EVALUATING AIR TRAFFIC MANAGEMENT (ATM) BENEFITS OF ENHANCED AVIATION WEATHER DECISION SUPPORT USING A WEATHER-AWARE NATIONAL AIRSPACE SIMULATOR

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1 INTRODUCTION

Adverse weather remains the most disruptive constraint in the National Airspace System (NAS), contributing to the vast majority of air traffic delay, cancellation, and diversion impacts that occur annually. To mitigate these weather impacts, FAA traffic managers have developed several tools, procedures, and traffic management initiatives (TMI) that allow them to more proactively manage and match air traffic demand against weather-reduced airspace capacity. Moreover, the FAA, NOAA, and various research and development organizations have developed a number of weather decision support tools, forecasts, and guidance aids to assist traffic managers with decisions-making for proactive impact mitigation. Traffic management and weather decision support is evolving, however, and as the NAS moves towards NextGen operations, more innovations on both fronts will be required.

A prime challenge to developing and fielding new weather decision support designed for air traffic management (ATM) applications is evaluating and demonstrating operational benefits which justify its procurement and deployment, particularly in this current climate of budget austerity. Claimed benefits must be clear, well articulated, robust and well exercised, and readily defendable for FAA Investment Reviews.

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Ideally, this is accomplished via NAS simulations, but historically, NAS models have not been able to combine weather (actual and forecasts), airspace resources, realistic traffic, and TMIs with both the needed resolution and sufficient computational capabilities to assess potential ranges of outcomes (and potential benefits) across perhaps hundreds of modified simulation scenarios and parameterizations.

The Dynamic Airspace Rerouting Tool (DART) is a weather-aware superfast-time NAS simulator that can intelligently model the impact of varied weather and forecasts (convective and non-convective) and the system's response in the form of reroutes, delays, cancellations, or diversions for 50,000+ flights across a day of U.S. CONUS operations. This paper describes how DART can be used to evaluate and objectively estimate ATM benefits associated with 0-8 hour convective weather forecasts targeted for operational deployment by the FAA NextGen Weather Processor (NWP). A unique DART feature developed for this research is the hybrid simulation mode, where a set of historical TMIs or user-designed "what-if" alternative TMIs can be enforced while all other NAS events and responses are simulated by DART automatically. As a result, simulated NAS response differences (and differences in delay, cancellations, etc.) with and without NWP-derived TMI decisions can be objectively analyzed (and even reviewed in "side-by-side" playback mode) for targeted and robust benefits estimates.

Implications of initial DART-enabled NAS operational benefits analyses of convective weather forecasts to broader aviation weather research and development needs, priorities, and operational requirements are discussed.

2 DYNAMIC AIRSPACE ROUTING TOOL (DART)

Requirements for Fast-Time NAS Simulation Models

Fast-time simulation models are the tool of choice for ATM-related research. When evaluating the potential gaps in current operations, the needs of NAS operations given alternative procedures, traffic demand, operating environments and tools, and the potential benefits of new technology or innovative changes to air traffic operations, NAS simulators become indispensable. This is because it is only through fast-time simulations that a wide enough range of future / "what-if" scenarios can be examined to produce robust cost and performance measures that serve as quantified benefits estimates for planned technology investments.

In order to be useful for this kind of analysis, a model must satisfy a number of requirements (Klein et al. 2009). Apart from the obvious need to be able to emulate and account for primary elements of NAS operations (e.g., routing traffic using full flight plans, accounting for airport, airway, waypoint, and Air Traffic Control (ATC) sector-based flight operations, etc.), there are additional, specific requirements including:

