Weather-Aware Integrated Air Traffic Management Technology Development

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***Abstract*—Air Traffic Management (ATM) balances expected demand with available capacity at airport and airspace resources for multiple hours into the future. Predicting demand and capacity levels at these time horizons is challenging due to highly dynamic conditions, especially during periods of adverse weather. This is compounded by the fact that decision support technologies are often stove-piped and do not translate weather impacts into key decision metrics, which limits their effectiveness. This paper describes an integrated suite of technologies being developed to enable more effective weather-aware decision support for ATM needs. Technologies tailored to specific needs in terms of weather situational awareness and impact translation at airport, terminal and en route airspace resources are described. Details of some of the key technology components and operational prototyping efforts with NAV CANADA are described. Finally, the paper outlines how they will ultimately be integrated along with other advanced ATM automation systems to support the evolution of NAV CANADA's operations, for example towards network management and Trajectory Based Operations (TBO). This effort could provide valuable insights for other world regions experiencing similar ATM challenges, including the US & Europe.**

Keywords—ATM weather impacts; demand/capacity balancing; integrated decision support.

I. Introduction

One of the primary objectives of Air Traffic Management (ATM) is to balance expected demand with available capacity at airport, terminal and en route airspace resources throughout the system for hours into the future, as illustrated in Figure 1. The process starts with effective predictions of the weather and demand profiles over the relevant time periods. Then there is a need to translate weather into capacity impacts on different parts of the aviation system, as shown in the blue box. Next is the need to assess the temporal and spatial profiles of these capacities relative to demand from which imbalances can be identified. The right side of Figure 1 illustrates an example of weather moving through a region, causing the capacity of resources such as airports, terminals and en route airspace to fluctuate, as shown by the blue line. If demand exceeds the forecast capacity (i.e., demand over-delivery shown by the solid red line), there will be operational challenges requiring responses such as airborne deviations, holding and diversions. More efficient strategies involve proactively managing the demand to bring it back into balance with the expected capacity as a function of time, as shown by the dotted red line. A range of so-called Traffic Management Initiatives (TMIs) can be used to do this (shown by the feedback loop in Figure 1), modifying demand at locations

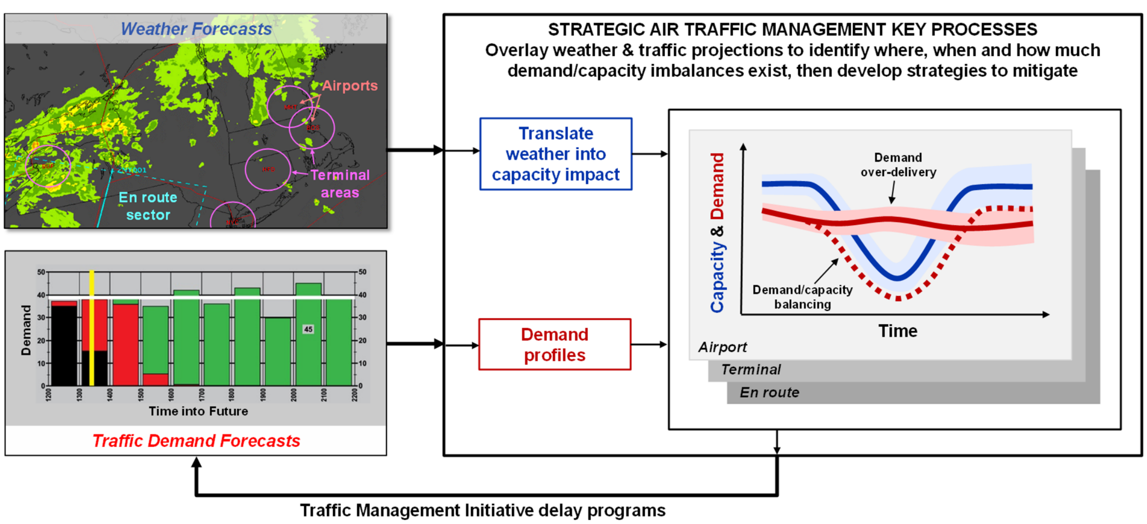

Figure 1. Simplified air traffic management processes to balance capacity & demand during weather events.

*See Acknowledgments section for the full development team.

and times when it is expected to exceed capacity. For example, strategic re-routes can be used to avoid large regions of convective weather, but these often must be initiated many hours before the weather impact. Other initiatives, such as time-based metering with an Arrival Manager (AMAN), can be applied more tactically at shorter timeframes to help manage demand more surgically.

However, predicting demand and capacity profiles for many hours into the future to support these TMI decisions can be very challenging due to highly dynamic conditions (which generate considerable forecast uncertainty, illustrated by the shading around the capacity and demand profiles in Figure 1), especially during periods of adverse weather. Currently, ATM decision support technologies are largely limited to aviation-specific weather forecasts over 0-12 hour timeframes, but the translation to capacity impacts and demand/capacity imbalance prediction components are largely missing. In the absence of this, traffic managers need to mentally estimate weather impacts on capacity and then combine their estimates with demand and other constraints in the future for various regions of airspace of relevance to their TMI decision-making. This is a challenging endeavor which often leads to high workload, inconsistent decision-making and sub-optimal use of resources, leading to either excess delay (over-delivery of demand) or inefficient use of available system capacity (under-delivery of demand).

