New Southern Sky (NSS)
Collaborating to Reduce Emissions from Aviation

Report to Civil Aviation Authority of New Zealand

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Air New Zealand and Jetstar A320s waiting to depart, December 17, 2017 at Auckland International Airport. © Jordan Tan | Dreamstime.com used under licence.

Executive Summary

This report identifies enhancements to the current aviation system that would enable operators to reduce aircraft emissions at source.

Avoidable emissions are, in essence, waste from a production process, where aircraft are operated for longer than absolutely necessary to execute a flight. Waste occurs when aircraft are delayed in traffic congestion, or fly longer than necessary to make the journey. Solutions involve process changes which minimise air traffic congestion, and minimise flight time.

Benefits of minimising waste operating time include an estimated annual savings at Auckland and Wellington airports of 6,000 to 9,000 tonnes of CO_2, and $7M to $10M in aircraft direct operating costs. There are reasonable expectations of additional gains from ongoing process improvement and at other locations.

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Minimising Air Traffic Congestion

Minimising air traffic congestion requires operating processes which moderate the density of air traffic at capacity bottlenecks. Doing so efficiently requires ground delay processes which hold aircraft prior to engine start. When airborne, flights have limited ability to efficiently absorb delay. To minimise congestion, ground delays are therefore essential. Because both arrival and departure traffic flows share the runway capacity at New Zealand's essentially single runway airports, the ground delay process needs to manage both the inbound and outbound flows of traffic to optimise the use of capacity.

Ground delays, when correctly sized, do not necessarily affect aircraft arrival times. In principle, they efficiently transfer delays which would otherwise occur when the aircraft is moving, to a pre-departure time when the aircraft engines are off and emissions are minimal.

An effective ground delay process would deliver additional benefits, including better use of airport capacity, reduced overall delays, and improved on-time arrival performance. Traffic flows improve in the absence of congestion. Further, peak flow through capacity bottlenecks can only be achieved in the absence of congestion. Both factors reduce overall delays. A ground delay process which is schedule-aware would be in a position to ration delays between flights in ways that optimise on-time arrivals. An effective ground delay process thus improves environmental outcomes, airport throughput and punctuality for scheduled flights.

Realising these benefits requires increased precision in the pre-departure process. The process of readying aircraft for departure is well known for variability and uncertainty. Yet, international experience shows that aircraft readiness timing can be predicted from the sequence of flight status events leading up to that point, including from upstream airports, with adequate precision for ground delay planning. Actual departure timing can then be managed with sufficient accuracy by controlling the flight's start request time. Overall, the process enables airline, airport and gate agent operations to collaboratively deliver ground delays precise enough to address the needs of congestion management.

The pre-departure ground delay process is essentially an airport-centric business process. Airlines and airports are the actors, have the required data, and the business interest in the resulting environmental and punctuality benefits. As a business process, the ground delay system might be created as an airport/airline collaboration using contemporary commercial technologies to deliver business benefits at a pace not normally available in the safety sphere.

Minimising Flight Time

Changes to the current PBN navigation infrastructure to reduce flight time include shorter or more optimally aligned approach and departure procedures, and more direct en route flight paths.

The current en route structure combined with approach and departure procedures creates a seamless system from origin to destination runway. The system incorporates strategic separation between opposite direction traffic, and between climbing and descending traffic approaching or departing aerodromes. The strategic separation design creates some indirectness in certain flight paths.

More direct flight paths may reduce flight time, but may also increase the need for ATC intervention and aircraft manoeuvring, offsetting some of the efficiency gains. Fast time simulation may be needed at the design stage to balance reduced flight path length against increased ATC workload and the added emissions resulting from any required interventions.

The current PBN approach and departure procedures are based on a standardised template and designed for general use. The procedures are the minimum reasonable size to provide reliable and stable approaches given the ICAO design rules. Reducing approach and departure procedure lengths is likely to require using more advanced aircraft capabilities. Options for improved procedures include using curved segments (radius to fix (RF) legs), precision approaches using satellite-based augmentation system (SBAS), or for suitably equipped fleets, required navigation performance – authorisation required (RNP-AR) approaches. Designs may need to trade off or choose between reducing flight path length, and reducing minimum approach heights (these may reduce the frequency of diverted flights in poor weather). Benefits are likely to be more reliably delivered at lower traffic airports where ATC vectoring is less frequent.

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Glossary

A-CDM Airport Collaborative Decision-making

AMAN Approach Manager

ANSP Air Navigation Service Provider

ATC Air Traffic Control

ATS Air Traffic Services

ATFM Air Traffic Flow Management

Block Time Flight duration from "off blocks" at departure gate stand to "on blocks" at destination gate stand.

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CANSO Civil Air Navigation Services Organisation

CAM Collaborative Arrivals Manager

CDM Collaborative Decision-making

CTOT Calculated Take-off Time

DMAN Departure Manager

DMAP Divergent Missed Approach

EOBT Estimated Off Blocks Time

ICAO International Civil Aviation Organisation

PBN Performance Based Navigation

RECAT Revised Wake Turbulence Category

RNAV Area Navigation

RTA Required Time of Arrival

TOBT Target Off Blocks Time

TSAT Target Start Approval Time

TTOT Target Take-off Time

Introduction and Purpose

Purpose

This report aims to identify opportunities to reduce carbon emissions from aviation. It is accepted that the need to reduce anthropogenic GHG emissions is real and urgent. Where practicable this report identifies those emissions reduction opportunities that are independent of aviation safety and can be implemented using commercial means for business benefits at a pace not normally available in the safety sphere.

Scope

The focus of the report is on reducing emissions at source through revised operating processes. This report addresses operating processes at the strategic and tactical operational levels which would reduce emissions, including performance measurement, changes to operating processes, decision support technologies, and changes to navigation infrastructure.

The scope does not include non-operational means toward net zero emissions, and excludes considering the use of more efficient aircraft, fuel substitution (hydrogen or electric propulsion), sustainable (net zero carbon) aviation fuels, or the use of emissions offsets.

National Context

Response to Climate Change

New Zealand's Climate Change Response (Zero Carbon) Amendment Act 2019 "aims to contribute to the global effort under the Paris Agreement to limit the global average temperature rise to 1.5°C above pre-industrial levels by reducing net emissions of greenhouse gases (GHG) other than biogenic methane to zero by 2050" ('net zero goal'). Emissions budgets for each four-year period leading up to 2050 are to be set, with the first three periods set by May 2022[1].

The Climate Change Commission's evidence report notes that "early actions to help reducing emissions in air travel includes improvement on airspace operations and infrastructure efficiency with collaborations between airlines, airports and air traffic management." [2]. In the Commission's first advice to government the demonstration path assumes further improvements in aviation efficiency from this collaboration. In response to the commissions advice, the all-of-government Emissions Reduction Plan (ERP) is being prepared for consideration by Cabinet and public consultation.

This report addresses ways in which the aviation industry might reduce emissions, in particular by collaboratively improving processes that otherwise lead to avoidable wastes.

Existing Capabilities

The NSS programme has delivered significant efficiency gains. The current system includes:

- Performance based navigation (PBN) Navigation Infrastructure:
  - Area navigation (RNAV) approach and departure procedures of minimised size at airports with scheduled air services
  - Parallel one-way routes, close to direct between frequently used airport pairs
  - Short "required navigation performance – authorisation required" (RNP-AR) approaches at several locations for operators with the required capability
- ADS-B surveillance with expanded coverage outside controlled airspace
- Independent air traffic flow management (ATFM) regulating the flows of arrival traffic at Auckland, Wellington, Christchurch and Queenstown
- En route flight timing and approach sequence management for flights to Auckland using Airways approach manager (AMAN) system
- Elements of airport collaborative decision-making (A-CDM) infrastructure at Auckland and Wellington, intended to manage departure traffic flows. At present no formal decision-making process to regulate departure flows is in place.

Inefficiencies remain. This study seeks to enhance and leverage the existing system, in line with the climate commission expectations, using collaboration between airports, airlines and air traffic management to improve operational efficiency, and potential navigation infrastructure enhancements to reduce flight times.

[1] (New Zealand Government, 2019) sections 5Q and 5X(3)

[2] (New Zealand Climate Commission, 2021a) Chapter 4b, p 18

Approach

This report takes a waste reduction approach, adopted from "lean" production process thinking (Appendix A). Lean thinking aims to remove wastes from processes, where waste is defined as "any action or step in a process that does not add value to the customer"[3].

For the purposes of this study, customer value is defined as

Customer Value: On time arrivals with minimum aircraft emissions

Avoidable aircraft emissions are, in essence, waste from a production process. Aircraft delayed with engines running, or flying longer than necessary flight times, produce unnecessary emissions whilst simultaneously not progressing toward their destination.

Including the on-time performance objective brings additional benefits. It improves the customer experience. Improved schedule adherence increases the financial returns from emissions reduction processes, possibly substantially. It also increases airport capacity. By moving away from first-come-first-served capacity rationing, runway capacity can be optimised to increase throughput.

Reducing waste also makes a wider contribution. It reduces the offsets required to achieve net zero emissions and reduces the energy required for flights powered by other energy sources.

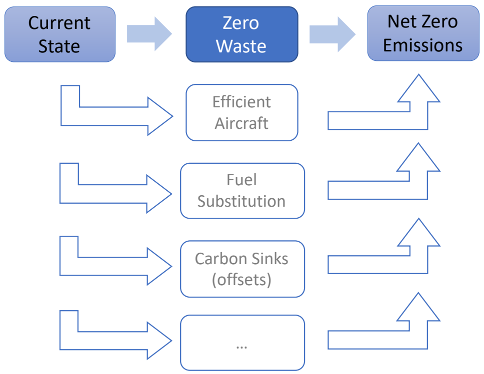

Figure 1 Waste Reduction Contributes to Other Emissions Reduction Initiatives

Limitations and Assumptions

All of the opportunities identified in this report create *marginal* gains by reducing the energy intensity of flight operations. Whether a net absolute reduction in carbon emissions occurs depends on the effectiveness of other carbon emissions mitigations, and the size of counter-acting growth in emissions resulting from an increase in aviation activity.

The terms of reference for this report exclude accurately quantifying benefits or providing definitive guidance on when any future benefits may be delivered. It is scenario based and indicative only. It does draw on previous benefit studies to illustrate the general scale of the benefit opportunity and to identify the areas where improvements would be most beneficial. It assumes that any implementation plans would start with quantifying the benefits and developing the most effective opportunities in order of greatest impact.

[3] (Skhmot, 2017)

Overview

Avoidable waste emissions occur when flights are delayed with engines running or incur longer than optimum flight times

Identifying Sources of Waste

Waste emissions can be identified by comparing current operations with the ideal flight. An ideal flight would operate as efficiently as possible from gate to gate. The system would enable an aircraft to fly the minimum *air miles* between origin and destination, with no delays due to traffic congestion queues.

Within the limitations required for clearance from terrain, obstacles and other airspace an ideal flight would:

- taxi without delay to the runway,
- take-off and turn toward its destination at the earliest safe height,
- fly a route toward the destination that minimises fuel burn (this may not necessarily be direct if it takes advantage of reduced headwinds),
- make a turn onto the final approach at the minimum safe height and distance from the runway consistent with ensuring a stable approach,
- land and taxi without delay to its gate stand, which would be unoccupied and ready to receive the flight, arriving on time.

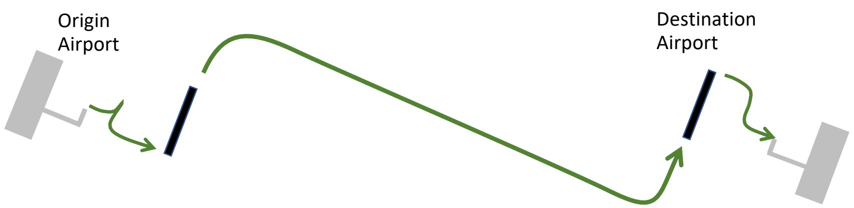

Figure 2 The Ideal Flight

Waste emissions occur when flights diverge from this optimum, either by being delayed in traffic congestion or by flying for longer than the optimum flight time.

Minimising Waste Emissions

Problem domain

- Waste occurs when aircraft are delayed with engines running during taxi-out, when airborne in dense traffic, or on taxi-in.
- Taxiing delays can occur due to surface movement traffic congestion, while waiting during taxi-out for runway access, or during taxi-in while waiting for a prior departure to clear the assigned gate stand.
- Airborne delays occur when aircraft queue in traffic congestion at capacity constraints. In New Zealand there is little evidence of airspace capacity constraints. Most air traffic congestion occurring approach, where arrivals conflict with each other and with departures for access to runways.
- Waste also results from suboptimal flight paths adding air miles to the journey.

Solution space

- Optimising flight paths requires optimising approach and departure procedures, and enabling minimum duration routing.
- Minimising congestion at affected airports requires processes which reduce air traffic density to within the airport capacity, enabling traffic to flow freely.
- Flights between two capacity constrained airports can be optimised by coordinating between the two the airport flow control processes, to align the flight with demand at both origin and destination runways.

Enabling strategies

Minimising congestion requires addressing complexity and fragmented decision-making resulting from incomplete data, isolated processes, or multiple systems. Two strategies are useful:

- "Lean" process thinking. The lean waste reduction philosophy includes reducing process waste by working only to the quality needed, avoiding having multiple systems, and by using the expertise of front-line people to refine processes.
- Collaborative decision-making (CDM) using shared, relevant information to enable stakeholders to collaborate and make context-aware decisions.

Overview

Minimising waste due to air traffic congestion requires managing traffic density and absorbing delays more efficiently. Benefits include reduced emissions, improved use of capacity, and improved on-time performance

Minimising Waste from Air Traffic Congestion

Waste emissions arise from delays created by excessive traffic density

- Congestion at capacity constraints occurs when air traffic density would reduce aircraft spacing below the required longitudinal separation distance (Appendix C).
- When minimum separation limits are reached, aircraft must wait behind traffic ahead. On the ground, aircraft slow or stop and wait. In the air, aircraft must slow if possible, or extend their flight path either in a holding pattern or by flying off route. Flights on different inbound routes, even if well separated, may also need to wait if they would become too close to aircraft ahead once traffic streams merge to approach the destination runway.

Efficient delay absorption avoids waste emissions

- Minimising waste emissions requires efficiently absorbing the delays caused by capacity constraints, using means that do not add emissions over and above that of an unimpeded flight. Delays can be absorbed on the ground before start-up without creating emissions and, to a limited extent for some flights, delay may be efficiently absorbed airborne by reducing the aircraft speed.
- A system to minimise emissions during delays thus requires just two processes: **pre-departure ground delay**, and **airborne timing control**. Figure 3 illustrates the experience from an aircraft point of view. In the alternative, absent effective traffic density controls, aircraft would instead experience the same delays wastefully in traffic congestion on the ground and airborne.

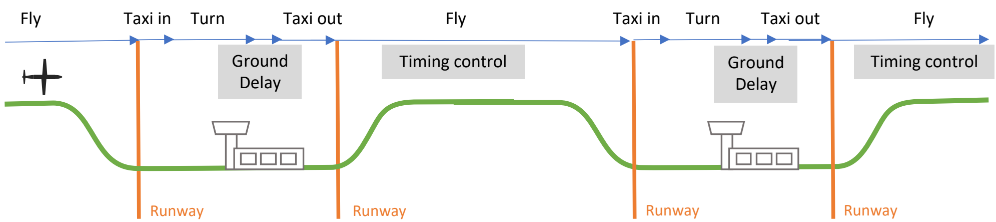

Figure 3 Life of an Aircraft in a Flow Controlled Environment

[4] (Air New Zealand, 2020)

Environmental and On-time performance Benefits

Emissions Reduction Benefits

- Previous studies have measured emissions from taxi delays at Auckland and Wellington, and airborne delays approaching Auckland. Conservatively, estimated waste emissions on taxi-out were about 6,477 tonnes of CO_2, and at least 6,965 tonnes from airborne delays. It is reasonable to assume additional wastes at other airports in proportion to traffic congestion levels (Appendix B).
- Initial estimates show that optimising traffic density may reduce these wastes by 6,000 to 9,000 tonnes of CO_2 annually (Appendix D). These benefits have a similar magnitude to Air New Zealand's carbon reduction programme, which has saved between 10,000 and 15,000 tonnes of CO_2 in each of the last few years[4], and the estimated 4,182 tonnes of CO_2 saved annually by the NSS PBN programme[5].

