercial airport in the state can be considered reasonably similar to at least one of the selected airports.

4. Operational and infrastructure assessment of California airports

The contractor must evaluate the present-day energy supply capabilities and procedural operations of selected California airports (Task 3) to determine the feasibility of ZE taxiing implementation.

A detailed study of each of these airport's operational procedures and current infrastructure must be assessed, and how the operations and infrastructure would have to change to accommodate zero-emission taxiing. It is important that proposed changes made to operations or infrastructure would neither decrease an airport's efficiency by slowing typical landing/take-off rates, nor negatively impact the routes or service of airlines operating at those airports (in adherence with the Airline Deregulation Act of 1978). This task can be divided into three parts:

A. First, for each airport the contractor must determine the Flight Percentage with Current Infrastructure, $\mathbf{FP_{CI}}$, here defined as the percentage of the current flights that could be taxied with ZE using the airport's current energy, space and runway infrastructure, requiring only modifications to airport operations. Knowing the energy requirements of market-ready ZE technologies based on determined characteristics in Task 1, the flight demand of selected airport, and the results of airport modeling (see Task 5), the contractor can determine the $\mathbf{FP_{CI}}$ for each of the selected CA airports.
B. Determine *specific operational modifications* that will need to be made for the airport to operate at its $\mathbf{FP_{CI}}$? Can each of these operational modifications be implemented without impacting airport efficiency?
C. Determine operational *and* infrastructure modifications needed to operate the selected airport's typical flight-load with ZE taxiing penetration at each quartile interval above the $\mathbf{FP_{CI}}$. E.g. Suppose the contractor determines the present infrastructure at LAX could support ZE taxiing for 38% of flights performed, so $\mathbf{FP_{CI}}$ for LAX = 38%. What infrastructure modifications and additional operational modifications would be required for LAX to achieve 50, 75 and 100% of flights taxied with ZE? For each modification made to each each quartile of penetration, determine impact on airport efficiency.

Note: The percent penetration should be based on the fraction of incoming and outgoing flights that are taxied with ZE, such that if 100% of all outgoing aircraft are taxied from the gate to the runway, but 0% of incoming flights are taxied from the runway to the gate, the percent penetration is 50%. It may be determined that ZE taxiing inbound flights is much more challenging than outbound flights. If this is determined to be the case by the contractor, they should separate the $\mathbf{FP_{CI}}$ into two separate parameters, $\mathbf{IFP_{CI}}$ and $\mathbf{OFP_{CI}}$ for incoming and outgoing flights, respectively. Additionally, each quartile of penetration percentage above the $\mathbf{FP_{CI}}$ will need to be divided into incoming and outgoing parameters as well.

The contractor should also address any additional technical challenges that may be encountered in reaching higher penetrations of ZET application.

The contractor's assessment of operational, infrastructure, and technical modifications in parts B and C of this task must address at least all elements listed below, as well as any additional elements the contractor deems necessary.

Operational elements to be addressed by contractor:

- Adjustments to pilot and flight checklists.
- Communication protocols or other standard operating procedures.
- Additional training needed by pilots, gate attendants, or tug operators.
- Additional staffing for tug operations.

- Modifications to air traffic control to accommodate change in airport circulation.
- Additional approvals needed by governing agencies (including but not limited to the Federal Aviation Administration) to allow operational changes.
- Address if any modifications could have any impact on routes taken by airlines during flight.

Infrastructure elements to be addressed by contractor:

- *Energy resources* – Is necessary electric power available for electrification technologies? Are there hydrogen storage capabilities if hydrogen power is to be used?
- *Space requirements* – Is there available space for charging locations or hydrogen storage? Will additional service roads along runways be needed for external tug units to transit while uncoupled? Are regions for tug-aircraft coupling/uncoupling available?

Technical - Some ZE technologies may only work on certain size or type of aircraft. How will that or other technical challenges factors limit ZE taxiing application?

5. Modeling of ZE taxiing at selected airports

For the selected California airports in Task 3, the contractor should construct a model that can simulate the real-time use of ZE units tugging aircraft from gates to take-off points on runways. An example of this type of modeling for using external tug units has been done by Yu Zhang and Joseph Post of the University of South Florida.[11]

The contractor should focus central modeling efforts on using ZE external tugs such as Taxibot at the selected CA airports. They may make some efforts modeling using onboard electric technologies such as WheelTug, provided that the cost benefit analysis, Task 6, of using WheelTug will make it feasible. The following data elements must be gathered by the contractor and used to inform the airport model to ensure accurate simulation of real-time flight taxiing:

- Runway layouts either from airport management or from an online map's aerial view. Based on these layouts, the contractor will identify:
    - Locations along taxiways and airport apron that could be used recharging electric ZE units.
    - Taxiways or service roads that can be used by electric tug when taxiing an aircraft and/or when driving uncoupled.
- Real-world flight data that details the arrival and departure rate of various size commercial aircraft, obtained from the FAA Aviation System Performance Metrics[12] or similar source. This data should include:

  - Arrival and departure times of flight of all incoming and outgoing flights.
  - The type of aircraft used for flight, to determine the type of tug needed.
- ZE unit charging rates if electric, acceleration rates, maximum speeds, braking times, and time to connect and disconnect the aircraft from the tug as determined in Task 1.