Developing techniques to forecast weather-impacted capacity of different airport and airspace resources has received a lot of attention in the research literature, consistent with its importance. In the airport domain, a standard approach to predicting airport capacity has been to use empirically-derived achieved throughput envelopes [1], then using convex hulls at selected high percentile levels of the achieved throughputs to estimate capacity in different airport configurations. Explicitly accounting for weather impacts and uncertainty on airport capacity has also been widely studied using a variety of approaches, e.g., [2], [3]. Modern machine learning techniques are now also being explored for modelling the impact of adverse weather on airport capacity, e.g., [4]. Assessing weather impacts on airspace has also been studied extensively, for example in the terminal [5] and en route [6] domains, which resulted in the development of the Convective Weather Avoidance Model (CWAM) concept which is now used extensively within the aviation community, e.g., [7].

Despite the breadth of work in these areas, there has been limited focus on either (1) explicit prediction of demand/capacity imbalances in the airport and airspace domains, or (2) technologies that integrate the coupled effects of weather in an ATC ecosystem in terms of airport, terminal and en route airspace impacts. This paper addresses these needs by describing an integrated suite of technologies being developed to enable more effective weather-aware decision support for ATM needs consistent with the process shown in Figure 1. Technologies tailored to specific ATM needs in terms of weather situational awareness and impact translation at airport, terminal and en route airspace levels are described at a high-level in Section II. A deeper dive into the advanced technology being developed for one of the components is provided in Section III. Section IV outlines the development plan for the technologies and how they will ultimately be integrated along with other advanced ATM automation systems to support the evolution of NAV CANADA's operations into the future. Section V presents a summary and next steps.

II. Overview of Weather-Aware Integrated ATM Decision Support Technology Vision

The red elements of Figure 2 illustrate the main weather impacts which disrupt aircraft in different flight phases, which in turn can make ATM challenging. Airport and/or downstream weather and traffic volume constraints can lead to the need to hold flights at the departure airport. Weather impacts at a variety of airspace resources which the aircraft is planning to use, including departure routes/fixes, en route

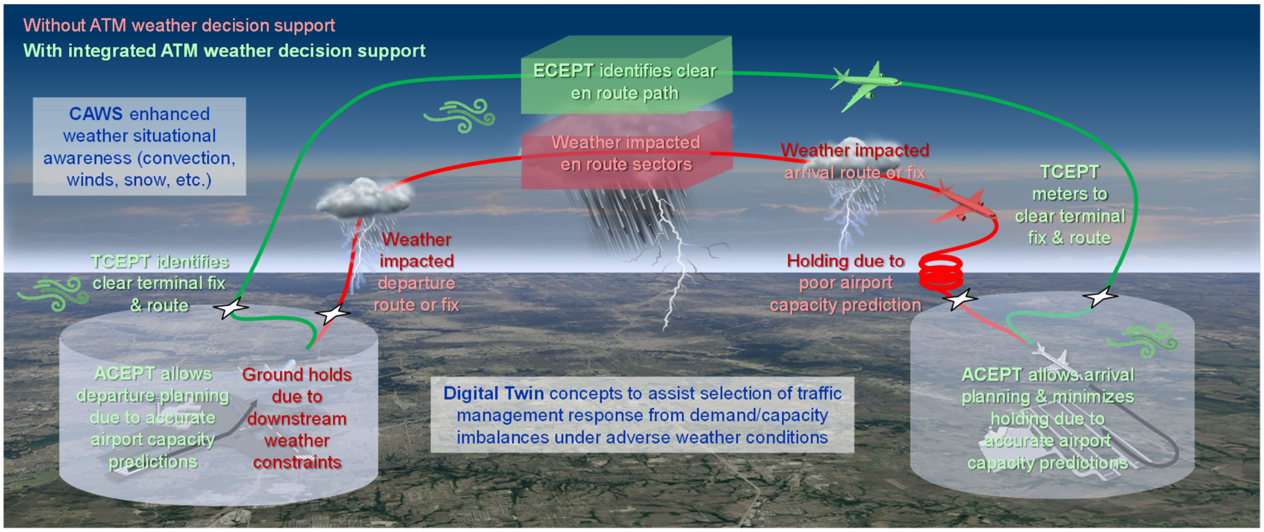

Figure 2. Primary weather impacts (in red), integrated ATM weather decision support opportunities (in green) and supporting technologies (in blue).

airspace sectors and arrival routes/fixes can lead to the need for airborne re-routes, speed changes, vectoring, holding and other sources of airborne delay. Finally, constraints at the arrival airport can lead to the need for vectoring, holding and/or diversion of the aircraft.

All these impacts can be mitigated through the development and deployment of effective advanced weather decision support technologies tailored to the individual airspace regions and associated weather impacts. The primary weather impacts which drive capacity (and hence ATM decision-making) in the different flight phases, are shown in Figure 3. Convective storm intensity and height in en route sectors determines whether flights will need to fly around or can over-fly bad weather, and hence what capacity can be expected from the impacted airspace sectors. Storm intensity relative to departure and arrival routes and fixes, as well as strong wind profiles (e.g., those causing "compression" in aircraft flow separations) are key determinants of terminal airspace capacity. Finally, airport capacity is largely driven by winds, ceiling & visibility and precipitation (which affects runway conditions) given these weather challenges impact what specific runway configurations and arrival rates will be achievable.