- Ability to simulate rerouting around dynamic, adverse weather constraints (e.g., convection) and to integrate airborne reroutes with on-the-ground delay assignments as alternative means of traffic congestion resolution (and apply cancellations when delay solutions become exorbitant);
- Ability to assign airborne delays and recognize and account for airborne holding and diversions as legitimate costs given impacted operations and outcomes of ATM impact mitigation decision-making;
- Ability to use – and blend – both actual and *forecast* weather information for NAS simulation and rerouting, and to account for different risk / safety margins, aircraft range limitations, airspace users' cost objectives, and reroute strategies related to weather;
- Integrated weather-impacted *airport* capacity and demand management reflecting the impact of airport surface and Terminal Radar Control (TRACON)-airspace weather (both non-convective and convective), weather-impacted *airspace* capacity and demand management, and TMIs used to manage air traffic constraints, into a single NAS-wide model;
- Ability to simulate all primary TMIs, such as Ground Delay Programs (GDP), ground stops (GS), Airspace Flow Programs (AFP), Miles-In-Trail constraints (MIT), and Playbook reroutes.

However, even if a model satisfies the above requirements, to be truly useful it also needs to be sufficiently fast, so that extensive parametric analyses of NAS operation using large sets of NAS evaluation events (including weather-impacted operational events/scenarios) can be supported effectively. A target benchmark for simulating an entire "day-in-the-NAS, accounting for the above requirements, is less than five minutes.

Dynamic Airspace Routing Tool (DART)

Air Traffic Analysis, has developed the Dynamic Airspace Routing Tool (DART) to satisfy the above requirements. DART is a weather-aware superfast-time NAS/ATM simulation model. DART is currently used in several FAA and NASA research and analysis programs. DART meets most of the above requirements and exceeds the target performance benchmark, being able to simulate a highly complex day-in-the-NAS scenario with 50,000 flights and a multitude of TMIs – given adverse weather constraints - in less than three minutes on a desktop PC.

DART is comprised of several primary model components. DART's airport/terminal simulation module evolved from the original Weather Impact Traffic Index (WITI) model (Klein et al. (2007) and is used to:

- Estimate realistic arrival and departure capacity (and degraded throughput, given adverse convective or non-convective weather) for major airports;
- Generate departure sequencing and associated ground delays when demand exceeds these estimated capacities.

Flights departing to airports whose arrival capacity is constrained may be subject to simulated GDPs. The augmented Estimated Times for Departure (ETD) are passed on to the DART rerouting module.

Using a blend of actual and forecast en route convective weather, the rerouting module generates an economical combination of ground delays (additional to those already incurred due to airport capacity constraints) and reroutes to move individual flights around strong convective weather. DART will cancel individual flights if the total ground delay for that flight exceeds a user-definable threshold.

Next, convective weather/forecast information is used by DART to estimate airspace capacity degradation in NAS airspace units such as ATC sectors and/or en route centers. To accomplish this, a weather permeability model (Klein and Cook, 2011) is utilized to estimate weather-induced capacity degradations which may require traffic rerouting. If the initially computed traffic demand in airspace units exceeds their weather-degraded capacity, additional rerouting and/or ground delays follow (i.e., the ETDs may be modified further). Rerouting and ground delays are in this case used to both avoid the hazardous weather and mitigate airspace capacity constraints. Additionally, simulated AFPs, GSs, FAA Playbook reroutes, and MIT restrictions are applied as required. DART can use various reroute strategies and cost functions for economical rerouting (e.g., minimum arrival delay, shortest path, or minimum cost) and user-definable safety margins. Once the flight departs, DART will recheck the aircraft's situation regularly (typically every 30 min as a default), and if, given new weather information that requires additional constraint management, flights may need to be rerouted while airborne – and DART will try to accommodate this. If no reroute is possible, a flight in DART will execute airborne holding. If airborne holding cannot be accomplished, or if total holding exceeds a parameterized limit (set as a proxy for fuel-usage constraints), DART will register the flight as an airborne diversion.

Abundant statistical output is produced by DART, and simulated flight plans trajectories can be exported in a variety of formats for post-processing and targeted analysis.

Figure 1 illustrates both an individual flight reroute executed in DART to avoid significant convective weather as well as a snapshot of DART's simulated traffic and weather display, highlighting individual flights requiring reroutes. Permeable weather in a hexagonal grid is shown in green, non-permeable weather in red.