Airport Capacity and On-time performance Benefits

- Both traffic flow theory and empirical measurements of air traffic in New Zealand show that peak traffic flows can only be achieved in the absence of congestion (Appendix C). Controlling congestion therefore can be expected to increase throughput at capacity constraints, and reduce flight block times.
- At New Zealand's single runway airports, departure and arrival traffic flows affect the capacity available for each other by up to 50%. Managing both flows of traffic in a single ground delay process would optimise use of runway capacity, increasing throughput and reducing delays (Appendix E).
  - On-time performance could be further improved by moving capacity rationing away from first-in-first-served to schemes which ration by schedule, For example, ground delays could be reduced for flights facing headwinds or risking running late. Any scheme that ensures that traffic density is controlled within capacity constraints would minimise emissions. The greatest financial and customer service benefits would result from operating practice that focusses on **maximising on time arrivals.** Financial benefits may exceed those from emissions reduction (Appendix B).

[5] (Acuo, 2018)

Overview

Maximum benefits would be realised by an airport centric pre-departure ground delay process

Delay Absorption Strategy

Aircraft in flight have limited ability to absorb delay efficiently.

- Typically, aircraft can only efficiently absorb delays in the order of about 5% (2-4 minutes/hour) by slowing down. Air New Zealand advise that A320s flying at Mach 0.78 may be able to slow to Mach 0.72 (8%), but significant savings can only be realised in the climb and cruise phases of flight before top of descent, after which aircraft ideally will descend at flight idle with low fuel flow.
- Many individual flights may be less flexible. Aircraft flying at cost index zero (maximum trip fuel efficiency) cannot change speed at all without increasing the total flight fuel burn[6]. For aerodynamic reasons, aircraft that are heavy and high can have a very limited ability to change speed at all.
- The short flight duration of most domestic flights in New Zealand mean that very little time can be absorbed efficiently in flight, if any. In practice, research finds that flight departure times must be managed by ground delays first so that any remaining airborne delays are in a small, feasible range[7]. Uncertainty in wind forecasts and the limits of precision of airborne delay controls mean, for minimum waste, all but approximately 1-3 minutes per flight hour of delays need to be taken on the ground.

Ground delay is considered essential as the primary means of minimising waste.

- Ground delay is ultimately efficient. Aircraft absorb congestion delays with engines off, minimising emissions.
- Ground delay is effective. Aircraft can be held for arbitrarily long periods if required[8]. Only ground delay is capable of fully absorbing congestion delays.
- Ground delay is the only option for reducing taxi-out wastes.
- Ground delays can be applied both to arriving and departing flights to manage the whole of congestion created by runway/airport capacity constraints.

Airport Centric Ground Delay Process

From the foregoing, minimising waste emissions from flights operating through an airport subject to air traffic congestion could largely be realised using a single process: a coordinated means of **managing flight start times** using ground delays.

The requirements of a ground delay process that would realise the efficiency, capacity, and punctuality benefits include:

- For efficiency, manage traffic density at capacity constraints to ensure largely free flowing traffic. The rate limiting factor is generally runway capacity. Applied ground delays should minimise queueing for the runway.
- The most influential factor on runway capacity is the balance between arrival and departure traffic flows (Appendix E). To make best use of runway capacity, the ground delay process needs to coordinate both arrival and departure flows jointly.

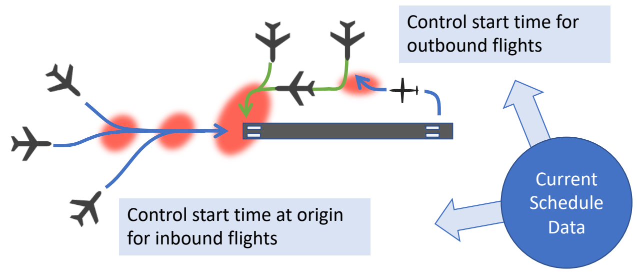

Figure 4 Airport Related Capacity Constraints and Ground Delay Controls

- To optimise punctuality, delay allocation decisions would need to take schedule adherence into account. This means the delay decision-making process must have access to current schedule data, and the engagement, buy-in and guidance from stakeholders to be trusted to deliver fair and equitable results.

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6 (Roberson, 2007)

7 (DeSmedt et al., 2015)

8 The duration of ground delay at a gate stand is limited by the need for a subsequent flight to use the occupied stand. Previous work (Mahino Consulting, 2019) found that less than 3% of flights at Wellington and Auckland could not wait for the necessary time at the stand. In these cases, efficient options exist, including simply allowing flights at busy stands to depart as a priority, or towing the aircraft to a holding point away from the stand.

Overview

A staged decision-making framework enables efficiency processes to exploit normal uncertainty and variability in operations.

Staged Decision-making Framework

In practice, uncertainty dominates planning.

- Flight durations are unlikely to match schedules. Actual flight durations on a route typically may vary by up to 20% from schedule (12 minutes/hour) due to the varying effect of head or tail winds on the day of operations.
- Flight durations also diverge from planning estimates. Residual uncertainty in weather forecasts, and the speed variation due to variations in aircraft loaded weight, mean that flight durations can differ from estimates used in air traffic flow planning, typically in the order of 1-2 minutes per hour.
- In contrast, the timing required during operations, to maximise the use of capacity, is an order of magnitude more precise than can be achieved pre-departure. Air traffic controllers merging flights on approach with a variability of 0.3nm (10% of capacity when 3nm separations are in place) at a nominal approach speed of 135kts are working to a precision of 13 seconds. The author has observed accomplished controllers consistently attaining a variability within 0.2nm (9 seconds).

Two techniques can bridge the gaps in planning capability at each stage. The uncertainties can be exploited to optimise air traffic flow control processes, and a staged planning framework can progressively refine air traffic demand to match the capabilities and limitations of each subsequent stage.

- Airlines typically schedule to achieve about 85% statistical on-time performance in the long run. This means that most flights have a little slack between scheduled departure and arrival. The ground delay process can exploit this slack to apply delays for efficiency without necessarily risking late arrivals.
- Conveniently, residual uncertainty at the ground delay planning stage approximately matches the capability of the air traffic control process to efficiently delay aircraft in flight (1-3 minutes/hour). This means that sufficiently precise ground delays may improve the ability of ATC to sequence and time flights efficiently.

ICAO guidance material in "The Asia/Pacific Seamless ANS Plan"[9], "The Asia/Pacific Framework for Collaborative Air Traffic Flow Management"[10], and "The Asia/Pacific Airport Collaborative Decision-making (A-CDM) Implementation Plan"[11] describe a four-stage collaborative decision-making framework. The stages correspond with the step change in uncertainty and planning capability between scheduling, ground delay, and tactical operations, and create clear roles and objectives for stakeholders at each step.

The stages are defined as:

- Strategic — Schedule creation, prior to weather forecasts being available
- Pre-tactical — In the 30 or so hours prior to flight when planning is more certain because weather forecasts are increasingly reliable and the progress of flights to the current time is known.
- Tactical — During aircraft movement under the control of ATC
- Post-operations — Periodic reviews of results to continuously improve processes

Decisions at each stage in the framework prepare air traffic demand for the capabilities of the subsequent stage. In this context, ground delay is a pre-tactical process, acting before aircraft move. Its objective is to meter air traffic demand such that the ATC processes can control flight sequencing and timing efficiently.

Stage	Purpose	Decisions by
Strategic	Set schedules for desired on-time performance	Airlines
Pre-tactical	Decide ground delays to minimise emissions and optimise on time arrivals	Collaborative
Tactical	Sequence and time flights for best use of capacity	ATC
Post-operations	Review decision-making processes for continuous improvement	All

Table 1 Collaborative Decision-making Framework

9 (ICAO, 2019b)

10 (ICAO, 2017)

11 (ICAO, 2019a)

Overview

Ground delay and ATC processes have distinct and complementary contributions to airport and network flight efficiency

Ground Delay Process and ATC Process Collaboration

The collaborative decision-making framework identifies two processes which work together to minimise emissions: pre-departure ground delay, and tactical ATC.

- Given the limited capability of airborne delays to efficiently reduce congestion, **the majority of congestion delays must be minimised by the pre-departure ground delay process.** The ground delay process primarily has the role of minimising air traffic congestion by regulating demand. The result is a reduction in emissions, and a contribution to minimising delays by enabling free flowing traffic, and optimising runway capacity.
- ATC, controlling all aircraft movements, are in a position and have the expertise to optimise throughput by sequencing traffic for best effect and, to a limited extent, adjust flight timing. ATC primarily have a role in maximising the use of capacity. The result is a reduction in flight delays, and a contribution to efficiency.
- Taken together the two stages would minimise emissions in a complementary way. Ground delays can regulate demand in bulk, with a precision in minutes. After a start request from the flight crew indicating readiness to move, ATC can organise traffic sequencing and clear flights to move as required with precision in the order of seconds. The outcome both minimises emissions and maximises the use of capacity, reducing overall delays.

Ground Delay and ATC Integration

Currently, the hand off between ground delay and ATC processes occurs when flight crews request a start clearance. There are benefits to retaining this interface.

- At present, Airways ATFM system (CAM) assigns ground delays to flights destined for Auckland, Wellington, Christchurch or Queenstown, Flight crews are responsible for organising the flight to meet a timing window around the take-off time calculated by CAM, and request a start clearance accordingly.
- The pre-departure process for A-CDM, intended to manage taxi-out delays, also assigns ground delay to pre-organise start/pushback timing, and advises crews a target time to request a start clearance.
- Actual aircraft movement sequence and timing are controlled by ATC once a start request is received. ATC processes generally handle flights tactically on a first-in-first-served basis after the crew request a start clearance providing that the aircraft is within a reasonable number of minutes of its assigned timing[12].

Lean wastes include wastes caused by working to higher quality or tighter tolerances than required (Appendix A). Applied to the ground delay and ATC processes:

- The simplicity of this interface enables the pre-departure ground delay process and ATC process to develop independently and play to their strengths. By using the flexibility between start request (from the ground delay process) and start clearances (from the ATC process), the pre-departure ground delay process can work to an accuracy of a few minutes and the ATC processes can increase the precision to an order of seconds while simplifying both processes.
- The ground delay process would manage traffic density in the large, without needing the level of detail that ATC processes require to finely sequence and time aircraft movements. At the same time, the ATC process would be relieved from the complexity of constant replanning imposed by the uncertainties and variability of the pre-departure processes, and deal only with realised tactical demand.

Inter-Airport and Cross-Border Coordination

The decentralised, airport centric system is readily extensible inter-airport and cross-border. It is consistent with the ICAO Asia-Pacific flow management concept of a "distributed multi-nodal ATFM network", which envisages coordination between airport centric flow management systems to achieve flight efficiency across the region without any central network management function[13]. To manage flights between capacity constrained airports subject to air traffic congestion:

- Negotiation between two airport ground delay processes would align the flight timing to minimise congestion at both origin and destination.
- Coordination between ATC units would enable en route timing controls (in an efficient range) to deliver the flight efficiently into the ATC assigned slot in the arrival sequence at the destination.

[12] To enable ATC planning, flight plan EOBT, or another agreed method of indcating ground delay, needs to be communicated to ATC.

[13] (ICAO, 2017) 1.5 p1

Overview

Ground delay distribution affects capacity and punctuality. Stakeholder priorities need to guide ground delay allocation

Schedule adherence and ground delay process performance

Ground delays transfer congestion delays from wasteful waiting during aircraft movement to efficient waiting beforehand, minimising emissions. Appropriate ground delays would not necessarily alter arrival times; however, some improvement should occur as free flowing traffic enables maximum use of capacity (Appendix C).

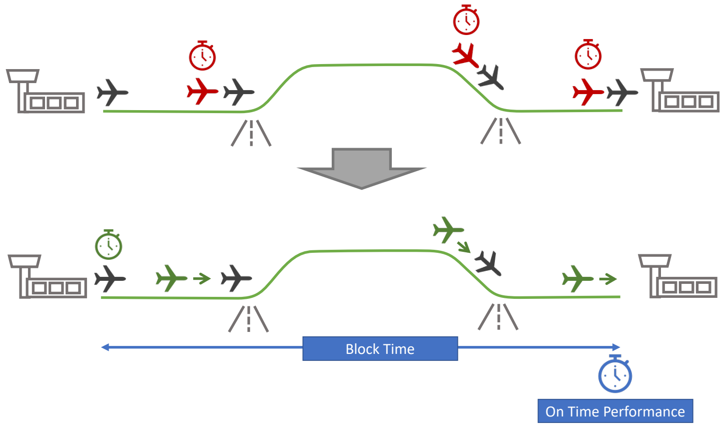


Figure 5 Inefficient waiting in congestion is transferred to efficient ground delay

The ability of the ground delay process to alter flight timing gives stakeholders an opportunity to realise additional benefits in improved block times and punctuality.

Improving Runway Throughput

- Other than severe weather, such as fog conditions, the most significant factor affecting throughput at New Zealand's single runway airports is the balance between departure and arrival flows.
- A ground delay process that simultaneously managed the flow of both arrival and departure traffic is in a position to optimise the arrival/departure balance and therefore help maximise runway throughput.
- Increased throughput at the runway would reduce overall delays. This may improve punctuality, but may also result in some transfer of delay between arriving and departing traffic.

Delay transfer between flights

- As well as transferring delays to adjust the arrival/departure balance, the ground delay process is able to transfer delays between flights generally. Stakeholders may wish to consider using this capability to improve arrival punctuality.
- Although appropriately sized ground delays will maximise efficiency regardless, rationing runway capacity on a first-come-first-served basis may produce a suboptimal result for throughput and punctuality. Evenly distributed ground delays would disproportionately affect flights with less schedule slack in the circumstances. The amount of schedule slack available for each flight will depend on the timeliness of the flight's readiness for departure, the net headwind on the route, and the configuration of origin and landing runways.
- When airports are configured to use duty runways not aligned with the route, additional track miles are consumed in the departure and arrival procedures. On shorter flights, the additional flight time may be significant. For example, in northerly conditions, flights travelling south from Wellington to Christchurch must take-off and land toward the north. They can incur an additional 15-20 nm in both the departure and arrival procedures, adding perhaps 40nm to a trip between airports 164nm apart.
- Stakeholders may wish to consider what policy should be applied to the distribution of ground delays amongst various flights. Biasing ground delay away from flights which have minimal schedule slack, without making other flights arrive late, could enhance punctuality, capacity, and recovery from disruption.

Delay allocation policy and performance management

Schedule adherence and capacity rationing affect the airline and airport business, product and customer experience. The cost of late running can be significant. The post-operations and strategic CDM process stages could review both the ground delay and scheduling processes on efficiency and punctuality criteria.

- Flight Efficiency: Is traffic free flowing (minimal extended taxi time /flight paths)?
- Schedule Adherence:
  - Capacity. Is capacity fully used (peak flows near capacity)?
  - Punctuality. Are delays distributed optimally?
  - Schedule / Capacity balance. Is demand within capacity in the first place?

Overview

Capacity improvement initiatives may be insufficient to mitigate congestion. Flow management is essential to reduce emissions

Why not Just Increase Capacity?

The onset of congestion occurs when traffic density pushes aircraft up against the longitudinal aircraft separation requirement at the time (Appendix C). It can be tempting to pursue increasing capacity in the hope of improving flight efficiency, however caution should be exercised. Our view is that capacity increases are unlikely to sufficiently address waste emissions for several reasons.

- The marginal time savings that capacity improvement initiatives make are insufficient to mitigate congestion. Congestion delays are relatively long, but time savings from capacity improvement initiatives are relatively short.
  - Taxi out delays are up to tens of minutes per affected flight
  - Approach delays are up to several minutes per affected flight[14]
  - Many separation reduction initiatives – such as reduced runway occupancy, reclassified wake turbulence separations, or throughput increases by sequencing traffic or using time base separations – create benefits in the order of seconds per flight
- Capacity increases do not address the root cause of congestion. Congestion results from excessive traffic density, whereas capacity increases improve the maximum traffic flow (movements/hour). To increase flight efficiency, traffic density must be controlled.