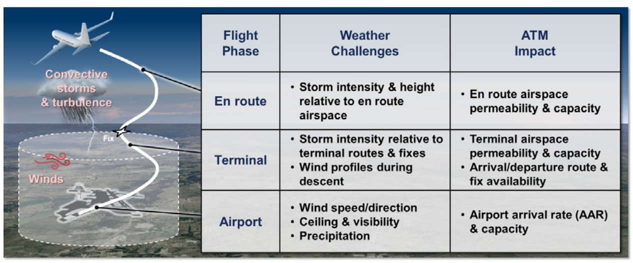

Figure 3. Key weather challenges and ATM impacts by flight phase.

There is a need to develop technologies to help with awareness of these different aspects to support decision-making at different timeframes, which are typically described as "tactical" over the 0-2 hour timeframe, and "strategic" over 2-12 hours. The technologies shown in the green elements of Figure 2 are designed to work together to mitigate many of these challenges to support effective ATM decision-making. The technology suite currently under development consists of:

A. *Airport Capacity Evaluation & Prediction Tool (ACEPT)* to predict weather impacts at key airports

B. *Terminal Capacity Evaluation & Prediction Tool (TCEPT)* to predict weather impacts on key terminal areas

C. *En route Capacity Evaluation & Prediction Tool (ECEPT)* to predict weather impacts on key en route sectors

Each of these technologies will be discussed in more detail in the following sections. The supporting technology of the Canadian Aviation Weather System (CAWS) is not discussed in detail here. But briefly, CAWS is a prototype technology currently in development which will provide foundational weather capabilities to enhance weather situational awareness for aviation stakeholders and will provide weather inputs to the other prototypes. CAWS will leverage MIT Lincoln Laboratory's long history of aviation weather technology development, including the Corridor Integrated Weather System (CIWS) [8], Consolidated Storm Prediction for Aviation (CoSPA) [9] (both of which will ultimately be integrated into the NextGen Weather Processor (NWP) [10]) and Offshore Precipitation Capability (OPC) [11] technologies developed for the Federal Aviation Administration (FAA). CAWS will build upon and optimize these technologies for Canadian operations by ingesting additional weather radar and Canadian numerical weather prediction model data. In regions without weather radar data, CAWS will train OPC algorithms and blend the resulting synthetic weather estimates with existing radar-based systems to create a seamless mosaic that provides full weather situational awareness over NAV CANADA's domestic and oceanic airspace. The initial CAWS prototype was released to users in November 2023.

A. *Airport Capacity Evaluation & Prediction Tool (ACEPT)*

ACEPT is a technology to predict airport capacity and demand imbalances to guide "day of" strategic planning and decision making for NAV CANADA and relevant stakeholders. The overall concept is shown in Figure 4.

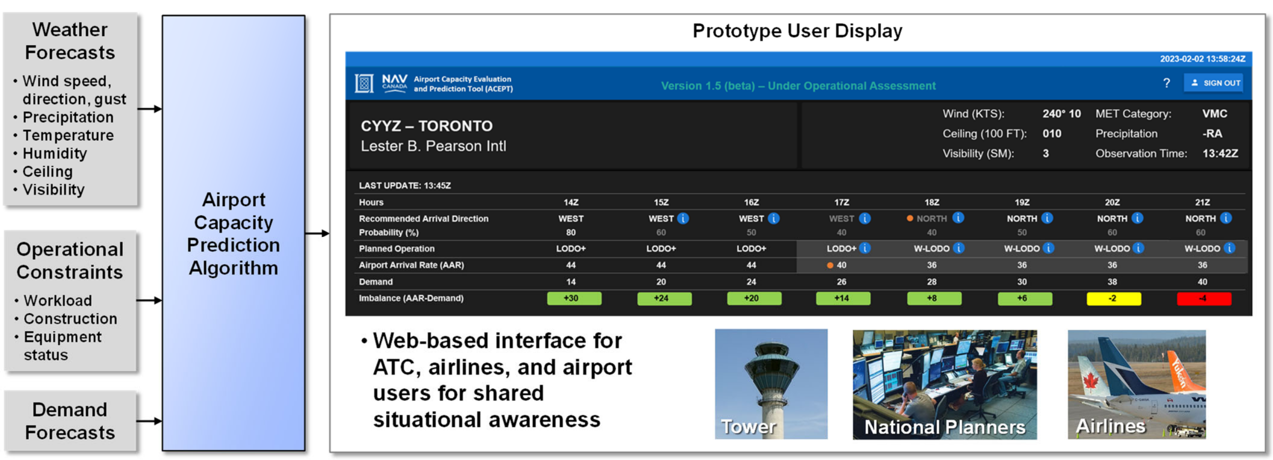

Figure 4. ACEPT inputs & prototype display.

ACEPT ingests weather forecasts (e.g., of winds, ceiling, visibility & precipitation), demand forecasts and constraint information (e.g., in terms of which runways are available) and uses subject matter expert-approved rulesets to determine the most likely airport configurations in one hour time bins for 8 hours into the future as a function of these inputs. From this, airport capacity in the form of Airport Arrival Rates (AARs) can either be entered manually by an ATM supervisor or calculated and compared to expected demand in each time bin. In this way, potential airport demand/capacity imbalances can be explicitly identified hours ahead of time and this information can be used to determine when traffic management initiatives may be needed to modify demand into the airport to better align with the expected capacity. Making this information available to all stakeholders supports effective Collaborative Decision Making (CDM) by providing a common source of information from which discussions can proceed. The initial ACEPT prototype was developed for operations at Toronto Pearson International Airport (YYZ) and released to users via a web application in April 2020. Since then, a number of iterative refinements have been made which have increased the fidelity and accuracy of the weather information, airport configuration options and arrival capacity and demand prediction elements. More details on the ACEPT technology are presented in Section III.