Using the above inputs, the contractor will construct a model that can output estimates of the following:

- The number of ZE units needed for the airport to sustain its typical operation at the ZE penetration percentage investigated. This number will be used to inform cost analysis in Task 6.
- The total electric load (kWh) and electric load as a function of time (kW) required for charging ZE technologies on a typical business day.
- The limiting infrastructure element at each quartile of ZE penetration.
- The impact on airport efficiency of using ZE tugs.

Modeling should be done in tandem with operations/infrastructure assessment (Task 3) as each will inform the other. The model should initially represent airports with their current resources and infrastructure to determine the $\mathbf{FP_{CI}}$ for each airport, and the number of ZE units required for that $\mathbf{FP_{CI}}$. Additionally, the contractor must report what specific infrastructure element of each example airport is limiting the $\mathbf{FP_{CI}}$ value. For example, the modeling may indicate the limiting element to be one of the following:

- Not enough space for charging units.
- Not enough spaces near runways to attach or detach tugs without hindering flight traffic.
- Limited service roads for tugs without aircraft to taxi on such that tugs interfere with other tug-aircraft traffic on the taxiways.
- Other infrastructure element.

After model runs are performed representing the current resources and infrastructure of each airport, the model must be modified to represent necessary infrastructure modifications to reach each penetration quartile above the $\mathbf{FP_{CI}}$, and the key model outputs listed above must be determined for each quartile. The results of this model should help to inform needed infrastructure modifications in Task 4.

If for any reason it is not possible to obtain 100% ZE taxiing penetration even with infrastructure modification within the model, contractor must detail the hindrances that prevent penetration from reaching 100%. Furthermore, for any ZE taxiing penetration level that cannot be reached while sustaining typical landing/take-off rates, the contractor must detail the encumbrances preventing airport efficiency from being maintained.

6. Cost analysis

The contractor must perform a cost analysis for each of the quartile penetration levels at each CA airport studied. For the cost benefit analysis, the contractor must address the capital cost/savings of the following:

- ZE technology equipment purchase, E.g. Taxibot units.
- Infrastructure installation such as charging locations, hydrogen storage facility.
- Construction costs for airport layouts change (if needed), including modifications to airport apron, taxiway, or runway areas.
- Operational costs (staffing, maintenance, and replacement). Fuel costs (such as electricity or hydrogen) and savings (such as jet fuel).

Finally, the contractor will group all commercial airports in CA as being most similar to one of the selected CA airports in the feasibility study. Using this airport categorization, and the results of the emission and cost analysis, the contractor will estimate the total cost investment at a statewide level.

A summary of information required for Tasks 4-6 for each CA airport investigated is shown in table below. Note: penetration percentages may not be as shown in table as they will depend on the $\mathbf{FP_{CI}}$ for each airport. Additionally, if it is determined that ZE taxiing between the gate and runway is substantially more difficult for either outgoing or incoming flights, the ZE penetration parameters should be split into incoming and outgoing portions, as discussed in Task 2. This would result in two of the below summary tables, one for inbound flights and one for outbound.

ZE Penetration:	FP_{CI}	**50%**	**75%**	**100%**
Infrastructure modifications:	NA	Detailed list	Detailed list	Detailed list
Limiting Infrastructure element:	Identify	Identify	Identify	Identify
Operation modifications:	Detailed list	Detailed list	Detailed list	Detailed list
Tugs required	Quantity	Quantity	Quantity	Quantity
Cost investment	Dollar Amount	Dollar Amount	Dollar Amount	Dollar Amount
Electric demand	Total (kWh) and vs time (kW)	Total (kWh) and vs time (kW)	Total (kWh) and vs time (kW)	Total (kWh) and vs time (kW)

7. Trial safety and risk assessment (SRM) panel

The contractor will organize and lead a trial SRM panel to determine major safety risks associated with taxiing aircraft with zero emission technologies and possible risk mitigation methods. The technologies discussed on the panel must include Taxibot, but may include other technologies as well. The panel may be held either in person or online and must include the CARB contract manager and at least one expert from each of the following organizations/offices:

- FAA Air Traffic Control
- FAA Flight Standards District Office
- Safety and Risk Management of a major CA commercial airline
- Safety and Risk management of a major CA airport authority
- The ZE manufacturer being discussed, e.g. Taxibot

Prior to the panel each attendee should be asked to compile their primary operational and safety concerns related to implementing ZE taxiing. The panel must convene for at least two hours or more. The agenda of the panel will be as follows:

- Discuss all operational concerns with implementing the ZE technology of interest.
- Determine all safety and risk concerns (SRC) associated with implementing the ZE technology of interest.
- For each SRC identified, rank risk in terms of level of danger and likely frequency of the SRC occurring.
- For each SRC identified, identify possible risk mitigation approaches that could be applied to minimize the SRC.