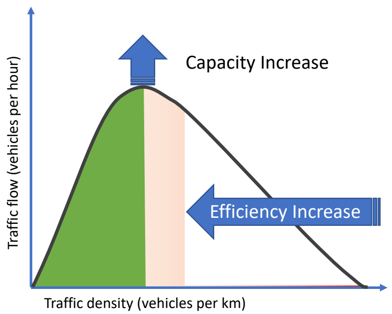


Figure 6 Distinguishing Between Capacity and Efficiency Improvements

- Without flow control, nothing prevents unconstrained traffic from bunching. Regardless of the ultimate capacity, traffic congestion can still occur. To ensure that waste emissions from congestion are mitigated, flow controls are essential.

Benefits of Increased Capacity

- Increased capacity enables a higher peak flow of traffic. The potential increase in flights per hour increases scheduling flexibility and enables more intense scheduling to service travel demand.
- The emissions reducing effect of capacity increases may be moot. Given the same level of traffic, capacity increases may create a marginal emissions reduction. Whether a net reduction in emissions occurs depends on whether the total quantity of traffic changes. If more flights are added to flight schedules, taking advantage of increased capacity, emissions will rise.
- Nonetheless, relatively small capacity increases may have an amplified efficiency benefit at peak times. Delays compound along a convoy of aircraft at minimum spacing. Small capacity improvements similarly compound to create an amplified benefit, depending upon the number of aircraft in the convoy.

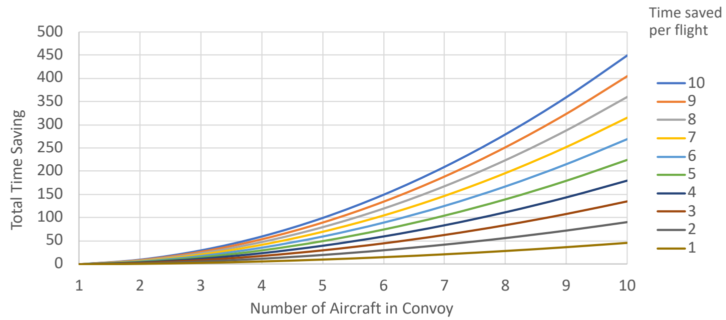


Figure 7 Effect on Convoy of Capacity Increase

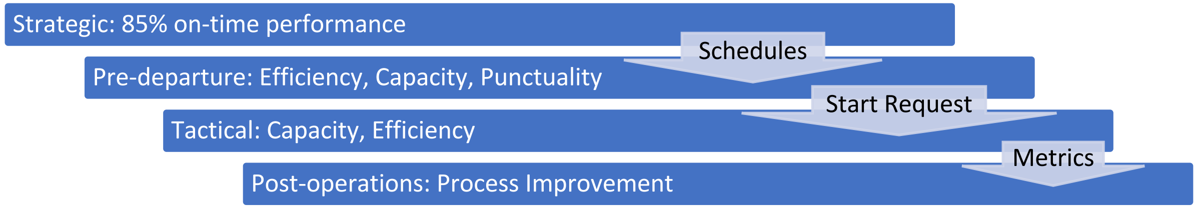
Appendix C distinguishes between capacity and efficiency improvements more fully, including differentiating their benefits, and identifies metrics that would aid management decision-making when selecting performance improvement investments.

[14] Queenstown airport is a possible exception, with greater per-flight delays. Because of the long occupancy time of the single-user segment of the approach, inbound aircraft waiting for the approach incur more lengthy approach delays.

Overview

Observations and Conclusions

Theme	Observations	Conclusions
Flight Efficiency	• Ground delays can efficiently absorb time delays resulting from air traffic congestion. • There is minimal ability to efficiently absorb delays airborne • Increasing capacity (peak traffic volume capability) is not sufficiently effective to mitigate congestion delays	• An effective ground delay process is the primary means of maximising flight efficiency.
Airport Capacity	• Waste emissions resulting from air traffic congestion are concentrated around airport capacity constraints, of which runway capacity is dominant • Runway capacity is strongly affected by the interaction between arrival and departure traffic flows	• An airport ground delay process could improve both flight efficiency and airport capacity by managing both arrival and departure flows in a coordinated manner.
Arrival Punctuality	• Delays resulting from capacity constraints can adversely affect punctuality • The ground delay process can transfer delays between flights	• Ground delay decisions could improve on time arrival performance. • Optimal ground delay decisions would consider the effect on punctuality.
Staged decision-making	• Optimising the use of capacity requires precise timing in ATC processes. • Weather forecast and operational uncertainties limit the precision of ground delay planning.	• The pre-departure ground delay process and ATC processes can be de-coupled by using the natural "firebreak" that occurs at the point where aircraft request start clearances. ATC can give a precise instruction in response to a start request that is reasonably timed on advice from the (pre-departure) ground delay process.
Network	• Flights between capacity constrained airports need to conform with ground delay processes at both airports	• Airport ground delay processes could coordinate with peers to ensure flights between them operate efficiently at both airports.
Performance	• Efficiency, punctuality, and peak flow capacity can be directly measured. • Efficiency and throughput are affected directly by the ground delay process • On time arrival performance is limited by schedule/capacity balance.	• Post operations reviews enable stakeholders to tune system policy and performance. • Scheduling/Capacity balance would be informed by these reviews.



Airport Pre-departure Ground Delay Process

Ground delay process capabilities include predicting runway demand, rationing runway capacity, and advising actors

Overview

The task of the airport pre-departure ground delay process is to predict and then manage runway demand. At the overview level, the process needs to:

- Predict the time at which aircraft will be ready to depart, and the time required to get to the runway (including taxi time and, for arrivals, flight time),
- Predict runway capacity and allocate runway timing to flights, delayed in accordance with stakeholder priorities if necessary to manage traffic congestion,
- Calculate the optimum start request time and transmit it to crews.

The process has a continuous, real-time character, rather than being periodically pre-planned. The normal variability and unpredictability of operations both on the ground and in the air mean that both demand prediction and runway allocation must be continuously revised in real time as events unfold. Doing so allows the plan to respond to events.

To realise the potential environmental, punctuality, capacity and network benefits, the pre-departure ground delay process needs to:

- Manage both arrival and departure traffic.
- Communicate with stakeholders to enable aircraft to meet the required timing.
- Operate to a precision of very few minutes. The efficiency limitations of airborne delay mean that the ultimate environmental performance of the system as a whole, particularly for shorter flights, depends on the precision that the ground delay process can achieve. Increasingly precise operations will be necessary to improve on the current system performance.
- Consider arrival time punctuality when allocating ground delays.
- Coordinate with downstream airports regarding flights to a flow-controlled destination.

Current Ground Delay Processes

Two independent processes are currently intended to manage ground delays. Airways collaborative arrivals manager (CAM) controls ground delays for arrivals. Airport A-CDM processes are intended to manage ground delays for departures. Each use different means to predict demand, allocate capacity and coordinate flight timing.

Process	Predicting Demand	Runway planning	Start request timing
CAM (arrivals)	Flight readiness time is presumed to be the ATC Flight plan estimated off blocks time (EOBT)	Controlled time of arrival (CTA) is assigned automatically on a first-in-first-served basis in priority order of international arrivals, domestic jet flights, then domestic turboprop flights.	Calculated take-off time (CTOT) at origin is advised to crews. Pilots of arriving flights are required to adjust their departure process in order to depart within 5 minutes of CTOT[15]. Flight crews must estimate required taxi out time.
A-CDM (departures)	Flight readiness time is presumed to be the target off blocks time (TOBT) manually entered by gate agent or airline	Informal. The departure sequence is determined manually by the airport control tower.	Target start approval time (TSAT) communicated to airport systems. Flight crews are expected to request start approval at or soon after TSAT.

Table 2 Current Ground Delay Processes

The current process delivers significant environmental results for arrivals, however enhancements to the current processes are needed. To realise the additional benefits outlined in this document, enhancements could include:

- Increasing precision, both in the methods for predicting demand, and in managing flight start timing, including communication with crews.
- Combining and formalising arrival and departure delay decisions, including schedule factors, and coordinating with downstream flow-controlled airports.
- Applying lean thinking, stakeholders may also wish to reduce the multiplicity of systems and procedures to improve simplicity, development time and cost.

[15] (Civil Aviation Authority of New Zealand, 2016)

Airport Pre-departure Ground Delay Process

The A-CDM pre-departure sequencing process enables the necessary increase in departure timing precision

Managing Departure Timing

The need for increased precision

Air traffic congestion and waste emissions are not just a "peak period" phenomenon but can occur at any traffic level. If two aircraft arrive at once without any other traffic, one must wait for the other. From cumulative airborne delays at various flow rates for Auckland in 2016[16]:

- The onset of congestion occurs at flow levels as low as 10% of capacity
- Between 25% and 50% of traffic receive airborne delays greater than 2 minutes when arrival flow is above 35 movements/hour (54% of capacity)
- Most delays occur at moderate traffic levels between 30 and 45 movements per hour (54% to 80% of capacity)
- Reducing waste emissions requires managing traffic density at modest levels of demand. Doing so requires **increasing the precision** of ground delays.

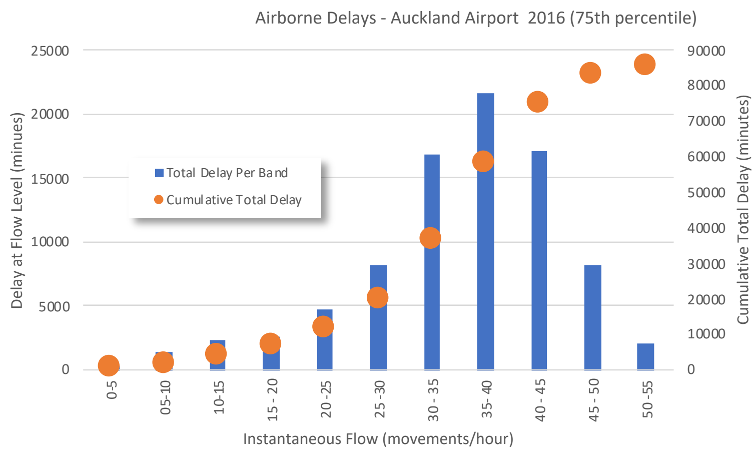


Figure 8 Airborne Delays vs Traffic Flow at Auckland in 2016

The A-CDM pre-departure timing process

The departure timing process described in the A-CDM concept of operations[17] enables relatively precise timing of departures.

- The process estimates demand from the target off blocks time (TOBT). The TOBT input represents a commitment by gate agents and airlines to be ready to depart.
- The ground delay process allocates a target take-off time (TTOT) at the runway, taking into account traffic conditions (and potentially any other conditions of interest to stakeholders such as schedule adherence)
- The process advises a target start approval time (TSAT) to crews, who are expected to request a start clearance on or about that time. TSAT allows time for start, taxiing, and aircraft preparation. Flights requesting a start clearance at that time can reasonably expect to take-off close to the assigned TTOT.

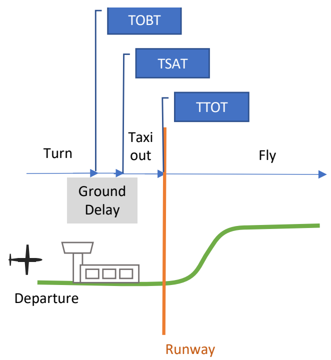


Figure 9 A-CDM Departure Timing Process

This process creates a "firebreak" between readying the aircraft for flight, and the start-up time. The precision of the process as a whole depends only on the flight crew requesting a start clearance close to TSAT. Some variability in achieving TOBT is tolerable, provided that TSAT is at a later time and can be complied with.

Stakeholders could consider using TSAT to guide flight start timing for all flights. Doing so would increase flight timing precision and provide consistent procedures for crews.

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16 Data is sourced from (Mahino Consulting, 2019).

17 (Auckland International Airport et al., 2015)

Airport Pre-departure Ground Delay Process

Real time event-based prediction of demand has greater accuracy despite normal operational uncertainty and variability

Predicting Departure Readiness

Ensuring that TSAT is at an achievable time, and runway capacity is feasibly allocated to flights, depends on how accurately flights' departure readiness can be predicted.

The challenges of current systems

- The current ATFM system estimates departure readiness (at the origin airport) for arrivals from the EOBT filed in ATC flight plans. EOBT can become out of date due to the administrative burden of updating the flight plan as events unfold.
- For departures, the current A-CDM system requires airlines or gate agents to estimate and enter TOBT manually. TOBT may be mis-estimated, and can also become out of date. Updating target off blocks time during aircraft turnaround is challenging for gate agents as the turnaround process has a high intensity workload. Late or missing changes to TOBT mean the opportunity for the system to respond to change is lost.
- The least predictable operation in air transport is loading and readying aircraft for flight. Manual predictions are uncertain. Data from Auckland shows that actual start readiness (ASRT) has a standard deviation of around 4-5 minutes compared with TOBT, spreading most departures over +/- 10 minutes[18].

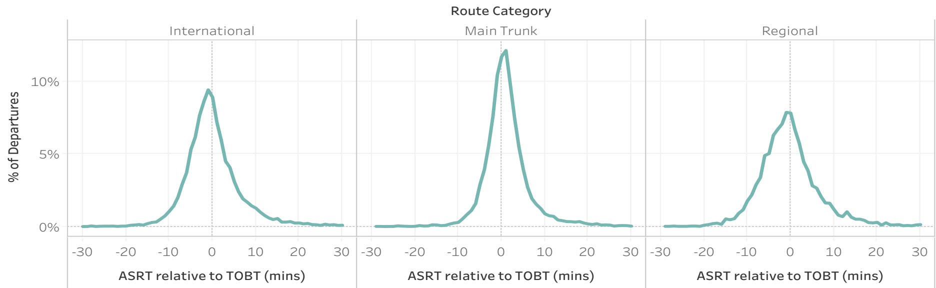

Figure 10 Variability of Start Readiness Time (ASRT), Auckland

- Due to the high variability of actual start readiness time compared with TOBT, TOBT is not trusted by ATC staff as a basis for planning departure ground delays.

Event Based Prediction

- Event-based prediction can create a more stable and accurate picture of forward demand.
- A-CDM is a milestone driven process aiming to help plan and organise airport activities related to aircraft turn-around. Experiments in Europe researching simplified A-CDM systems found that a stable, and increasingly accurate TOBT could be generated automatically from specific flight status events that add value to the prediction. These include take-off from the upstream airport, landing, in-blocks time, start and end of boarding. The automatically generated TOBT was adjusted in response to milestones as they occurred, or became late, enabling TOBT to move with events in the case of any delays. Provision was made for gate agents/airlines to amend TOBT in case of exceptional circumstances.
- TOBT calculated and updated using selected events was able to deliver a TOBT that was stable 50 minutes prior to departure, accurate to within 5 minutes at the time of departure of the flight on its previous flight leg, within 4 minutes at the time it arrived in-blocks, and within 2 minutes at the start of boarding[19].

Benefits of Event Based Prediction

- Automatic TOBT estimation is widely used. Benefits include improved accuracy, the ability to keep TOBT updated as events unfold, and the ability to improve performance over time, by enhancing the prediction algorithm in the light of ongoing experience.
- Automated TOBT estimation relives airlines, gate agents and airline workloads. TOBT estimates would need to be updated manually only on a manage-by-exception basis for unusual events.
- More accurate TOBT, in combination with a ground delay that is trusted to conform with stakeholder's priorities, is more readily complied with. Currently, some flights depart out of conformance with flow control timing. Contributing factors include TSAT (or for ATFM, CTOT) being inappropriately set for the flight, often too early by not being replanned to accommodate pre-departure delays. Automatic revision to TOBT allows TSAT to be appropriately revised, increasing the ability of flights to conform with flow control.