B. *Terminal Capacity Evaluation & Prediction Tool (TCEPT)*

TCEPT predicts terminal airspace and fix (also known as "bedpost") availability and capacity to guide strategic and tactical planning in convective weather. This will allow proactive re-routing of arrivals and departures to available fixes and more effective conditioning of arrival demand for transitioning to time-based arrival management during convective weather.

The TCEPT prototype is also being developed initially for Toronto Pearson airport and the display currently available to users is shown in Figure 5 for an example day when convective weather is impacting the region. It currently comprises a CIWS/CoSPA-based weather forecast situational awareness display (which will eventually be replaced by CAWS) zoomed into the YYZ terminal area. The arrival bedposts (named IMEBA, RAGID, LINNG, NUBER and BOXUM) are visible in cyan text within the weather display. The left side of the TCEPT display provides a tabular representation of the weather impacts on the terminal region, where the rows of the table are each bedpost (as well as a row for the overall Terminal Control Unit (TCU)), and the columns are times into the future in 30 minute time bins. Additionally, TCEPT provides estimated bedpost arrival demand over the next 2 hours (see panel at the bottom left of Figure 5) utilizing a combination of radar derived aircraft data and flight plan message data. This combination of predicted convective weather impact and arrival demand allows users to thoroughly evaluate potential flight over-delivery situations and plan mitigations accordingly.

For the day shown, convective weather is moving into the terminal area from the west to east and the south-west bedpost (NUBER) is being impacted over the next few hours as shown by the yellow and red impact colors in the cells of the table. By clicking on a bedpost, TCEPT also provides a graphical representation of the estimated "permeability" of the airspace around it over the available forecast horizon. Permeability represents the degree to which traffic flows are constrained by convective weather in a given airspace region. Permeability can be translated into a categorical impact metric (e.g., low/green, moderate/yellow, severe/red) or a quantitative measure of the achievable or sustainable traffic flow rates. These can be generated through a large statistical analysis of historical traffic flow rates, which can then be used to estimate capacity. In the figure, the weather impacts to NUBER over the next several hours are clearly visible, followed by recovery in the permeability as the weather moves away. This graph also displays 20th-80th percentile uncertainty bounds around

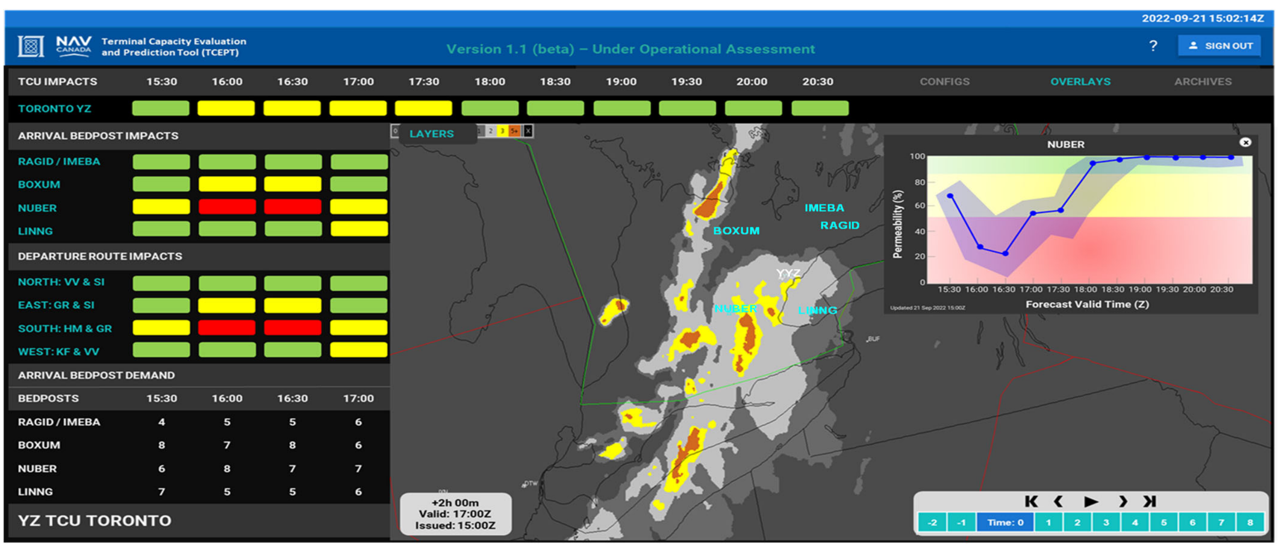

Figure 5. TCEPT prototype display.

the estimates so users can factor the confidence levels of the estimates into their decision-making.

C. En route Capacity Evaluation & Prediction Tool (ECEPT)

ECEPT refines and adapts existing Traffic Flow Impact (TFI) technology [12] (currently provided to FAA users via CoSPA) for the en route airspace regions upstream of the TCEPT terminal arrival regions at Toronto. It integrates multiple weather forecast products with extensive historical analysis of forecast accuracy and traffic flows, to generate an objective display of airspace permeability. This is based on the Lincoln-developed Convective Weather Avoidance Model (CWAM) [13] discussed previously, augmented by modern machine learning algorithms. Airspace permeability is displayed as a percentage along with a red/yellow/green categorical impact indication similar to TCEPT, but for en route airspace regions. Augmenting the display is an indication of forecast confidence appropriate to the current situation based on historical analysis of weather forecast performance. The prototype ECEPT display is shown in Figure 6. It looks very similar to TCEPT, except the table rows are different *en route* regions and the columns are *one hour* time bins out 12 hours to support the different decision needs in the en route domain. With ECEPT, all stakeholders have a common picture of the statistical distribution of capacity reduction for hours into the future so that discussions can focus on risk assessment, rate setting and determining the start and end times of TMIs.