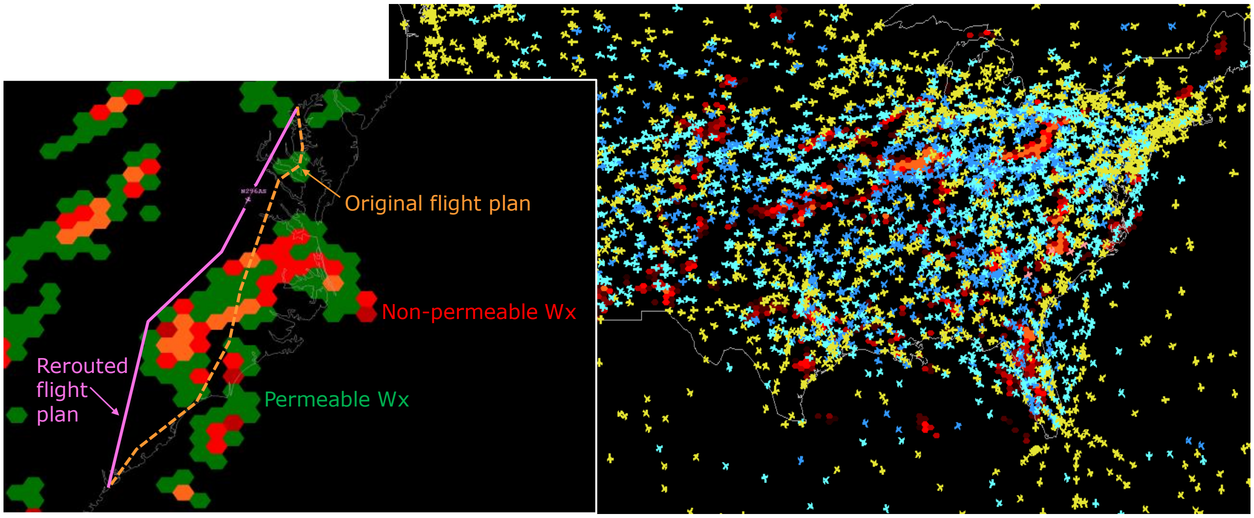

Figure 1. Example of an individual flight reroute to avoid non-permeable convective weather (left) and a snapshot of DART's traffic and weather display (right), showing flights requiring reroutes or delays (blue) and flights allowed to utilize filed flight plans with no delay (yellow).

A snapshot of DART's simulated weather and traffic display for a modeled severed weather event in the Northeast illustrates many of the TMI capabilities that DART can either simulate or enforce with this tool (Figure 2).

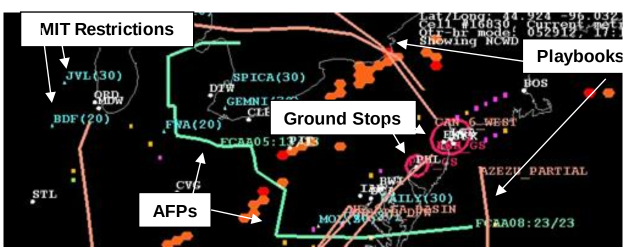

Figure 2. A sample of TMIs that can explicitly modeled or enforced in DART.

DART Hybrid Simulations

DART has the unique capability to operate in "hybrid simulation mode", where a set of historical or user-defined TMIs can be enforced while all other NAS events and responses are simulated by DART automatically. In this manner, simulated NAS response differences (and differences in delay, cancellations, flight trajectories, etc.) with and without targeted and isolated TMI options exercised explicitly in the model can be objectively analyzed (and even reviewed in "side-by-side" playback mode). Through this capability, targeted evaluations of potential operational decision-making benefits – associated with specific ATM improvements including enhanced weather forecast decision support – can be executed more realistically (e.g., enforcing all other NAS constraints beyond target analysis), with more defendable results.