[18] (Mahino Consulting, 2019)

[19] (Alvarez, 2018)

Airport Pre-departure Ground Delay Process

Realising the benefits of a ground delay process requires collaborative decision-making between stakeholders

Collaborative Decision-making (CDM)

Predicting demand and organising flight departure times requires collaboration between stakeholders. The operational decisions of various stakeholders interact. and can require a variety of data not necessarily held by any one stakeholder[20].

The Basis of CDM

Collaborative Decision-making is a real-time collaboration model in which stakeholders share information needed to make decisions where their operational decisions interact. The purpose of CDM is to break down siloed decision-making and enable fully informed collaboration, creating real time alignment between the actions of each participant.

CDM was developed "in recognition that increased cooperation between ATC, Airlines and Airports could achieve solutions to air traffic flow problems". The founding group led by US Air "established three tenets of CDM:

- Most problems have simple causes.
- Better information sharing eliminates a large proportion of the problems.
- CDM can only be successful if trust is established between the partners as the first step"[21].

Airport Pre-departure Ground Delay Process CDM

Examples of information sharing to enable an efficient ground delay process include

Shared Information	Outcome
Airport turn around milestone and flight status events, and current airline schedule intentions	More accurate demand prediction and ground delay planning
TSAT advice to gate agents and aircraft crews	Improved conformance with ground delays
Gate agent updates to TOBT if required	System can respond to disruption
TSAT advised to ATC. Enable ATC to update TSAT if required	Improved ATC sequence planning for increased airport throughput.

Table 3 CDM Shared Information

[20] (Vail et al., 2015) p1

Airport Collaboration to Predict Demand

Collaboration between several airports would enable more accurate demand estimation.

- Aircraft readiness estimates are necessary for both departing flights at the local airport, and for arriving flights at their airport of origin.
- The ground delay process needs to balance demand between flights of various durations that would use the runway at a similar time, including departing aircraft that arrived on short flights from nearby airports.
- To reserve runway capacity for departures and short duration arrivals, at the time of making ground delay decisions for longer duration arrivals, the timing of shorter flights must be forecast ahead of time.
- Forecasting flight demand from short sector flights may require looking up stream more than one flight and more than one airport ahead. At the ground delay decision time, some affected flights may still be inbound to upstream airports (Figure 11).
- Event data from upstream airports (often regional) may be needed by more than one flow-controlled airport. Airports might consider sharing event data, possibly via a commercial data aggregation service, to enable demand prediction jointly.

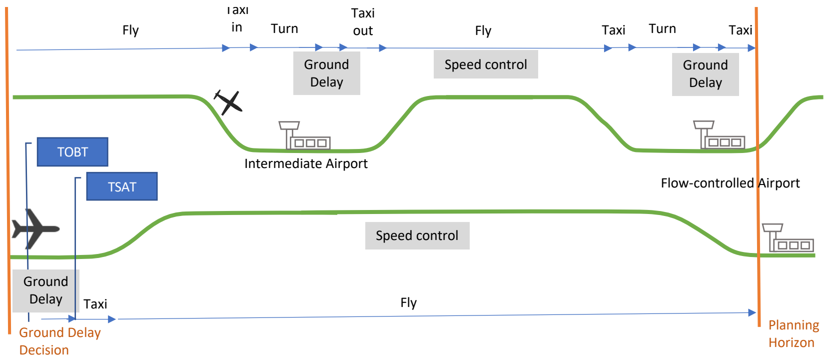

Figure 11 Ground Delay Process Planning Horizon

[21] (Morin, 2019)

Airport Pre-departure Ground Delay Process

Ensuring information is available to each actor enables stakeholders to collaborate and the ground delay process to function

Operational Crews Collaboration

For aircraft to be readied close to the predicted TOBT, and to request start clearances close to TSAT, both TOBT and TSAT need to be available to the relevant airport staff, gate agents, flight and cabin crews both at the local airport for departures, and at airports of origin for inbound arrivals at the pre-departure stage. Various methods are used internationally by airports operating ATFM and A-CDM processes.

- Hong Kong airport supplies an app for mobile devices which enables gate agents to amend the automatically generated TOBT if required, and advises gate agents and aircraft crews of the current TSAT.

Source: Hong Kong Airport Authority, Mr Herman Chung (Chung, 2021)

Figure 12 Hong Kong A-CDM Mobile App

- Amsterdam Schiphol airport uses a simple and cost effective option - publishing the relevant timing points on the web. The output is readily available to any internet connected device by entering the flight callsign into the web page at https://mobile.ehamcdm.nl

Figure 13 Amsterdam Schipol Web Portal

- Other options include displaying the relevant data on lead in guidance systems, or delivering it electronically via airport and airline internal systems. Currently, CTOT for inbound flights is included in digital clearance delivery by ATC, and passed by VHF radio from control towers.
- The method used is clearly a choice for stakeholders implementing a pre-departure ground delay process at any particular airport. Care needs to be taken that the information is readily available to all stakeholders who need it, including departures at upstream airports. Many of the options do not have universal reach to all of the people on the ground. Lead in guidance systems are not prevalent outside major airports, may not exist at all gate stands, and may not reach gate agents and ground crews. Likewise, electronic information flows to aircraft crews also do not reach gate agents, and smaller operators may not have electronic information delivery to the aircraft.
- Provision should be made to ensure that any manual data entry required, such as manual updates to TOBT by gate agents, or to TSAT by ATC can readily be made via equipment that is at hand for the person concerned.
- Aerodrome ATC planning for aircraft sequencing would be aided by having access to Target Take-off Time (TTOT) and TSAT in particular, in order to form a view about tactical demand. Inbound aircraft sequencing is performed by en route and terminal ATC sectors; however, aerodrome ATC are responsible for sequencing departures into the runway flow.

Distributed Systems

- Stakeholders could consider the simplicity and flexibility that providing the information via an application programming interface (API) could deliver.
- Upstream airports may have flights destined for more than one flow-controlled destination, and need access to TSAT from each. Information systems at these locations may wish to combine data from multiple destinations, to provide information about departures in a single interface for relevant stakeholders.
- Obtaining that data via an API from the destination airports would remove any need for a network scale centralised service, or the need for a single technology at all airports, with the associated vendor lock-in and increased development cost and time. An API service would enable data exchange between airport systems, enabling local systems to be simplified and suited to the local operation.

Airport Pre-departure Ground Delay Process

Dynamic decision-making enables the ground delay process to accommodate operational variation and disruption. Cultural and contractual changes to conventional operations, based on a wider perspective, may be needed to realise benefits

Dynamic Planning

Handling Operational Variability

The potential for late notice changes means that the ground delay process must be able to flexibly re-plan at short notice.

- Future air traffic movements become increasingly unpredictable as events affect flight timing, propagate along the aircraft's itinerary and cause the future flights to deviate from plan.
- The timing of readiness for departure is unpredictably fragile and subject to short notice change. A late or missing passenger can suddenly require a lengthy delay to unload baggage immediately prior to the planned start time of the flight. Technical events can also create last minute delays.
- Operator's responses to disruption can change future plans in real time. For convenience, airlines can re-allocate aircraft (tail swap) or adjust schedules at late notice to best deliver their obligations to passengers, in the light of airline resource requirements (aircraft and crew displacement) and passenger demand.
- Ideally, the ground delay process should respond to these emerging real time changes, (re-)planning ground delays for the situation at hand. Dynamic decision-making, leaving start timing decisions to the last prudent moment, would enable the system to accommodate variation and assist recovery from disruption.
- This means that the ground delay algorithm needs to operate, and continuously re-plan in real time. Using event-based prediction, and ensuring that schedule input is up to date, should automatically provide the ground delay decision algorithm with demand data reflecting the dynamic changes to operational plans.
- Airports have the required data in the normal course of events. It is essential to manage gate allocation and boarding / loading ground activities. As the input data, the output (crew coordination via TSAT), and the actions all occur at the airport, before any aircraft ask to move, the ground delay process is most simply viewed and implemented as a fundamentally airport related, pre-departure function.
- To enable ATC planning, the process may need to ensure that the ground delays (TSAT, updated flight plan EOBT, or other as agreed) are communicated to ATC.

Culture Change

- Minimising emissions may require a change of goal for airline operations from local optimisations such as achieving on time departure, to a system wide perspective aimed at realising on time arrivals. Flexibility is needed at the point of departure to wait for the ground delay period, in order to realise the environmental, punctuality, and capacity benefits.
- Gate agents and others may currently be contracted or incentivised to target on time departures. This objective would need to change. Changes might include targeting "on time readiness" as an alternative performance metric for the aircraft turnaround process. A requirement to engage with the ground delay process might be added to ensure that the stakeholders realise the benefits of the ground delay process.
- After departure, tactical optimisations using a local perspective can be counter-productive. As a rule of thumb, flight crews and air traffic controllers seek to maximise the progress of the flight toward its destination. Where traffic permits, flights can seek or be given direct clearances after take-off, avoiding some of the twists and turns of instrument procedures, and instead fly a straighter path. However, savings may not be realised if an earlier than planned arrival enters or creates congestion at the destination. In general, minimising emissions will require not only a broader plan but the willingness of all involved to follow it. Trust in the process is likely to help. Practitioners recommend that front line people be involved in developing the process, in part to develop understanding and this trust.
- The pre-departure ground delay process would enable airlines and airports to autonomously regulate air traffic demand as mutually agreed. Historically, ground delays have developed as a split operation, partly, and first, by air traffic control operated flow management (ATFM) for arrivals, and more recently by the A-CDM predeparture process for departures. Drivers for harmonising the two into a single, coherent airport related process include advantages in cost and time to develop, and the alignment with information supplies, business benefits, and actors. The strongest driver for a single decision-making point in our view is the mutual contention for runway capacity of the two traffic flows. Separate systems working to predetermined, or negotiated arrival and departure acceptance rates respectively are less likely to fully use runway capacity. The coordination between the systems, and duplication adds complexity and cost.

Airport Pre-departure Ground Delay Process

A single coherent pre-departure CDM process would realise emissions reduction, punctuality, and capacity benefits

Combined Arrival and Departure Ground Delay Process

Process Milestones

Drawing the preceding discussion together, an airport-centric pre-departure ground delay process could include the following elements:

- Manage both arrival and departure traffic flows across the runway to ensure capacity is best used given the balance between arrival and departure demand
- Use flight status information to predict TOBT to realise a real-time picture of demand.
- Use TSAT to enable more precise control of demand for both flows of traffic.
- A ground delay algorithm would predict runway capacity (weather and demand related) and allocate runway timing to arrivals and departures. In conventional nomenclature, arrival traffic would be allocated a controlled time of arrival (CTA) and departure traffic a TTOT at the runway.
- The ground delay algorithm would set TTOT or CTA as the case may be, in line with stakeholder defined priorities, including the effect on schedule adherence.
- Each flight would be given a TSAT that enabled them to meet the assigned runway time, allowing time for movements from origin gate to the runway.
- Realising the pre-departure ground delay would involve airline and gate agent readying the aircraft to meet TOBT, and flight crew requesting a start clearance (or at uncontrolled origin airports, starting) at TSAT.

CDM Framework

- The airport pre-departure ground delay process would pre-arrange traffic demand to match available capacity, by organising the start request timing for flights.
- Movements at the airport would be controlled by ATC. In particular, flight sequencing is an ATC function, and enables ATC to maximise throughput at the detail level, considering the various aircraft separation requirements involved. ATC would issue start clearances to achieve the planned sequencing.
- Inter airport and cross border flow control, at the pre-departure stage, would involve negotiating with downstream airports to align TTOT for departures, with CTOT from the downstream airport.

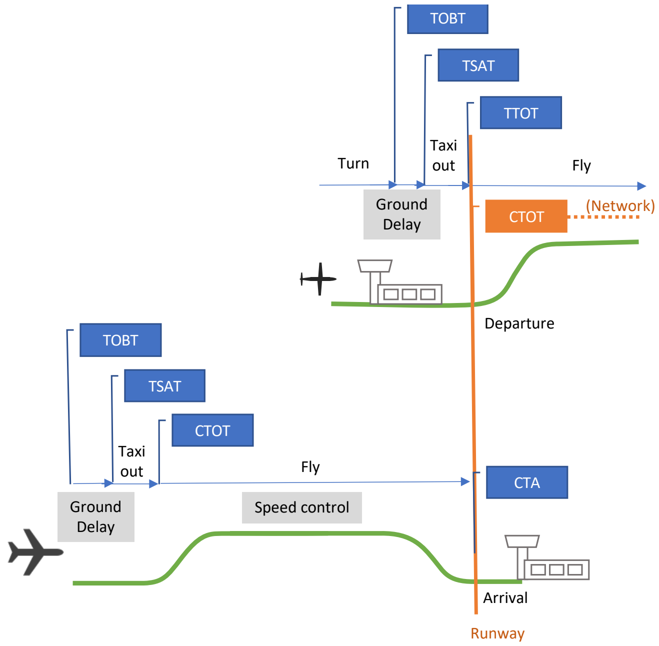

Figure 14 Combined Arrival and Departure Ground Delay Milestones

Post operational reviews

- Ground delays affect taxiing and flight efficiency, on-time performance and block time for flights.
- Extended taxi and flight time would occur if ground delays were insufficient.
- Extended block times would occur if ground delays are too large.
- On time arrival performance is affected by the way in which delays are rationed
- Given suitable objective performance metrics, post operational reviews could check, and change as needed, both the demand prediction (TOBT) and ground delay allocation processes to improve the above performance criteria.

Airport Pre-departure Ground Delay Process

A pre-departure ground delay process could be a distinct airport related function enabling CDM between stakeholders

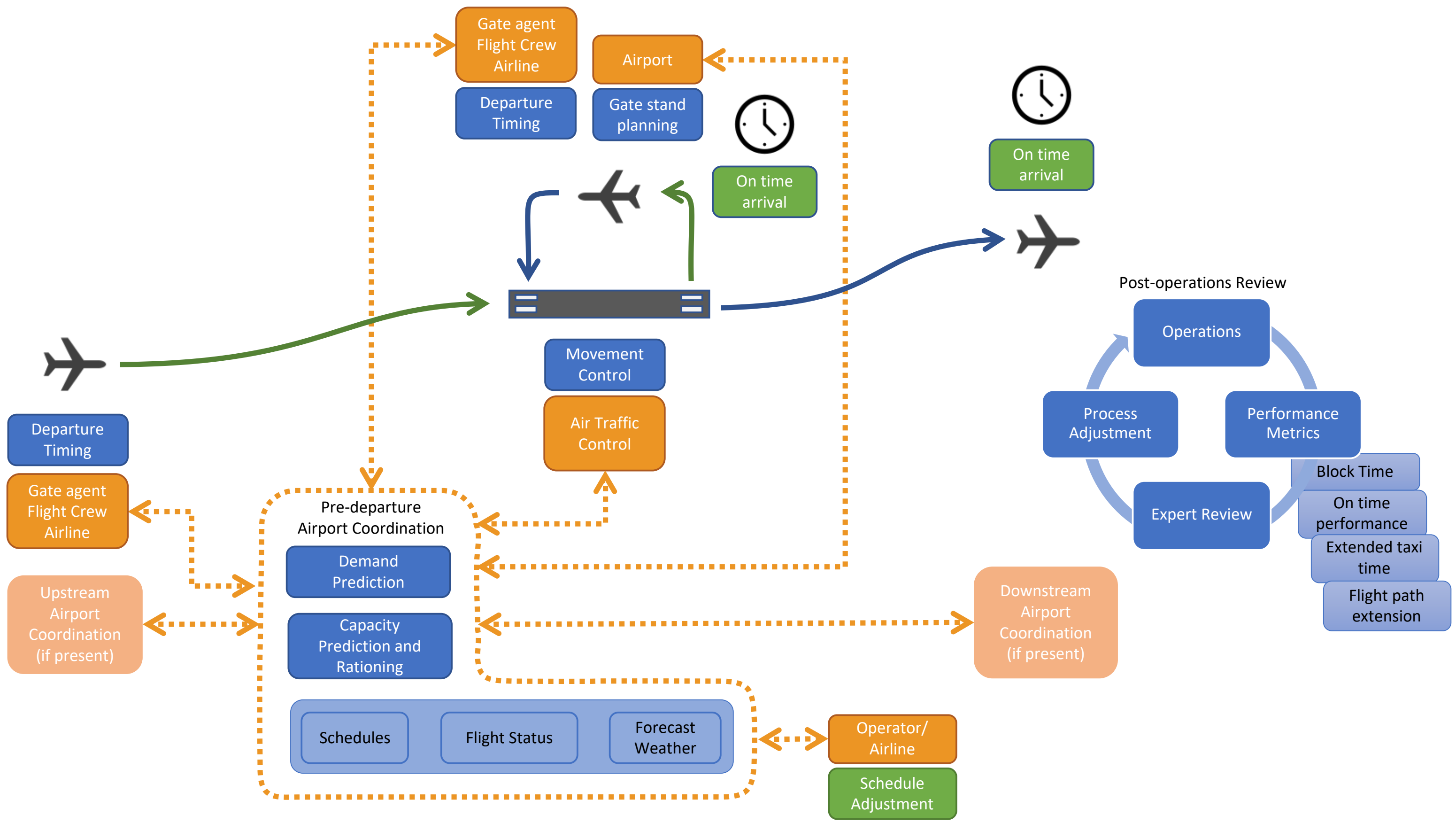

Figure 15 Pre-departure Ground Delay Process as a Distinct Element of Airport Operations

In the airport context, the pre-departure ground delay process forms a distinct and separate airport capability, enabling collaboration between gate agents, aircraft crew, airport operations and air traffic control to align flight demand with capacity and optimise on time arrival performance.