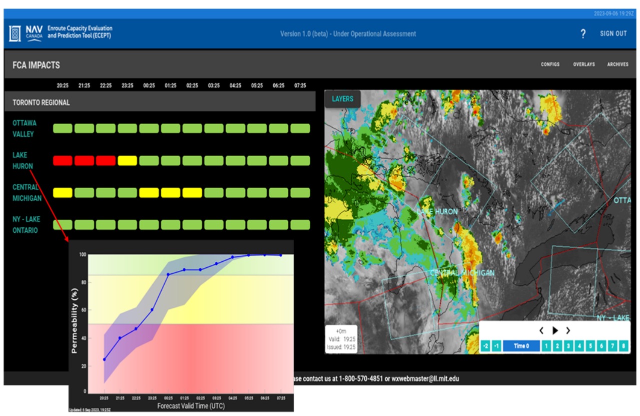

Figure 6. ECEPT prototype display.

III. ACEPT Technical Details

The previous section gave a high-level overview of the individual technologies being developed for NAV CANADA which make up the envisioned integrated tool suite. There are significant technical development activities underpinning each of these technology areas, but complete descriptions of them all are outside the scope of this paper. However, in order to illustrate some of the novel technology development areas needed to bring this vision to reality, this section provides more detail on elements of ACEPT which is currently the most mature of the development areas. The following sub-sections cover details on the airport configuration and capacity selection process, the current Toronto ACEPT prototype and information on the weather uncertainty quantification approach.

A. Toronto Pearson Configuration and Capacity Discussion

At Toronto Pearson International Airport there are four possible airport configurations that are a function of the runway layout as shown in Figure 7.

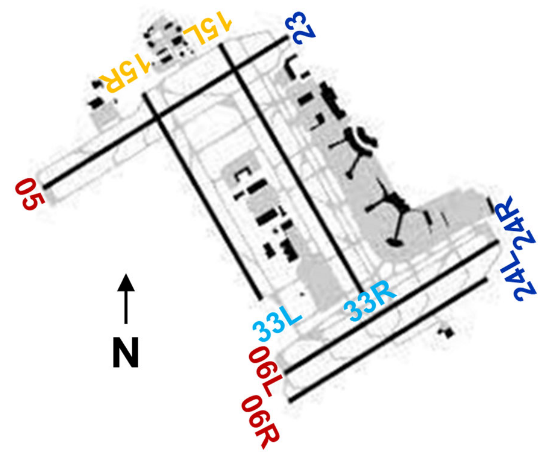

Figure 7. Toronto Airport runway layout.

These configurations are commonly referred to in the four cardinal compass directions as follows:

- NORTH = arrivals on runways 33L/R
- EAST = arrivals on runways 05, 06L/R
- SOUTH = arrivals on runways 15L/R
- WEST = arrivals on runways 23, 24L/R

There are also several different types of airport operations for Toronto Pearson that are a function of the number of runways available for landing/departing, ATC workload, and equipment status. The possible airport operation modes are: TRIPLE, DUAL, LAND ONE DEPART ONE (LODO), LODO with offloads (LODO+), and SINGLE. Table I presents the planned AAR as a function of airport arrival direction and airport operation in the absence of any visibility constraints.

Table I. Toronto typical AAR as a function of arrival direction & operation.

Arrival Direction	Operation				
	Single	**LODO**	**LODO+**	**Dual**	**Triple**
North	28	36	36	N/A	N/A
East	28	36	44	52	60
South	28	36	36	N/A	N/A
West	28	36	44	52	60

As can be observed in the table, with ideal weather conditions and all available runways, the highest possible AARs can be achieved with a WEST or EAST arrival direction and hence they are the preferred airport configurations. But weather conditions (e.g., cross-wind, tail-wind, ceiling and visibility limits) can force the airport to operate in NORTH or SOUTH configuration. This causes a significant reduction in the AAR, and awareness of time periods requiring a NORTH or SOUTH configuration are critical for proper arrival rate setting. Even more critical is awareness of a likely shift to/from one of these configurations during peak demand periods to perform effective ATM planning.

An example of how the airport configuration and corresponding AARs in DUAL (WEST and EAST) or LODO (SOUTH and NORTH) under Visual Meteorological Condition (VMC) as a function of wind speed and direction is shown in Figure 8.

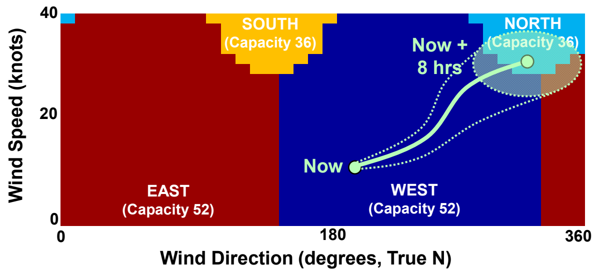

Figure 8. Toronto Pearson airport configuration and capacity under VMC as a function of wind speed & direction.