In a conventional standalone fast-time simulation, the model generates its own TMIs to balance traffic demand with available capacity in presence of weather. The TMIs may or may not be similar to the ones actually applied by ATM on that particular day. In a DART hybrid simulation of the same day, significant historical TMIs (those important to NAS performance analyses specific to considered impact types or phase of flight) are *enforced* by the model according to user settings. They are then immersed into the residual DART simulation environment and merged with various other, less-significant TMIs generated by the model automatically, as well as all other DART-supplied goings-on in the simulation (e.g. non-TMI reroutes, delays, cancellations, etc.) The result is a stronger TMI accountability and realism for hybrid simulations as compared to conventional ones.

3 SIMULATING OPERATIONAL ATM BENEFITS ATTRIBUTED TO ENHANCED WEATHER FORECASTS

The FAA NextGen Weather Processor (NWP) seeks to combine key weather diagnostic and forecast capabilities from several legacy and prototype weather decision support tools as a single-source for state-of-the-art aviation weather and impact translation technology. Primary components of NWP include 0-8 Precipitation, Echo Tops, and Winter-Weather Forecasts, as well as initial weather-to-ATM translation capabilities (Figure 3). These forecasts have been tested operationally, or are under development, as part of the Corridor Integrated Weather System (CIWS) and CoSPA programs (Weber et al. 2007; Wolfson et al. 2008).

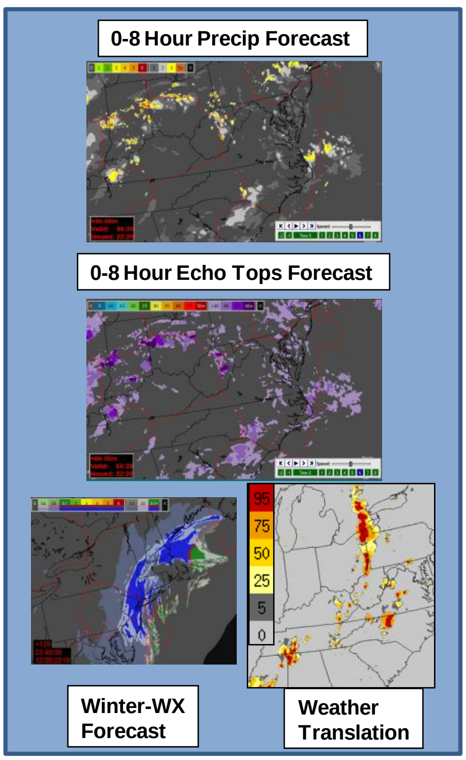

Figure 3. Core capabilities envisioned for the FAA NextGen Weather Processor (NWP).

Previous evaluations of both CIWS and CoSPA weather depiction and forecast capabilities have demonstrated significant delay savings and operational benefits (e.g., Robinson et al. 2011, 2006, 2004). The approach used in these operational benefits evaluations relied upon detailed observations of forecast prototype applications and derived decisions made by traffic managers during live operations impacted by adverse convective weather; followed by rigorous case study analyses completed manually using these field observations and input from Subject Matter Experts.

Results were rigorous and well-defended, passing independent validation tests by the FAA. However, with this approach, results were still largely perceived by the FAA as subjective. Moreover, these results have typically emphasized beneficial applications of the prototype weather forecasts – the primary focus of field observations – but have historically neglected detrimental decisions and ATM results when forecasts are inaccurate or misinterpreted by ATM decision-makers. Finally, results from these past evaluations often leveraged case study results focused primarily on the "local" benefits – those aircraft directly benefitting from improved decisions – (by necessity, given workload involved in painstakingly recreating those events manually), thus potentially failing to estimate the broader benefits that can cascade through the tightly coupled NAS network.