The contractor will detail all operational concerns, SRCs, associated risk rank, and mitigation approaches identified during the panel and include in an intermediate or final report given to CARB.

Methods and materials needed

We estimate that this project will require one year of time from 2-4 engineers to complete. It will also require access to a real-world flight data information as detailed in Task 5.

Schedule of completion of work/tasks

- Initiation of Contract: May 2, 2025

- Quarterly Reports:
    - 1st Quarterly report: Aug. 1, 2025
        - *Completed*: Task 1
        - Evidence of Progress: Tasks 2, 3, 7
    - 2nd Quarterly report: Nov. 7, 2025
        - *Completed*: Tasks 1, 2, 3, 7
        - Evidence of Progress: Task 4,5
    - 3rd Quarterly report: Feb. 6, 2026
    - 4th Quarterly report: May 1, 2026
- Final Report and Presentation:
    - Draft of Final Report: Aug 1, 2026
        - *Completed*: All Tasks
    - CARB provides Draft Report comments: Sept 1, 2026
    - Second Draft of Final report: Oct 1, 2026
    - CARB provides Second Draft comments: Nov 1, 2026
    - Presentations and Final report: November 30, 2026.

Products or deliverables:

Meetings

Prior to beginning the contracted work, the Contractor shall meet with the CARB contract manager and other CARB staff. The meeting location will be at CARB's offices in Sacramento, Riverside, or via teleconference and will cover the overall project plan, details of performing the tasks, the project schedule, items related to personnel or changes in personnel, and any issues that should be resolved before work can begin.

The contractor will participate in regular progress meetings with the CARB project manager and other CARB staff. It will be required for both the contractor's project manager and the engineers working for the contract to attend these meetings. These meetings will most likely take the form of telephone conferences. The contractor must plan to meet with CARB at least once a month for 1.5 hours. If CARB requests, more frequent or longer meetings may be necessary. The contractor should be prepared for open, two-way communication with the CARB project manager throughout the course of the project.

Quarterly Reports

The Contractor will provide quarterly electronic progress reports. These progress reports will discuss in detail the status of the project to date, the progress since the previous progress report, significant problems addressed during the quarter, significant problems to be addressed in the next quarter, and work planned for the next quarter. The quarterly progress report should also quantify the percentage of work accomplished to date and the percentage of budget used to date. Quarterly reports must have completed or show evidence of progress on specific tasks as specified in the schedule of completed work/tasks section above. The progress report should make a statement about any need to revise the schedule or budget class amounts to reflect changes needed over the existing schedule or budget. Templates for developing these documents will be available from the CARB contract manager.

Draft Final Reports

Four months prior to contract termination date, contractor will deliver the draft final report for review by CARB staff. After 1 month of review, CARB staff will provide feedback to the contactor for any edits. Two months prior to contract termination date, contractor will return a second draft of the final report to CARB. Again, CARB will have one month to provide comments or concerns to contractor. The contractor will then have one month to complete their final report and presentation. Together with the final report, the contractor will deliver a set of all raw and compiled data in a format specified by the CARB project manager.

Final Report and Presentation

After two rounds of edits over a four-month period, the contractor will submit their final report to CARB, and will hold a public workshop to present all the findings of the feasibility study. The workshop will be open for any stakeholders to attend and provide comments. Once finalized, together with the final report, the Contractor will deliver a set of all raw and compiled data in a format specified by the CARB project manager.

References

1. Contingency Measure Plan for 1997 Ozone Standard (aqmd.gov)
2. 2022_State_SIP_Strategy.pdf
3. Aircraft Tugs | eTT Series Electric Aircraft Tugs (eagletugs.com)
4. e-TAXI: Safran (safran-group.com)
5. WheelTug

6. Taxibot (taxibot-international.com)
7. ISO – Technology Readiness Levels
8. Schiphol taxibot trial
9. Frankfurt airport deploys taxibot
10. Air India to deploy TaxiBots - BusinessToday
11. Taxibot modeling report - Zhang & Post
12. FAA Aviation System Performance Metrics