Conceiving the ground delay process as a single coherent function simplifies the interactions with stakeholders, and any extension to network level coordination. The distinct, defined process would empower post operational reviews by becoming a clear vehicle for delivering improvements.

Airport Pre-departure Ground Delay Process

The enhanced ground delay process could be delivered by airport/airline collaboration. Airports and airlines are the actors, have the required data, and the business interest in the environmental and performance benefits.

Airport/Airline Collaboration

The combination of business interests, data requirements, and the pre-departure and airport centric nature of the ground delay process suggest that its development and operation would well suit an airport/airline collaboration.

CDM Information Requirements

The information needed for the pre-departure process to predict demand, and to predict and allocate runway capacity is already possessed by airports and airlines, and is not generally available within ATC. Almost all of it is in the public domain via commercial data aggregation services such as Cirium, FlightAware and Flightradar24, creating a variety of rapid development options for stakeholders.

Purpose	Input Data	Sources
Raw demand: Predicted off blocks time (TOBT)	Airport turn-around milestones, take- off and landing times (flight status events)	Airports, commercial suppliers, manual data entry by gate agent for exceptions
Predicted runway traffic demand	Predicted flight durations	Airline, commercial suppliers, ATC.
	Unimpeded taxi duration between gate stand and runway	Airport statistics
	Target off blocks time (TOBT)	Automated (from above)
Predict runway capacity	Weather (wind, visibility) forecast	Airport, commercial suppliers
	Traffic demand	From above
Pre-departure runway timing for flights (TTOT/CTA algorithm)	Predicted traffic demand and runway capacity	From above
	Flight schedules and stakeholder priorities	Airlines
Start request timing advice (TSAT)	Runway timing, flight and taxi durations	As above. Possible amendment by ATC for convenience.

Table 4 Ground Delay Process CDM Information Requirements

Airport pre-departure ground delay as a business process

- Under the CDM framework, the ground delay process acts entirely pre-departure, before any aircraft move. This means that the most effective emissions reduction decisions are made outside of the aviation safety space by collaboration between airlines and airports. **Emissions reduction via ground delays can be characterised as a business process improvement with environmental, commercial, operational, and product quality benefits for these stakeholders.**
- Conceiving the pre-departure ground delay process as an airline/airport business activity moves the process closer to the stakeholders who benefit and who must act to realise the process, and may simplify both the operation and the funding of a ground delay system. As a business process, supporting technologies might use contemporary commercial techniques, including deployment as a cloud-based service, reducing the cost and time to reach deployment.
- It is conceivable that the airport centric pre-departure flow management process could be jointly developed and / or operated by airlines and airports collaboratively. This is already the case at a national level for IATA slot management, used to ration airport capacity to international flights at the strategic/scheduling phase of the CDM framework. The Board of Airline Representatives of New Zealand (BARNZ) and the New Zealand Airports Association jointly own the non-profit Slot Coordination New Zealand Ltd (SCNZL)[22], which delegates the slot allocation process to ACL International Coordination Ltd[23].
- Pace may also be aided by the distributed airport-centric nature of the ground delay process. Airports seeking genuine green credentials may wish to move rapidly, and could implement a ground delay process without risking future incompatibility with the initiatives of others or the strategy for the ICAO region. The decentralised scheme described here avoids the time, complexity, and costs of developing and operating a more complex, centralised or network wide scheme that would require coordinated development by a wider range of actors on a larger scale.

[22] (Companies NZ, 2021)

[23] (Slot Coordination New Zealand Limited (SCNZL), 2020)

Airport Pre-departure Ground Delay Process

International experience recommends stakeholders collaboratively develop and progressively deliver new processes

Collaborative Process Development

Realising effective ground delays is primarily a process development exercise and not a technology implementation project. Changes in the way stakeholders work are necessary, and trust in the process is likely to be a key prerequisite to successful change. Advice from locations that have successfully implemented CDM based departure management processes[24] includes the following factors:

- ***Engagement***. Engaging stakeholders is essential to build trust, and to ensure that the process actually considers all of the factors needed. Without this engagement, the process can be perceived as 'just an airport [or other party] process' or as a data gathering exercise. The process is ideally co-created by the stakeholders involved, producing a clear line of sight from action to result, and a sense of ownership and influence of the process.
- ***Education***. The process works when all of the stakeholders act toward the desired result. Benefits and results occur remote from the actors (ground delays at origin airports reduce congestion and improve arrival punctuality at the destination). Without clearly understanding the impact of their actions, actors may lack the motivation to execute the process due to the invisibility of the results.
- ***Trust***. Understanding the process, and taking part in developing it, helps develop trust amongst the stakeholders. Including punctuality as a benefit and goal may also help. Trusting that delays required to reduce waste emissions do not compromise airline business goals may help stakeholders support the process.
- ***Human-centred design***. One of the lean wastes is the waste of human potential. Many of the details that need to be taken into account may only be known by front line staff. Involving front-line and end-user staff in the design develops trust, and ensures that the design "addresses the whole user experience"[25]. Ideally the development team would be multidisciplinary and diverse, including pilots, cabin crew, gate agents, and airport operations staff as well as domain specialists. Experts in "lean", and in experts in traffic management or complex process design could bring applied science and knowledge from relevant fields in order to create a process that is as simple and well directed as practicable.
- ***Collaboration***. The need for relevant stakeholders to collaborate arises for similar reasons as the needs for engagement and expertise; to ensure the process design is feasible and takes account of the needs of the stakeholders involved. Participants should include all those involved in enacting the process – airports, major airspace users, gate agents and ATC. Stakeholders should develop a common understanding of the changes required in procedures and systems[26].
- ***Benefits driven***. Performance metrics should drive both the procedure and system development and ongoing improvements. Establishing metrics at an early stage would also consolidate stakeholders' views on the results to be achieved.
- ***Iterative development***. Certain needs will emerge as understanding grows during development. Stakeholders can expect gaps between the design and user needs to be identified and the design to evolve over several iterations.
- ***Progressive delivery***. Progressively introducing the solution elements enables the required learning and process quality to be realised, along with delivering early gains. A delivery sequence might include metrics as a first step; predicting local airport TOBT, establishing departure ground delay calculations, then the TSAT based start request process to deliver taxi-out efficiencies; extending the TSAT/TOBT process to origin airports to deliver runway capacity benefits and flight efficiency for arrivals; adding schedule and delay distribution capability to improve punctuality; and extending the system to inter-airport domestically and cross-border coordination, in sequence.
- ***Leadership***. (Vail et al., 2015) recommend that airports lead CDM initiatives as they alone have business relationships with all stakeholders. With the small and well-connected nature of the New Zealand air transport system, airline leadership might also be considered here, as conflicting traffic creating congestion is frequently from the same company. If a common, cloud-based technology supporting several airports is envisaged, airlines and airports as a group may wish to pursue a joint project collectively, to create common procedures and supporting digital information systems.

[24] (Ratcliffe, 2021; Subramaniam, 2021; Vail et al., 2015)

[25] (HungaroControl, 2020)

[26] (Ratcliffe, 2021)

Observations and Conclusions

Theme	Observations	Conclusions
Precision	• Airborne congestion can occur at quite low traffic levels due to timing conflicts between aircraft. • Using TSAT to control start request timing can more precisely manage demand.	• Increased precision is needed in flight start timing. • Stakeholders could consider using the TOBT/TSAT process pattern to control flight start timing for both departures and arrivals.
Responding to Variability and Uncertainty	• There is material uncertainty and variability in the timing of aircraft readiness for flight. This makes demand somewhat unpredictable. • Predicting the timing of departure readiness from prior flight status events, including previous flight sectors, has been found to produce stable and accurate enough timing predictions. • Manual data entry or flight-plan based demand prediction has modest accuracy and creates unacceptable administrative workloads	• Using event-based demand prediction would increase the accuracy of the ground delay process and enable it to respond to emerging change. • Using event-based demand prediction would simplify data gathering and reduce workload for stakeholders. • Ground delay decisions are ideally taken at the last prudent moment, to allow the system to respond to emerging events. This means the ground delay decision-making process needs to operate in real time and be continuously revised, rather than using a fixed prior plan.
Additional Business Benefits	• Runway capacity is significantly affected by the radio of arrival to departure traffic flows. • The distribution of ground delays can affect punctuality and airport capacity in addition to minimising emissions	• To maximise the use of capacity, and minimise delays, ground delay process should manage arrival and departure traffic streams together. • Ground delay distribution decisions should take account of airline and airport stakeholders' priorities
Stakeholder Collaboration	• Ground delay decisions primarily affect airline and airport business operations, their product, and their customer experience • Actions to realise ground delays can be taken by airline and airport front line staff, prior to any aircraft movements • The data required for event-based demand prediction is already held by airports and airlines	• The ground delay process is ideally conceived as an airport/airline collaboration. • The pre-departure ground delay process can be seen as a business, rather than a safety system. As a business system, technical support infrastructure to enable an effective ground delay process could be created at a pace, using contemporary technologies.

Increasing Flight Operations Efficiency

Options to reduce flight duration include more direct routing and tailored approach/departure procedures

Overview

The current navigation infrastructure has defined IFR procedures from runway to runway which creates a number of efficiencies for air traffic flow management and ATC workload. Further improving efficiency, by reducing flight path lengths, could involve changes to approach/departure procedures and the en route structure, however both are relatively well tuned for optimal traffic flow and are designed for general use. Enhanced approach/departure procedures would be likely to need more enhanced PBN capacities in aircraft. Enhancing the en route structure may be quite challenging. This section discusses technology options and performance trade-offs that stakeholders may wish to consider.

Current Navigation Infrastructure

- The current New Zealand PBN navigation infrastructure comprises more or less parallel pairs of one-way IFR routes between the airports most frequented by scheduled air transport, one in each direction. The system sets up an anticlockwise circular flow of traffic between airport pairs, creating strategic separation between opposite direction traffic, and between aircraft climbing from or descending to airports.
- In main airport terminal areas (TMA), standard instrument approach and departure procedures (SIDs, STARs), create a three-dimensional strategic separation between departing and arriving flights. The SIDs, STARs, and their transitions connecting to the wider fixed route structure are runway dependent and change with the duty runway configuration of the airport.
- Transitions from the airport approach and departure procedures to the en route circular flow enable runway direction changes at airports without changing en route flight paths, minimising the disruption to traffic and reducing the ATC workload as various airports change duty runways with the evolving weather.
- The combination of the en route structure and airport related procedures creates a seamless navigation system. The strategic separation between traffic flows reduces conflict between flights, minimising the need for ATC intervention and aircraft manoeuvring. As a result, ATC are able to handle higher traffic volumes. On-procedure flying maximises the predictability of air traffic, improving the planning and results of air traffic flow management.

Drivers for improvement

- Further reducing flight path length is desirable. Savings from even modest flight path reduction can be substantial, as changes to the infrastructure deliver marginal savings for every flight. The NSS PBN programme delivered 3,120 tonnes of CO_2 savings annually from an average flight path reduction of 2.15nm at affected airports.
- The anticipated introduction of battery-electric powered aircraft in this decade adds impetus to the desire for increased efficiency in the navigation system. For routes at the limit of electric aircraft range, marginal improvements may make the difference between the route being viable for electric aircraft, or not.

Improvement Opportunities

- Further reducing approach and departure procedure flight path length is likely to require enhanced PBN capabilities. Current PBN (RNAV) approaches are designed for general use by aircraft with basic RNAV capability. At most airports the RNAV approaches are the minimum practicable size given the ICAO design criteria, the selected aircraft category being catered for, and operators' requirements for stabilised approaches. Options for further reducing flight path length would need alternative technologies and might include:
    - Procedures using curved "radius to fix" (RF) legs to improve the geometry of approaches for aircraft with RF capability,
    - Precision approaches using RNP-AR capability to enable minimum path lengths for fleets with RNP-AR capability,
    - Precision approaches using a satellite-based augmentation system (SBAS).
- Options for further reducing en route flight path length may be complicated. Fixed routes service SIDs/STARs from either end of runways, and may not be perfectly aligned for either. Changes seeking to make flights more direct are likely to increase the quantity of crossing traffic needing ATC intervention and aircraft manoeuvring. Modelling and fast time simulation studies may be needed to assess whether a net gain can be obtained. Changes may need to trade-off predictability, complexity, and ATC workload. Of these, a reduced predictability would affect flow management and the ability to manage air traffic congestion.

Increasing Flight Operations Efficiency

Shorter approach and departure procedures could be created for operators having suitable aircraft PBN capability

Tailored Approaches

- RNAV instrument approach procedures at most airports use an ICAO standard “T-bar” pattern. The shaft of the T contains a runway aligned intermediate and final approach. The procedure allows entry from any direction, via one of the initial approach fixes (IAF), is useable by aircraft with basic RNAV capability (orange line, Figure 16), and is close to the minimum size that can ensure that operators are able to achieve stabilised approaches at the published maximum entry speeds[27]

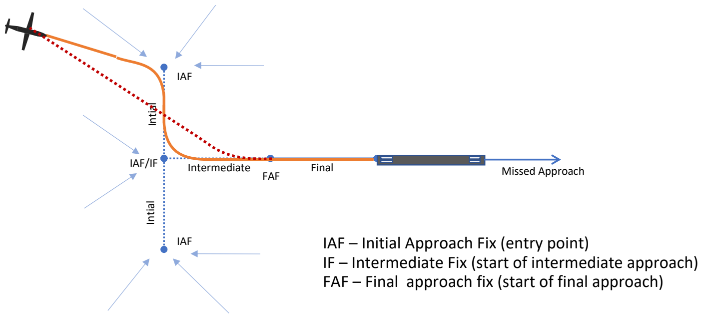

Figure 16 PBN Approach "T-Bar" Design Pattern

Operators seeking shorter or better aligned approach flight paths could consider commissioning, in close consultation with ATC, alternative approach or departure procedures to take advantage of enhanced aircraft capabilities.

- Approaches incorporating curved (RF) segments may enable the geometry of an approach to be improved (dotted line, Figure 16). Benefits can vary. Design constraints in the ICAO standards (limitations on RF turn radius and change of heading, or a requirement for a minimum straight path distance before the final approach fix) may limit the advantage that can be obtained.
- The flexibility of precision approaches or departures using RNP-AR offer the shortest available designs, minimising flight path length for routes in some directions. The advantage is greatest for routes that approaching or departing an airport downwind, from a direction opposite to the runway heading. In this case, both the runway heading and the downwind tracks are shortened.