A primary FAA Investment Analysis goal for NWP is to utilize DART to objectively assess the NAS response given improved operational tactical (0-2 hr) and strategic (2-8 hr) ATM decision-making derived from NWP. By using DART, benefits estimates from previous CIWS and CoSPA field evaluations will be enhanced, in that evaluation results for the NAS response to improved weather planning decisions will be extended to:

- Analyze the larger NAS traffic implications (and potentially larger pool of achievable benefits) attributed to specific weather impact mitigation decisions;
- Assess operational improvements beyond the initial results focusing primarily on delay mitigation (e.g., can account for cost savings associated with reduced cancellations and airborne diversions);
- Include benefits assessments across a larger suite of case days and weather

impact events through model batch processing;

- Analyze forecast-derived ATM decisions that may be beneficial OR detrimental to operations (resulting in either decreased delay savings or increased costs); This aids the FAA with their risk mitigation reviews, a key component of FAA investment analyses of new technologies;
- Automate NWP benefits assessments for more objective results.

A scenario-driven approach was developed to recreate previously identified beneficial decisions derived from NWP in DART (either from its CIWS or CoSPA forecast components) to simulate the NAS-wide air traffic response to these applications. With this approach, specific types of NWP-derived beneficial ATM decisions can be recreated in DART – and then isolated from the broader NAS management strategy and decisions for weather impact days in question – to simulate NWP benefits (or costs) associated with that application. For each of these types of scenarios, across all selected candidate weather impact events, two scenarios are generated for each benefits case:

1. Scenario *WITH* the NWP-derived beneficial decision(s)
2. Scenario *WITHOUT* the NWP-derived beneficial decision(s)

The differences in the DART-simulated NAS responses for the two modeled scenarios, including variability in airspace availability and subsequent routing improvements or mitigated airborne or on-the-ground delay, as measured by the various output metrics provided by the model, are the estimated NWP benefits (or costs) for the specific decision-types(s) and case day(s) in question.

A flowchart summarizing this general approach for simulating the NAS response to NWP beneficial decisions and estimating air traffic benefits is provided in Figure 4. DART's hybrid simulation capabilities are leveraged heavily to accomplish this approach. Specifically, target TMI decisions that are either observed being changed based on the use of enhanced weather decision support or are expected to be altered given improved decision support are modified and parameterized in DART (for 'with' and 'without' decision-making) and all other constraints and impact mitigation actions can be enforced as they occurred during the event in question or modeled explicitly by DART. In this manner, the targeted decision for evaluating potential benefits is simulated more realistically, in the context of broader NAS constraints and decision-making.

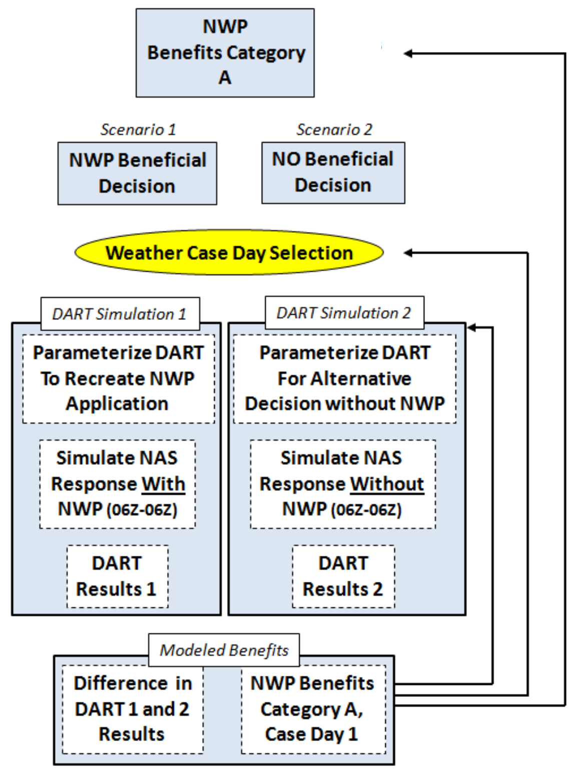

Figure 4. Approach for using DART to evaluate the potential NAS benefits of NWP-derived ATM decisions.