The EAST and WEST arrival directions are shown by the red and blue regions with an AAR of 52, while the SOUTH and NORTH arrival directions are shown in yellow and cyan with an AAR of 36. An example forecasted wind profile is illustrated by the green curve as it moves from "now" to eight hours in the future. The forecast begins in WEST configuration and as the wind increases and shifts, the airport arrival direction may need to change from WEST to NORTH. As discussed earlier, this will be highly impactful to airport capacity and if this occurs during a peak demand period it may result in significant delays through holding, diversions and cancellations.

Also depicted in Figure 8 is a green oval and two dashed curves which represent the potential uncertainty in the weather forecast. For decision makers, the fact that the green oval overlaps three airport configuration, one of which is highly impactful, makes the decision to pro-actively limit the AAR during the expected time of NORTH configuration very challenging.

In today's operational decision-making environment, air traffic managers integrate their favorite weather forecasts (which may vary from one person to another), together with judgement on which operation will be possible, to plan the airport's AAR. The assumptions that go into this decision-making process are not fully transparent to all stakeholders and decisions may be inconsistent from one traffic manager to another, potentially leading to inefficient collaborative decision making and sub-optimal operational outcomes.

B. Airport Capacity & Evaluation Prediction Tool

ACEPT is being explicitly designed (with stakeholder input) to address all these needs by meeting the following objectives over an eight-hour forecast horizon:

- Curating accurate weather information which, over time, will become the definitive weather source for supporting AAR decision-making.
- Explicitly calculating and presenting weather forecast uncertainty information to support risk-based decision-making (see more details in the next sub-section).

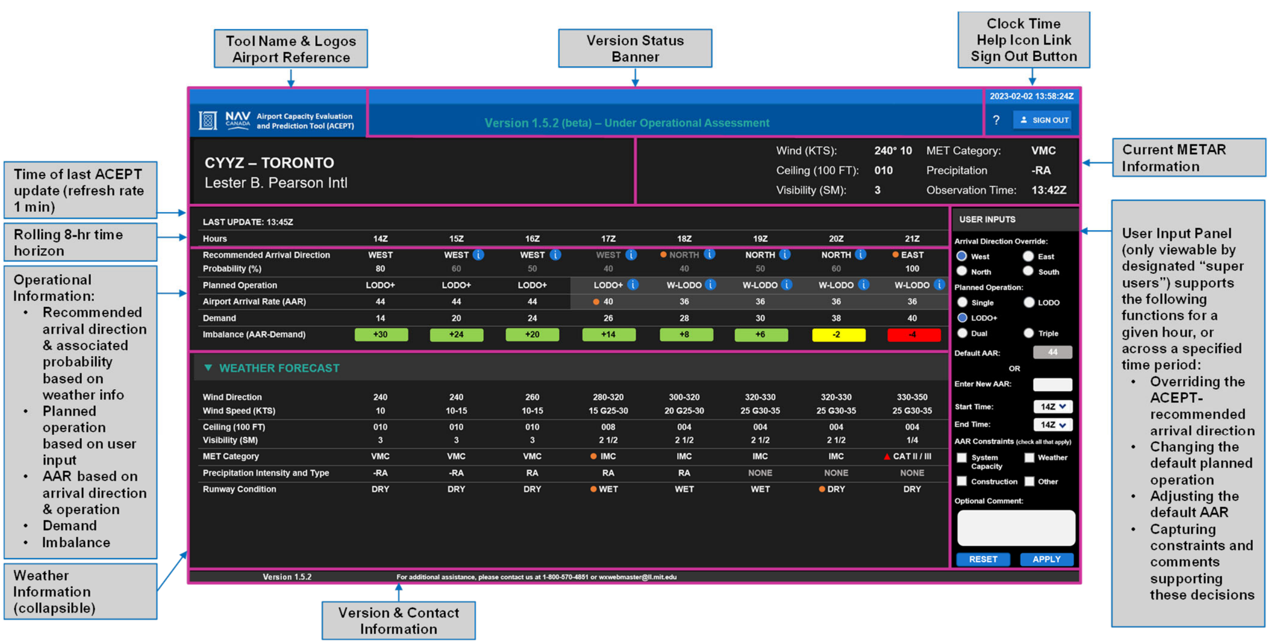

Figure 9. Current ACEPT prototype display.

- Clearly presenting operational constraint data to users, and translating this and the weather data into a recommended airport arrival direction with associated probability and Airport Arrival Rate.
- Clearly presenting the "official" demand information (in this case from the Traffic Flow Management System (TFMS)-derived data)
- Clearly presenting the potential imbalance between the AAR and demand levels eight hours into the future and color coding as green (AAR is more than 3 greater than demand), yellow (AAR is within ±3 of demand) or red (demand is 3 or more greater than AAR). This presents a "quick look" functionality to users of the likely operational state of the airport over eight hours, and whether any demand modification techniques should be discussed to bring the airport back into balance using the principles introduced in Figure 1.

Figure 9 presents the current version of the ACEPT prototype being tested by Toronto stakeholders, annotated with functionality. In the example shown, a potential "red" airport imbalance situation could exist in the eighth hour due to the circumstances presented. If this information is being used by all stakeholders, ACEPT provides a common basis for effective collaborative decision-making well in advance of impacts.