[27] (ICAO, 2020)

- A satellite-based augmentation system (SBAS) is expected to be operational and certified by 2025[28]. Precision approaches using SBAS can implement instrument landing system (ILS)-like approaches using “localiser performance with vertical guidance” (LPV). LPV approaches provide glideslope advice to aircraft and have increasing precision as the aircraft draws nearer to the runway. Depending on obstacle clearance, LPV approaches may enable lower minimum approach altitudes, reducing the frequency of flights diverting in poor weather.
- SBAS approaches may include RF legs. ICAO design rules[27] from 4 November 2021 allow for SBAS based precision approaches in which PBN routes join to the final approach heading via an RF leg, creating the potential for improved flight path geometry. However, limitations on the radius of RF legs turning onto the final heading (2.55nm) and a requirement for a minimum straight segment before reaching the glide slope mean that LPV approaches might not be shorter than the existing approaches in many cases.

Applicability to aircraft fleets

- RF, SBAS and LPV capabilities would be required in aircraft using approaches based on those features. These capabilities are becoming widely available, including in relatively affordable equipment for GA aircraft.
- Acquiring RNP-AR capability is costly. The capability is available for several jet operators and the Air New Zealand ATR72 fleet, and Air New Zealand intends to seek it for all new aircraft. Operators are unlikely to retrofit smaller aircraft.

Benefit driven implementation

- Reduced emissions benefits will be created where overall flight time is reduced either by shorter flight paths, or where lower minima mean fewer diverted flights. A systematic review of existing approaches (route / runway combinations), and the frequency of use and of diversions, may help stakeholders identify feasible and worthwhile emissions reduction opportunities.
- The benefits delivered by revised approaches will be location specific, as terrain and obstacle clearance, community noise concerns, and operational safety requirements embodied in the design standards will constrain what is possible. Benefits might be more reliably delivered at regional airports with lower air traffic congestion, where ATC vectoring off the procedures is less frequent.

[28] (Toitū te Whenua Land Information New Zealand, 2020)

Increasing Flight Operations Efficiency

The strategic design of the navigation system enables predictable traffic flows but may extend flight paths

En route Flight Efficiency

- The combination of fixed routes and variable TMA procedures (varying with duty runway) creates a compromise for flight efficiency. Fixed routes service SIDs/STARs from both ends of a runway, and may not be optimally aligned for either. Various amounts of additional track miles must be flown as flights transition between routes, which are more or less direct to the TMA, and SIDs or STARs connecting with the duty runway (Figure 17).
- Segments of fixed routes may be shared by flights between more than one city pair. Doing so reduces database and map complexity but may result in the shared route being not quite direct for any of its users.

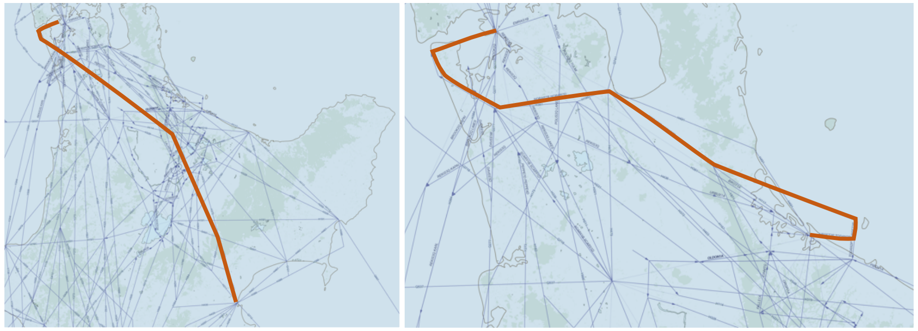

Figure 17 Standard Routes to Auckland Runway 05R from Napier and Tauranga

Case study

Figure 18 shows the commonly flown IFR routes from Auckland runway 05R to Tauranga runway 07 (brown) compared with the minimum distance "perfect flight" route (blue). The hypothetical perfect flight is 92nm, 10% shorter than the 103nm route via (A).

In this particular case, a more efficient flight path might entail making the flight path more direct (east of B), and removing the dog-leg in the approach at Tauranga, perhaps using an approach with an RF leg, with or without SBAS/LPV. These changes could reduce the flight path length by about 7 nautical miles.

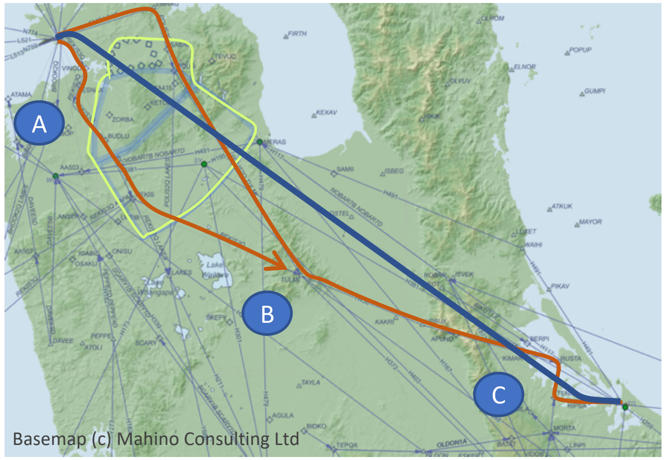

Figure 18 PBN Instrument Flight Procedures Between Auckland 05R and Tauranga 07

More generally, it illustrates several of the factors that may limit reaching perfection.

- The route must avoid other airspace, in this case (yellow) around Ardmore and Drury aerodromes and their approaches from the south which protects controlled flights from higher density, uncontrolled general aviation traffic.
- Terrain constraints (Kamai Ranges) prevent this route from entering the T-Bar approach in line with the final approach path.
- Moving the route may increase the frequency of separation conflicts with opposite direction and other traffic. Ad-hoc route optimisations differ from the current structured design, which strategically separates traffic flows, and risks increasing the need for ATC intervention and aircraft manoeuvring, potentially reducing the emissions reduction benefit of the shorter flight path and increasing the cost of safety. Whether the result is feasible and gains can be realised depends on the frequency of traffic on the conflicting routes, if any.
- ATC procedures may be affected. The route point at (B) is near the boundary between two ATC units. Moving the route may require changes to ATC coordination procedures and affect the complexity of traffic management in either or both ATC sectors.

Optimising flight path length requires balancing competing factors: efficiency, predictability, complexity and ATC workload

(More-)Direct Flight Paths

- Realising net benefits from more direct en route flight paths necessarily requires balancing the benefits of reduced flight path length against disbenefits due to any increased frequency of ATC intervention and manoeuvring to separate conflicting flights.
- The current en route design creates an anticlockwise circular flow, strategically separating climbing and descending traffic. The system reduces the frequency of ATC intervention but can create some structural inefficiency.
- As an example, the standard jet route from Queenstown to Auckland incorporates an additional 20nm (3.6% additional track miles) over and above a direct route. The route trends east to join the route from Christchurch at (A) (Figure 19), in order to separate departures climbing south out of Auckland from inbound flights on descent. In this particular case, a more direct route would conflict with jet traffic departing Auckland for both Wellington and Christchurch.
- Strategic separation between climbing and descending traffic is beneficial. Continuous climb and descent profiles are more fuel efficient. Tactical intervention which requires aircraft to level off is likely to be inefficient. In addition, limited information in ATC tools about wind gradients, and aircraft weight and thrust, create trajectory uncertainty. ATC may have limited ability to make firm judgements about when aircraft will reach desired altitudes during climb or descent, making tactical intervention more time consuming as well as less efficient in these phases of flight[29].

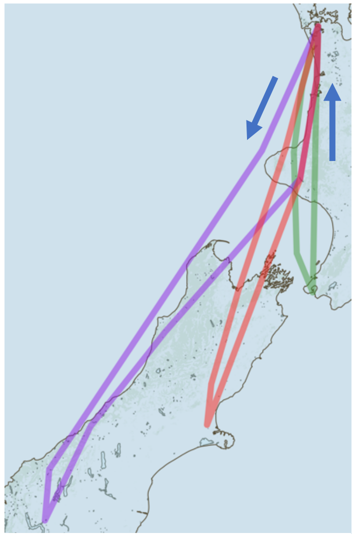

Figure 19 Standard Jet Routes to/from Auckland

More-direct routing might be realised by any of:

- *Ad-hoc tactical direct clearances* (current practice). Where traffic conditions permit, controllers may issue “short cut” clearances direct to a point further along the flight planned route.
- *Plannable direct routing*. Predefined routes which are more direct between origin airport SID and destination STAR transitions. These might be similar to ad-hoc direct routes, but able to be used in flight planning.
- *Free-route airspace* In free route airspace operators may plan and fly a user-preferred route free of the constraints of a fixed route network. Operators with a quality model of the wind field could select a minimum energy trajectory.

Balancing benefits and challenges

- Plannable direct routing enables pre-departure congestion management, as flight durations would be more predictable. In contrast, ad-hoc direct clearances may disrupt congestion management by changing flight durations after pre-departure ground delays have been taken.
- More direct en route flight paths might reduce flight time, provided that the aircraft do not need to deviate for traffic avoidance reasons. However, more direct flight paths reduce the strategic structure of the traffic flows. Depending on traffic density, this may increase the need for ATC intervention and manoeuvring, reducing the efficiency benefits for affected flights.
- Both free-route airspace and plannable direct routing increase complexity for ATC. (Appendix F). Controller tools such as medium-term conflict detection (MTCD) may help controllers planning, however airspace revision and additional ATC workload is generally necessary. Particular care is needed to minimise the risks of traffic conflicts close to ATC sector boundaries. In practice both plannable direct routes and free route airspace continue to need routing constraints to strategically separate traffic at ATC sector boundaries and entering or leaving terminal areas.
- To estimate the net benefits of any route changes, stakeholders may need to model the likely outcomes. Tools such as fast-time simulation may be useful to help judge whether potential savings would be realised by assessing the likelihood of any increased conflict between traffic flows, and the effect on ATC workload.
- At higher intensity airports, traffic congestion, even at low volume, may require ATC vectoring off instrument flight procedures. Benefits of direct routing may be more frequently realised at airspace and airports with lower traffic densities.

[29] (Knorr & Walter, 2011)

Appendix A Lean Process Improvement

Reducing aviation emissions is primarily a process improvement task aimed at reducing wastes

Lean Solutions

Lean identifies eight waste categories common to production processes. Six of these are directly applicable to minimising aviation emissions. Examples include:

Transport	• Aircraft fly further than necessary if using suboptimal flight paths.
Waiting:	• Aircraft queue in congested traffic.
Overproduction:	• Air traffic congestion results from introducing more flights than capacity constraints can accommodate.
Extra processing: (Multiple systems)	• Multiple systems with various owners affect traffic flows, including separate pre-departure flow metering for arrivals (ATFM) and departures (A-CDM).
Defects: (Insufficient information)	• Decisions to start/pushback flights or obtain more direct airborne routing may lack insight into the congestion that would be created or increased at a runway ahead. • Ground delay decisions may lack insight into the scheduling impact of the decision.
Non-utilised talent: (Process design)	• The knowledge and expertise of front-line people make them most capable of identifying problems and developing solutions.

This study uses a lean perspective to identify and formulate emissions reduction methods. Preference is given to changes that:

- Reduce waiting time and minimise over production. Ground delays do this.
- Reduce extra processing. The single, airport centric process reduces the multiplicity of systems and processes.
- Work to a suitable tolerance or quality level. The staged CDM framework achieves this result by having each stage work to the practicable level of accuracy, often modest, with subsequent stages increasing the precision of decisions appropriately.
- Reduce defects. Combining ground delay decisions for both inbound and outbound flights, pre-departure, considers the total traffic demand. Including punctuality factors reduces the costs of off-schedule running.
- Reduce transport wastes. Optimising flight paths avoids this waste.
- Use human talent. Human-centred design using front-line people develops trust and effective processes.

Figure 20 The 8 Wastes of Lean

Appendix B Empirical Measurement of Air Traffic Congestion Wastes

Flight efficiency is readily measured directly from surveillance data for both airborne and taxi delays.

Measuring Flight Efficiency

In congested traffic, aircraft must wait for traffic ahead.

- Aircraft taxiing can simply slow or stop and wait.
- In the air, aircraft cannot stop but must diverge from their flight path, either by extending the flight path in some other direction or entering a holding pattern to wait in place.

Waste emissions can therefore be directly measured from aircraft movement surveillance data. At a headline level:

- Taxi delays are measurable in the form of excess taxi time, compared with the time required for an aircraft to travel unimpeded between the runway and gate stand.
- Airborne delays can be measured from the extended flight path required to absorb any airborne delay, compared with the instrument procedure flight path that would be otherwise be flown.

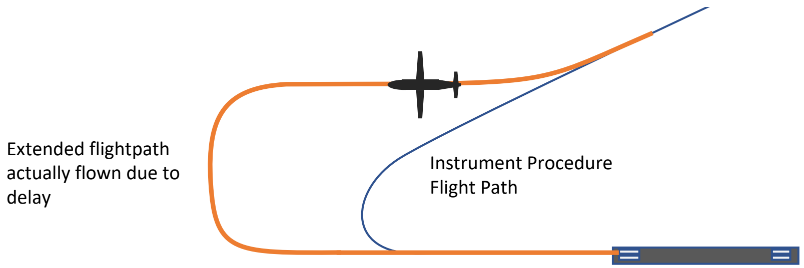

Figure 21 Flightpath Extension Due to Air Traffic Congestion Delay

Obtaining Flight Efficiency Metrics

- The ubiquity of ADS-B OUT in the aircraft fleet enables simple and direct flight efficiency measurement. Both taxi delays and airborne delays can be readily measured from aircraft movement data by observing taxi times and airborne route extension.
- Gathering surveillance-based metrics does not require a surveillance system to the standard required for ATC separation assurance. Data sources could include commercial data aggregators, including quite low-cost open data sources, or simple, low-cost ADS-B receivers suitably located. Both taxi delays and airborne route extension due to congestion occur within about 100nm of the airport and therefore within range of receivers located near to the airport.
- Directly measuring flight efficiency would inform investment decisions, and enable performance measurement, tuning and continuous improvement of emissions reduction initiatives.
- Stakeholders could consider gathering flight efficiency metrics as a first step, to inform decisions about where to invest in emissions reduction initiatives, and to measure the effectiveness of any changes

Location and Scale of Waste Emissions

Using these flight efficiency metrics, avoidable delays are found to occur in New Zealand predominantly when queueing for access to the runway – either on taxi-out for departures, or in flight for arriving aircraft. To a smaller extent, taxi-in delays can also occur for aircraft waiting to use an occupied gate stand on arrival.

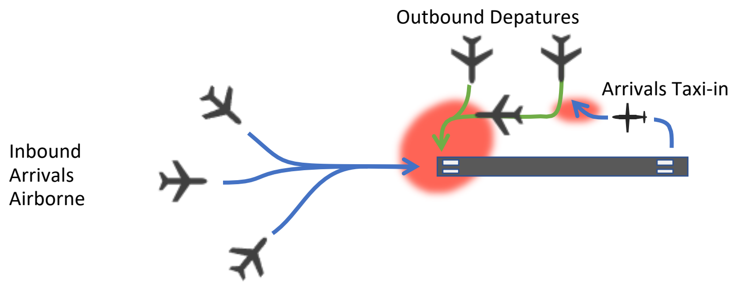

Figure 22 Air Traffic Congestion at Airport Capacity Constraints

Appendix B Empirical Measurement of Air Traffic Congestion Wastes

Waste emissions due to traffic congestion occur at runway and gate stand capacity constraints. Taxi-out delays dominate congestion costs and impact schedule adherence

Taxiing delays

Using surveillance based methods to analyse traffic between February 2017 and February 2018, the 2019 A-CDM report (Mahino Consulting, 2019) found that

- 25% of departure at Auckland and between 7% and 12% of departures at Wellington had avoidable taxi-out delays greater than 5 minutes.
- Additional but less frequent delays occur at taxi-in when a vacant available gate stand is not ready for an arriving aircraft. The 2019 A-CDM report found that, up to 3% of arriving flights at Auckland and Wellington were affected by taxi-in delays due to gate stands not being available.
- These excess delays were between 5 and 30 minutes per affected flight, disproportionately affected regional domestic flights, and were large enough to have affected on-time performance for some flights[30].