This approach is exercised by considering a specific Playbook reroute decision aided by 2-8 hour CoSPA forecast decision support (Robinson et al. 2011). On 20 July 2010, A Vulcan (VUZ) Playbook reroute was implemented by the Air Traffic Control System Command Center (ATCSCC) to move traffic demand from the South-Central and Western U.S. – destined for the Northeast – out of the Midwest (and off preferred flight plans), where convective weather constraints were expected to be significant, and into the Southeast, routing up the East Coast, in an effort to avoid this weather. During this event, traffic managers utilized CoSPA 6 hr precipitation forecasts to identify a large gap in convection, through the Midwest [and not evident in the operational Collaborative Convective Forecast Product (CCFP)], to reduce volume on the VUZ Playbook (Figure 5). With this information, traffic managers split the Playbook into an additional route – up the J29 airway through the Midwest – to reduce congestion on the original demand-heavy reroute and reduce congestion and delay.

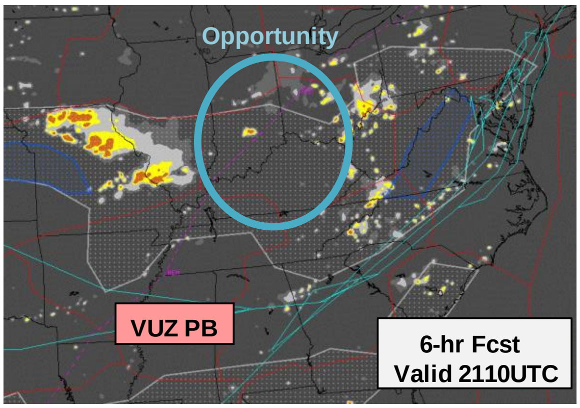

Figure 5. 6-hr precipitation forecast, valid 2110 UTC on 20 July 2010, demonstrating opportunity to reroute some VUZ Playbook (PB; light blue lines) traffic through the predicted gap in storms in the Midwest – a gap not readily evident in 6-hr CCFP forecast (large, stippled polygon).

This event was recreated in the DART simulation environment using two nearly identical scenarios. Both simulations included five GDPs/GSs in place in the NAS on 20 July 2010 for constraints beyond the attention of the targeted ATM decision. Similarly, both simulations enforced two additional transcontinental Playbook reroutes in place given adverse weather (through Canada and West Coast departures through the Midwest). The only difference enforced between the two DART simulations was that in the "With NWP" scenario, VUZ Playbook traffic was "split" off to J29 (for airport departures from Fort Worth and Memphis Center airspace to the Northeast), while the "Without NWP" simulation forced all reroute traffic to remain on the VUZ Playbook. Once fully defined, the DART scenarios were allowed to run for the entire operational day (06Z to 06Z), identifying differences in individual and aggregate flight delays, cancellations, diversions, etc.

A snapshot of DART's display, operating in synchronized "side-by-side" mode showing both reroute scenarios together for comparison, demonstrates differences in the simulated NAS response given the weather forecast-empowered change to this one ATM decision (Figure 6):

- Flights to the Northeast via the "split-J29" (alternative) reroute through the Midwest and the gap in convection are experiencing minimal departure delay (colored green in Fig. 6);
- Flights remaining on the VUZ Playbook still experience reduced delay given the excess reroute volume alleviated by the additional "split" reroute.