C. Weather Uncertainty Quantification

The green oval on Figure 8 motivates the need to reduce weather forecast uncertainty as much as possible given it directly impacts the planned airport operation and decision-making processes. Note the recommended arrival direction row and associated probabilities in the top panel of Figure 9. The blue circle "i" icons next to the recommended arrival direction can be moused over by a user to provide any potential alternative arrival directions and their associated probabilities based on the weather data so they can assess potential alternate scenarios and their likelihood. These probabilities are estimated using the translation from wind speed and direction as shown in Figure 8 and weather model "ensembles" to quantify forecast uncertainty, i.e., combining multiple representations of the forecast for a given weather situation. There are three possible types of ensembles for ACEPT: (1) *Multi-model ensembles*, which combine outputs from many models from different sources or using different atmospheric representations; (2) *Time ensembles*, which combine outputs from the same model but from several time-referenced runs; and (3) Spatial ensembles, which combine outputs from the same model but from several spatial points from the same time-referenced run to better capture phenomena such as gust fronts.

Some of the ensemble options being used (or evaluated) for ACEPT development are shown in Figure 10. The options for multi-model ensembles under consideration include the US Global Forecast System (GFS), the US High Resolution Rapid Refresh (HRRR), the Canadian High Resolution Deterministic Prediction System (HRDPS) and the European Centre for Medium range Weather Forecasts (ECMWF).

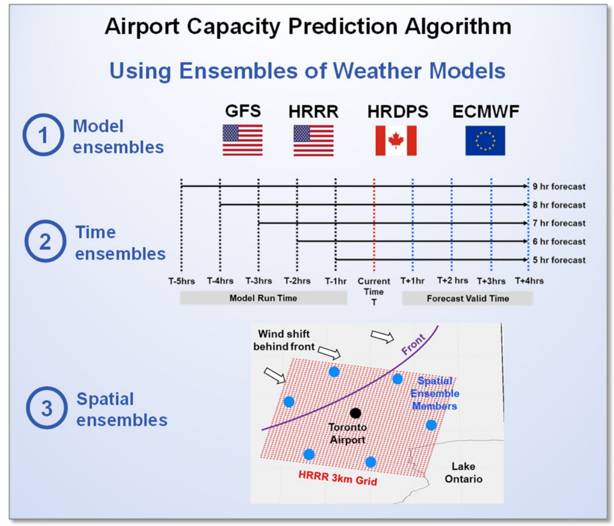

Figure 10. ACEPT weather model ensembles.

For current prototype deployments, only the HRRR model is being used, but future releases are likely to integrate additional models. Up to five HRRR time ensembles and up to seven HRRR spatial ensembles have currently been assessed, with the illustrative performance for these options shown in Figure 11. This Receiver Operating Characteristic (ROC) curve quantifies the accuracy of the critical NORTH configuration prediction at 4 hours lead-time in terms of the true positive rate of detection (i.e., NORTH was forecast four hours out and it <u>was</u> NORTH at that time) on the y-axis and false positive rate (i.e., NORTH was forecast four hours out and it <u>was not</u> NORTH at that time) on the x-axis as a function of the different ensembles. Perfect forecast performance (no uncertainty) would result in a point in the top left of this axis space. A notional "target performance line" is shown to illustrate how this approach can be used to set and track weather forecast performance relative to operationally-relevant targets. This is being used to drive algorithm design for future ACEPT releases.

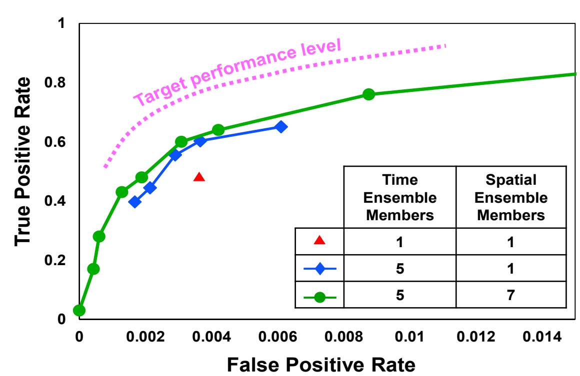

Figure 11. ACEPT sample ensemble performance impact (example prediction of NORTH at 4 hour lead-time, HRRR only).

IV. Development & Integration Plan

A. Development Plan

The technologies introduced in the previous sections are all at different stages of development, but each is following the general sequence of steps detailed in Figure 12.

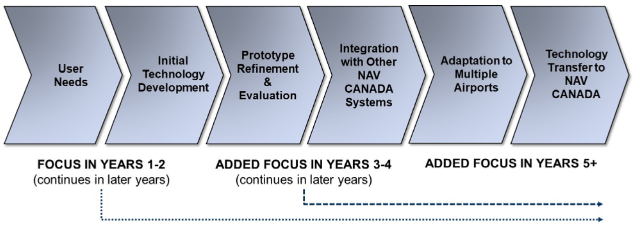

Figure 12. Technology development plan.