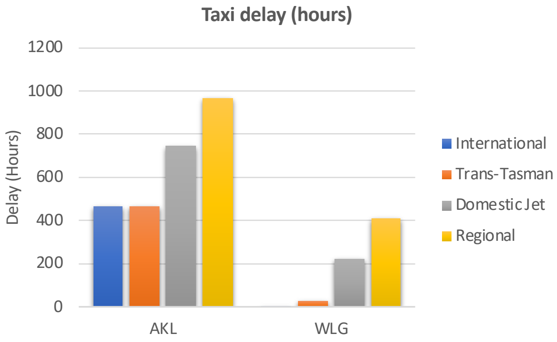

Figure 23 Annual Taxi Delays at Auckland and Wellington

- Taxi-out delays longer than 5 minutes are estimated to have burned 2,056 tonnes of fuel which was converted into 6,477 tonnes of CO_2 at a cost to aircraft operators of about $8.9M.

Including the cost of late running would increase both the penalty of taxi-out delays, and the return on investment in developing emission reduction processes, possibly substantially. The costs of late running can be considerable, and are understood to be equal to, or greater than the cost of waste emissions currently[31].

Airborne delays

The 2018 Acuo PBN CBA[32] found that

- 21% of all flights arriving at Auckland (2016 data) received airborne delays of between 1 and 3 minutes.
- Between 25% and 50% of arrivals were delayed by two minutes or more when the traffic flow rate exceeded 35 movements per hour – about 54% of airport peak flow capacity. (25% of all traffic arrived during these periods).
- Total airborne delays in 2016 were about 1367 hours. As with taxi delays, domestic regional operations are disproportionately affected. Airborne delays are estimated to have burned 2,211 tonnes of fuel, creating 6965 tonnes of CO_2 with direct aircraft operating costs of about NZ$ 4.88M.

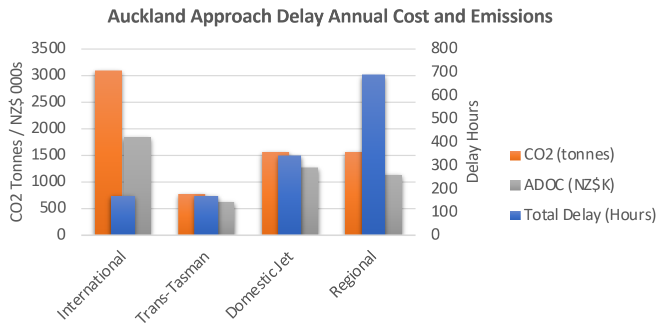

Figure 24 Annual Airborne Delay Hours, Emissions, and Cost at Auckland

30 (Mahino Consulting, 2019) p15

31 (Mahino Consulting, 2019) p 16.

32 (Acuo, 2018)

Experience suggests that delays of a similar nature can be expected at other airports during busy periods, particularly Wellington and Queenstown airports which have relatively low peak flow capacity, and high gate stand occupancy at peak times.

The above data is a sample snapshot. When deciding on emissions reductions investments, we assume that decisions would be based on objectively measured flight efficiency and prioritise the most cost- effective locations.

The Cost of Wastes

The cost and emissions volumes in estimates here are approximate and intended only to be reasonably indicative. Estimates use the traffic data from the relevant studies and a generic value for operating cost and emissions for each category of traffic. The fuel flow used here differs from the original studies, to better approximate the current more fuel-efficient fleet. Marginal costs are calculated as the sum of fuel costs and the marginal aircraft direct operating cost (ADOC) excluding fuel. Fuel cost uses the current jet fuel price of US 0.74/kg and exchange rate of 0.71 NZD/USD.

Category	Taxi Fuel Flow (kg/min)	CO_2 Emissions (kg/min)	Taxi Fuel Cost (NZD/min)	ADOC ex Fuel (NZD/min)	Total Cost of Taxi Delays (NZD/min)
Regional Domestic	6	18.9	6.24	14.9	21.14
Jet Domestic	11	34.65	11.44	37	48.44
Narrow Body International	11	34.65	11.44	37	48.44
Wide Body International	20	63	20.8	61	81.8

Table 5 Fuel, Emissions, and Operating Costs Per Aircraft Category

Appendix C Traffic Density and Flow

Limiting traffic density minimises congestion. Doing so enables the highest traffic flow, minimising both emissions and delays

Congestion is a Function of Traffic Density

Delays are a function of traffic density. As with road transport, air traffic delays occur when traffic bunches such that the density of traffic would become greater than the safe separation distance between vehicles (aircraft in the case of aviation).

In 1934, Bruce Greenshields analysed road traffic and formulated his seminal theory of road capacity. The research found that vehicle speed was most related to vehicle density and that this relationship is general. Once the density of vehicles exceeded the capacity of the road, the speed of all vehicles reduce[33]. The relationship between flow, density and speed are generic and illustrated in the macroscopic fundamental diagram of traffic flow (MFD).

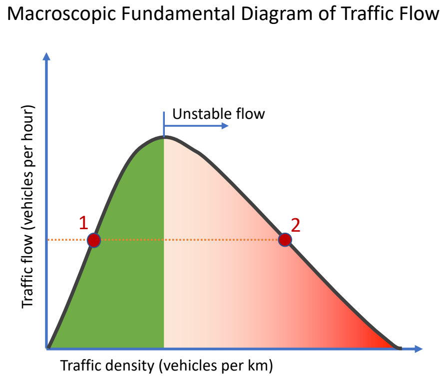

Figure 25 Macroscopic fundamental Diagram of Traffic Flow (MFD)

The depiction shows two familiar modes of traffic flow – unrestricted (green), and congested (red). When traffic density is below the capacity of the system (the peak flow point), traffic flows freely and the flow increases in proportion to the density of traffic. When density increases above the system capacity, flow decreases toward zero as the vehicles get closer together. The flow is unstable: vehicles held back by the vehicle ahead propagate the congestion back along the line of traffic, increasing the congestion behind them.

There are three key implications of the MFD:

- The decreased speed of traffic in congested conditions creates waste due to the longer journey time. Reducing emissions requires *controlling traffic density*.
- The same traffic flow be achieved efficiently in free-flowing traffic (1), or inefficiently in congested traffic (2). This means controlling traffic density can deliver the same traffic flow with efficiency, and without increasing overall delay.
- Throughput is higher when free-flowing than it is when congestion is present[34]. This means capacity can only be fully used when congestion is minimised.

The MFD applies to air traffic. As an example, for aircraft taxiing at Auckland and Wellington[35] delays increase when traffic density is above system capacity, and peak flow is only obtained in the absence of congestion[36].

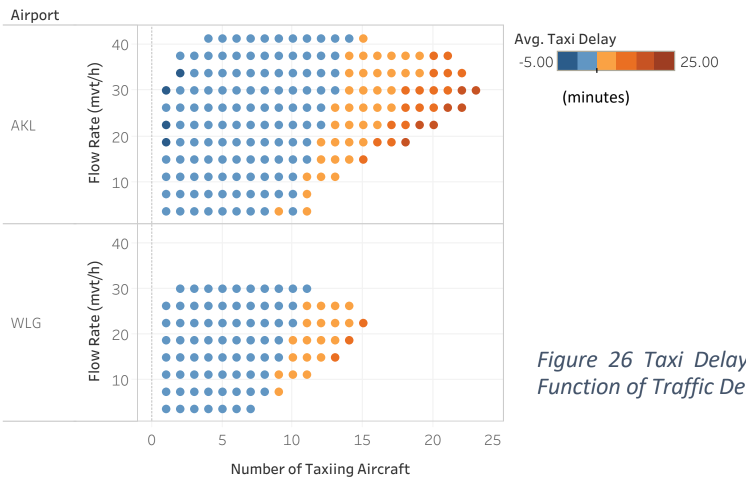

Figure 26 Taxi Delays as a Function of Traffic Density

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33 (Greenshields, 1935)

34 (Yuan et al., 2015)

35 (Mahino Consulting, 2019)

36 The chart is a density-flow diagram. Density is represented by the number of aircraft moving on the manoeuvring area. The colour at each flow/density point corresponds to the delays experienced by aircraft. Blue represents taxi delays of less than 5 minutes.

Appendix C Traffic Density and Flow

Solutions to improve efficiency are distinguished from capacity enhancement initiatives by whether they manage traffic density.

Distinguishing between Efficiency and Capacity Initiatives

The distinction between traffic density and traffic flow enables solutions for each to be clearly distinguished.

- The capacity of a constraint is normally described in terms of the peak sustainable traffic flow. Improving capacity requires an increase in peak flow.
- The rate limiting factor is normally determined by the minimum achievable separation between aircraft. Initiatives to increase **capacity** must find ways to safely reduce the achievable, sustained minimum **separation** between flights.
- Emissions wastes occur when traffic density causes aircraft spacing to approach the safe minimums, requiring various waiting behaviours.
- **Efficiency** improvement initiatives must find ways to manage traffic **density** so that aircraft remain separated sufficiently for traffic to flow freely.

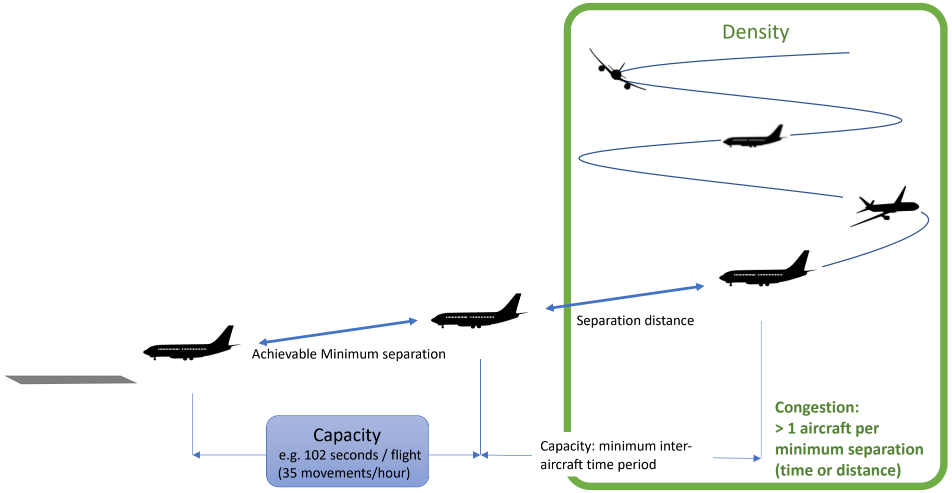


Figure 27 Distinguishing Capacity and Efficiency in Terms of Traffic Flow and Density

Demand Capacity Balance

Air traffic flow management is frequently discussed in terms of demand/capacity balance. Flight efficiency and punctuality are affected by two different balances.

- Efficiency is optimised when traffic density is balanced against separation constraints. The benefits of density/separation balance are minimised emissions and optimised flight efficiency.
- Punctuality is optimised when scheduled demand is balanced against achievable peak flow (capacity). The benefits of schedule/peak flow balance are optimum on-time performance and minimised delays.

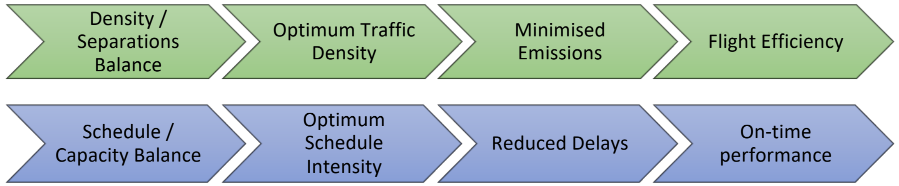


Figure 28 Distinct Benefits of Flight Efficiency and Improved Capacity

- Flight efficiency will vary if traffic density is not managed. To improve flight efficiency, this study focusses on solutions which manage traffic density:
  - *Ground delays.* By adjusting the start time of flights, ground delays can directly manage traffic density.
  - *En route speed controls*. By managing the ground speed of individual flights, traffic density can be adjusted. The restricted range of efficient aircraft speeds mean that en route speed control has limited scope to alter traffic density efficiently.

Appendix D Estimated Benefits of Reducing Air Traffic Density

Managing traffic density may save 6,000 to 9,000 tonnes of CO_2 and $7M to $10M ADOC annually.

Managing Traffic Density

By managing traffic density, an effective ground delay process could limit the maximum duration of delays experienced by aircraft in traffic congestion.

Although the maximum delay per flight may be reduced, delays for the affected flights may not be removed completely. The estimates below assume that affected flights would continue to experience the average delay of flights below the new, reduced, maximum. In other words, no change to normal operations is assumed other than reducing the density of traffic by managing flight start times.

The Value of Continuing Improvement

Emissions and cost reduction benefits will depend on the performance achieved by the ground delay planning process.

At the current state of the art, operational uncertainties will limit the degree to which the residual delay can be eliminated. To make a reasonable estimate of what might be achieved in the near term, the following analysis assumes moderate residual taxiing and airborne delays. The analysis estimates the benefits of the initial goal, and the marginal benefits of improving performance.

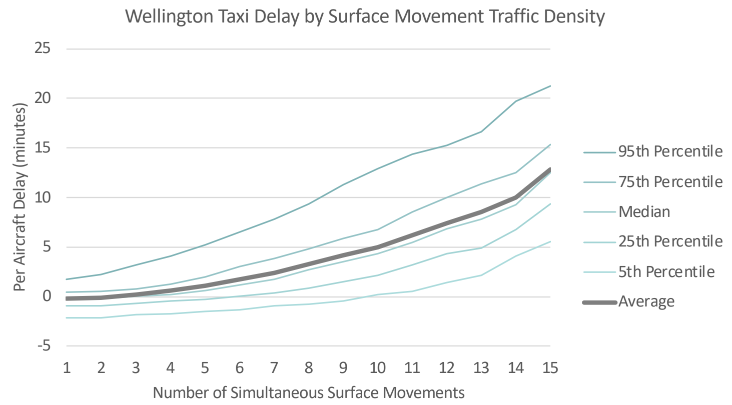
The marginal benefit of improved performance may be relatively large. Because most flights operate with modest delays, a greater number of flights are affected as the residual delay is decreased. This means that the marginal benefit of further improving the process increases as its performance improves. Stakeholders may initially find value in continuing to progressively improve the ground delay process.

Approach to estimation

The estimates here follow the methods used in the previous studies. Taxi delays are computed as the difference between the actual, and the unimpeded taxi time for the category of aircraft on the route between runway and gate stand. Auckland arrival delays are computed consistently with the "arrival efficiency" metric recommended in (CANSO, 2015) and outlined in Appendix B. The extended flight path, defined as the difference between the nominal route and the route actually flown within a 100nm radius of Auckland Airport, is converted to delay using the average speed of the aircraft over that distance.

Taxi Delays

Taxiing delays increase as the surface movement traffic density rises above a certain threshold. The threshold differs at each airport, depending on the traffic mix and the layout and size of the manoeuvring area, however the peak per-aircraft delays are similar at both Auckland and Wellington.



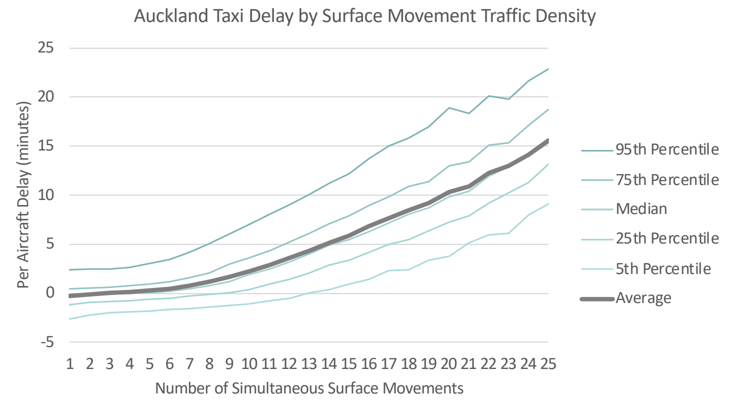


Figure 29 Variation of Per-aircraft Taxi Delay with Traffic Density at Wellington and Auckland

The following charts illustrate potential savings in CO2 emissions and ADOC depending on the extent to which residual taxi delays are reduced. As an example, but not to suggest a target performance level, the value of reducing taxi delays to no more than 5 minutes is shown, along with the value of a further 1-minute improvement. The uncertainty band shown results from the +/- 30 second uncertainty per flight in the source data, which recorded taxi times with 1 minute precision.

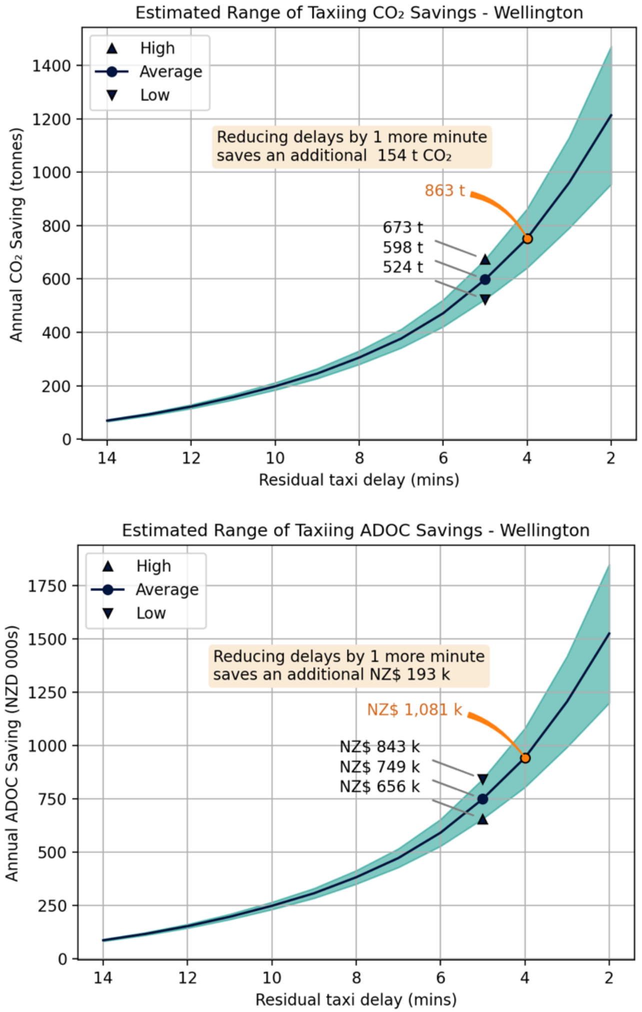


Figure 30 Benefits of Reduced Taxi Delay in Wellington

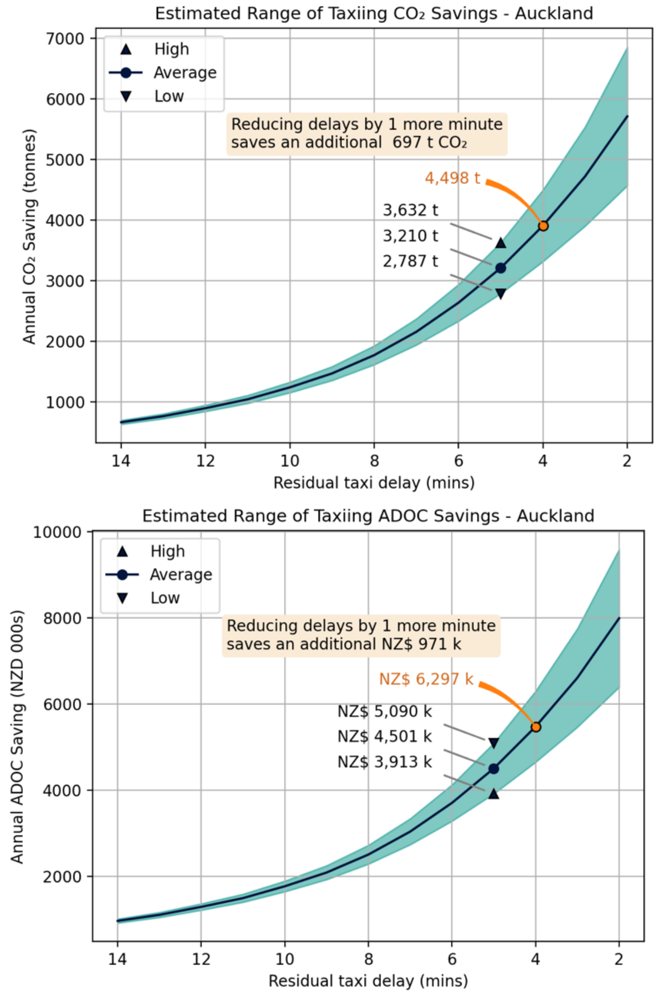


Figure 31 Benefits of Reduced Taxi Delay in Auckland

Appendix D Estimated Benefits of Reducing Air Traffic Density

Arrival Delays

Airborne arrival delays at Auckland also vary as a function of the traffic density in the airspace. That the lower quartile of traffic has negligible delay up to moderately high traffic density levels is consistent with PBN approaches continuing to be used by at least some traffic in busy periods.

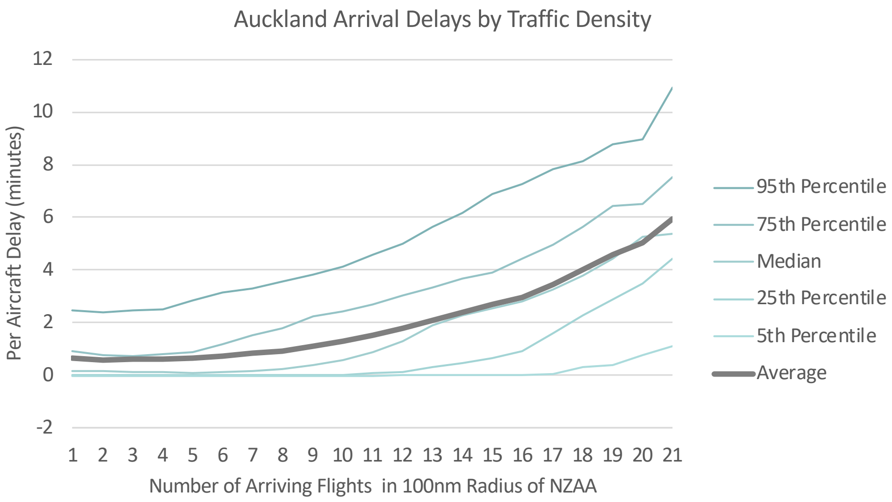


Figure 32 Variation of Auckland Arrival Delays with Air Traffic Density

Estimating Potential Delay Reduction

Benefits arise from limiting traffic density. However, the traffic density, as defined, has a floor. It is unrealistic to suppose that it could be reduced below the level required to deliver the traffic flow at the airport.

At the (rare) maximum arrival rate of about 35 movements/hour, at about 14 aircraft travelling at 270 kts, or 11 travelling at 350kts need to be within the 100nm radius of the airport to fully utilise airport capacity. At a lower flow of 25 arrivals/hour (the more frequent case), between 10 and 8 aircraft would be required.

In practice the ground delay process would ensure that traffic density was appropriate for the flow rate at the time. It is beyond the scope of this study to model that balance. For the purpose of estimating benefits, this analysis assumes that the peak traffic density would at least be reduced to the level required to fully use the airport capacity. In reality, greater savings can be expected. Data indicates that, frequently, more traffic than necessary arrive within the 100nm radius at all flow rates. Additional savings would be made at lower flow rates if an appropriate lower traffic density was assured.

The following chart illustrates the savings that would be made by limiting the peak traffic density. Delays reduce most for the upper quartile of delayed flights. As with taxiing delays, the benefits increase significantly with marginal reductions in traffic density, and ongoing improvement of the ground delay process is likely to create additional value.

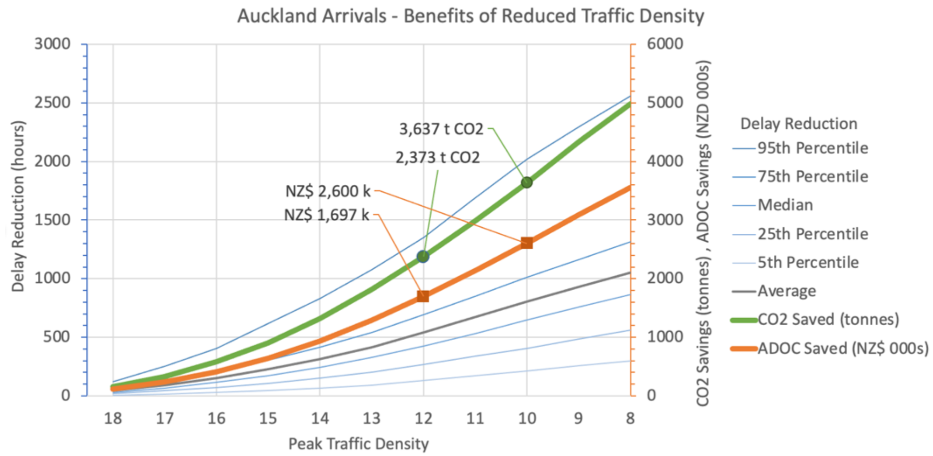


Figure 33 Benefits of Reduced Arrival Delays in Auckland

Summary

This analysis suggests that reducing air traffic congestion may realise annual savings of 6000 to 9000 tonnes of CO_2 and \$7M to \$10M in ADOC for the areas considered. The majority of benefits arise in reduced taxiing delays.

		CO2 (tonnes)	ADOC (NZ$M)
Taxiing	NZWN	598 – 863	0.75 – 1.08
	NZAA	3,210 – 4,498	4.5 – 6.3
Arrivals	NZAA	2,373 – 3,637	1.7 – 2.6
Total		6,181 – 8,998	6.95 – 9.98

Appendix E Airport Capacity

Runway capacity is more affected by the ratio of arrival and departure traffic than any other factor

Ground Delays Need to Manage Both Arrivals and Departures

Runway capacity not only varies with the wind[37] and visibility[38] but also with the volume of arrivals and departures. The balance between arrival and departure traffic flows is the most significant factor affecting runway capacity.

Auckland runway capacity, as measured empirically from actual traffic data[39], conforms with research on the topic[40], is typical of runways generally, and illustrates the relationship between departure and arrival flows and airport capacity.

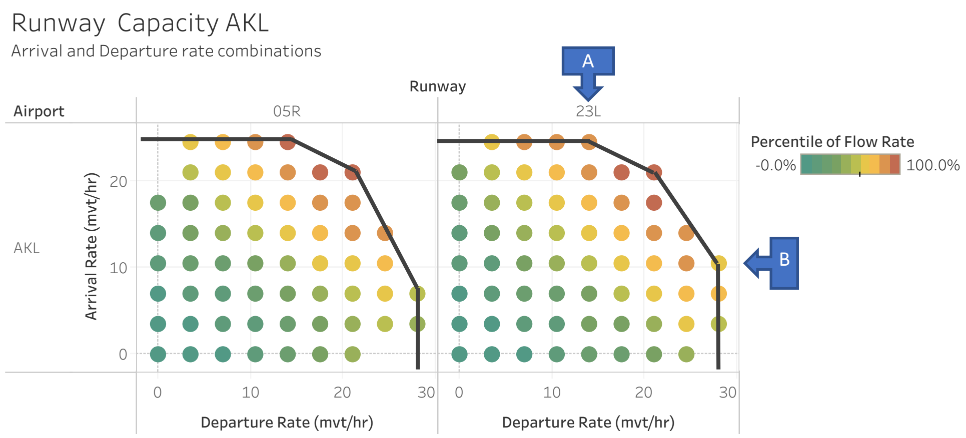


Figure 34 Runway Capacity Depends on Arrival / Departure Ratio

- The black line shows the demonstrated runway capacity with various arrival and departure rates.
- The maximum arrival capacity occurs when the departure flow is reduced (A), and vice-versa (B).
- The arrival and departure capacities vary by about 50% depending on the volume of the alternative traffic flow.

The mutual interaction between arrival and departure flows means that

- To best use runway capacity, ground delay rationing needs to trade off arrival and departure capacity, managing both arrivals and departure flows.
- Runway capacity cannot be predicted solely based on weather, but must take into account the likely demand from both arriving and departing traffic flows.

[37] The arrival rate is affected by the headwind component when arrivals are separated by distance. Higher headwinds create lower ground speeds, reducing the arrival flow rate when aircraft spacing is constant.

[38] Visibility primarily affects runway capacity in fog conditions. Historically, the arrival rate could be affected by cloud ceiling, if visual or circling approaches were in use, however there is a strong trend toward using PBN instrument approaches at the main aiports in NZ, and cloud ceiling is now less influential on arrival rates.

[39] (Mahino Consulting, 2019)

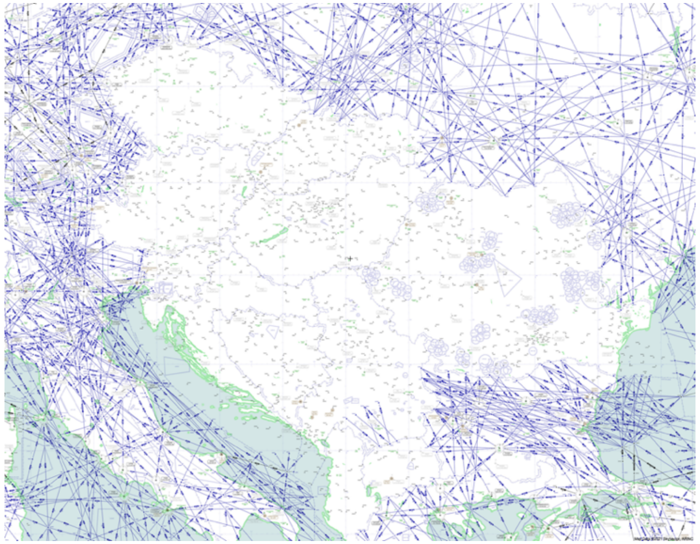
[40] (Kristan et al., 2017)

Appendix F Free Route Airspace

Free route airspace (FRA) delivers efficiency benefits in Europe. FRA changes ATC workload and may require airspace revision

Free Route Airspace

- Free route airspace (FRA) allows airspace users to fly their preferred trajectory unconstrained by fixed routes.
- Benefits for users include being able to plan flights to fly the most direct, or the most wind-effective flight path with environmental and financial advantages.
- FRA is mandated in Europe above flight level 310 from 1 January 2022[41]. A number of states have implemented FRA at lower levels. Portugal's entire FIR adopted free route airspace in 2009, Hungary in 2015, Slovakia in February 2021. Maintaining the fixed route structure is optional. Hungary, and others, disestablished the fixed route structure completely at all altitudes in some areas.



Source: Skyvector.com

Figure 35 South East European Free Route Airspace

ATC Experience

- FRA reduces the structured organisation of air traffic. Although conflictions may be reduced as a result of the traffic being more spread out, they may increase due to less organised flows. Hungarian experience[42] is that ATC workload may reduce where traffic is largely travelling in similar directions (the New Zealand case), but would increase where there is a substantial amount of crossing traffic.
- Removing the constraint of fixed routes creates a change in cognitive processing for controllers. "Hotspots" become more unpredictable. Sustained attention to a wider airspace is required. To ensure controllers can smoothly apply practiced actions, HungaroControl found that both simulator and on the job training time increased by 30%.
- Controllers benefit from decision support tools including projected flight path display, route adherence monitoring, medium term conflict detection, or conflict probe to check the likely outcome of ATC instructions before they are issued[43].
- The workload of the ATC planner role increased to a similar level as the executive controller as a result of the increased monitoring and coordination activity required.

Airspace and Navigation System

- Airspace re-alignment may be needed to structure boundary coordination where flights would otherwise frequently make very short duration transits (airspace clipping) or multiple transits across a sector boundary[44].
- Structure is still required in the navigation system. Entry and exit points to terminal airspace and fixed navigation procedures are required. Strategic separation between traffic flows can be aided using one-way entry and exit points, including across ATC sector boundaries. In particular, safety is enhanced where the navigation system reduces the chance of aircraft conflict close to an ATC boundary[45].

[41] (European Union, 2014)

[42] (Renner et al., 2018)

[43] (O'Keefe et al., 2015)

[44] (NMD/ACD, 2021)

[45] (MND/OPL, 2019)

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