Development for each technology starts with a detailed assessment of who the primary users are going to be and what their operational needs are. This process results in an identification of what gaps exist which could be addressed through the development of specific technologies and associated concepts of operation for their use. This process resulted in the identification of the need for Canadian-optimized aviation weather technology (being addressed by CAWS) and weather-impacted capacity and demand/capacity imbalance predictions at key airport, terminal and en route regions (being addressed by ACEPT, TCEPT and ECEPT respectively). The next step involves developing prototypes of relevant technologies and making them available to users in an operational setting to help refine the concept of operations and features. Iterative development and prototype deployments allow ultimate convergence to high impact technology solutions. Initial prototypes of ACEPT, TCEPT and ECEPT have already been deployed and are available to key decision makers at Toronto airport. These prototypes are undergoing iterative concept of operations and feature refinement. The next step will involve integration with other NAV CANADA automation systems, and this will be discussed in more detail in the next section. Subject to successful operational experiences at Toronto, the technologies may then be adapted for other regions, e.g., those making up the Canadian "four majors" (i.e., Toronto, Vancouver, Montreal and Calgary regions). Finally, after appropriate operational prototyping, the intent is to transfer the technologies (e.g., reference source code, documentation, etc.) to NAV CANADA for long-term deployment.

B. Integration Plan

In order to deliver the ultimate objective of weather-aware ATM decision support, the individual technologies described in the previous sections need to be integrated, not only with each other but also into the wider automation ecosystem being used by NAV CANADA. A potential integration concept is shown in Figure 13. At the top left, CAWS provides the foundational weather situational awareness to support the operational needs of Canadian airspace users. This information is then used by the technologies of ACEPT, TCEPT and ECEPT to understand the weather impacts to critical airport, terminal and en route resources as illustrated in the top middle box. A critical weather impact that is a current focus is capacity implications which, when combined with demand projections, can be used to identify periods when demand/capacity imbalances exist. However, without further automation, the user still needs to determine appropriate strategies to address the predicted imbalances. In the future, digital twin concepts shown at the top right could take these individual imbalance predictions and use advanced AI techniques to develop recommendations for optimal strategic ATM strategies against user-specified objectives [14]. The bottom half of Figure 13 shows the broader automation environment within which these weather decision support systems need to operate. The bottom left shows the NAV CANADA backbone automation systems which currently

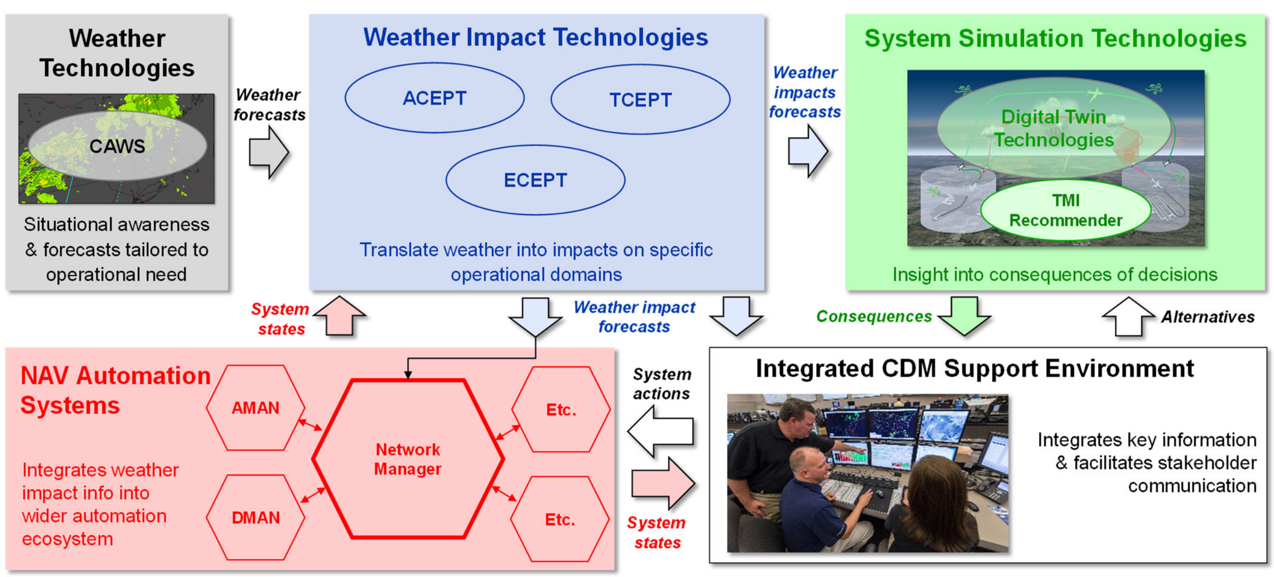

Figure 13. High level integration plan between weather technologies and broader NAV CANADA automation ecosystem.

exist, such as the Arrival Manager (AMAN) which performs time-based flow management and, ultimately, network management solutions.

One of NAV CANADA's main priorities for the future is to evolve its system towards a full implementation of the Trajectory Based Operations (TBO) concept [15]. The full set of weather technologies discussed in this paper, once effectively integrated, has the potential to revolutionize collaborative decision making which is at the heart of effective ATM decision making, and to be a key enabler for the TBO evolution. With effective integration into future automation systems (e.g., a network manager), these weather technologies could help determine weather-aware time targets to be implemented to enable the ultimate TBO vision to become a reality.

V. Summary & Next Steps

This paper has highlighted the critical role that weather-aware, integrated ATM technologies can play in delivering more efficient air transportation systems and enabling future concepts such as TBO around the world. Development of a range of technologies in collaboration with NAV CANADA have been described. Initial prototype deployments at Toronto Pearson airport are currently underway or being planned soon. Future activities will focus on iterative refinements of these technologies through close consultation with stakeholders, followed by adaptation of the technologies to other critical regions, integration with other ATM automation systems and ultimately, technology transfer for long-term deployment.

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