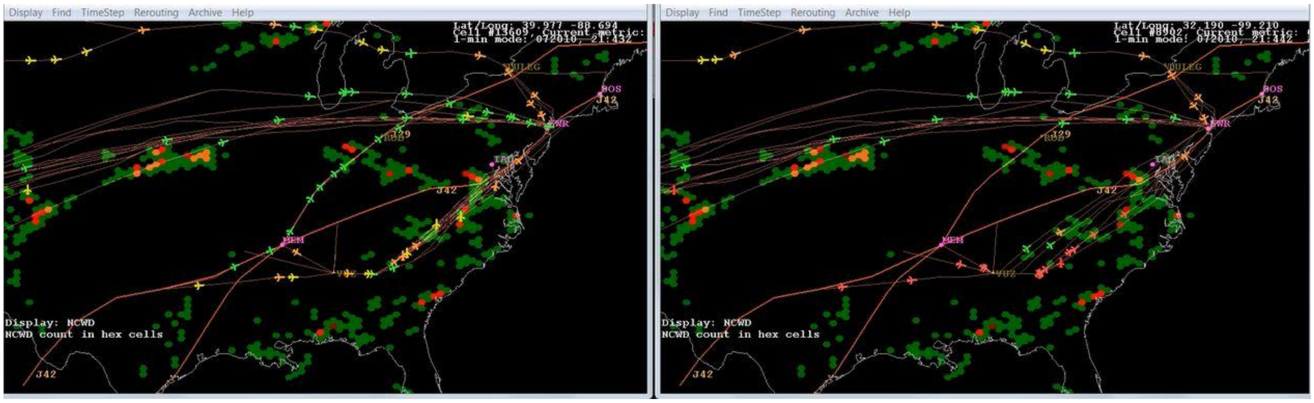

Figure 6. DART-simulated Playbook reroutes, 20 July 2010 – 2140 UTC, With (left) and Without (right) the alternative reroute decision to split VUZ Playbook traffic (bottom, up the East Coast) through the Midwest (and forecasted gap in convection). Flights color-coded by delay: 0-15 min (green), 15-30 min (yellow), 30-60 min (orange), 60-90 min (red), > 120 min (magenta).

Totaling simulated NAS delays, cancellations, and diversions in both DART runs and computing the differences for the entire operational day yields the estimated benefits attributed this NWP-derived ATM reroute decision (Table 1).

Results show that improved operational efficiency associated with this decision are primarily achieved through (a) reduced on-the-ground departure delays and (b) the reduced number of cancellations given reduced VUZ reroute volume and en route traffic congestion. The DART simulation shows that the altered state of the NAS network given these two difference reroute decisions actually resulted in an estimated *increase* in airborne holding, as modified schedule delays placed different flights in different airspace at times when en route and terminal weather constraints may have resulted in greater flight-specific impacts. This result, accounting for the coupled NAS network and requiring potential increased impacts/costs to be subtracted from quantified operational improvements, is realistic and results in more conservative and defendable weather forecast benefits estimates.

Table 1. DART-Estimated Delay / Impact Savings Associated with 20 July 2010 Forecast-Enabled Playbook Reroute Decision

NAS Delay/Impact Estimated by DART	Delay/Impact Savings
On-the-ground delay savings, Total (hr)	**154**
Airborne holding delay savings (hr)	**-2.2**
Airborne reroute delay savings (hr	**3.4**
Reduced cancellations (number of flights)	**31**
Reduced diversions (number of flights)	**1**
Reduced # flights delayed > 2 hr	**54**

Accumulating DART results for all specific Playbook reroute decisions (and other unique, specific types of weather impact management initiatives and strategies) made with NWP – for perhaps an annual period - would provide a total benefits estimate for this particular type of ATM application. Accounting for events when reroute decisions made proactively based on forecasts that were inaccurate would reduce benefits estimates, but provide more defendable and more realistic results. Moreover, focusing specifically on these events will demonstrate to FAA weather research and development programs as well as the aviation weather research community the potential operational improvements and priorities of still needed weather forecast enhancements.

Some key DART parameterizations may help uniquely exercise NAS-centric forecast performance evaluations. These include weather permeability “padding” and the safe-distance-from-heavy-weather-cells buffer which can be defined for scenarios with varied tolerances to risk directly related to actual or perceived forecast skill. In this manner, DART can be executed in Monte-Carlo fashion across a broad range of forecast risk/performance sensitivities – specific to individual or aggregate TMI applications, for instance – to evaluate the operational opportunities and consequences of alternative forecast characteristics. As a result, with this type of approach, DART can explicitly quantify NAS delay and impact costs (and potential improvements) associated with specific forecast characteristics, such as weather phenomenon initiation, cessation, duration, intensity, coverage, evolution, etc. – all of which as it may vary by time of day, time of year, for different airport / airspace regions, etc.

5 SUMMARY

Quantifying operational ATM benefits associated with enhanced weather decision support is very complex and requires careful attention to detail. Challenges include extending subjective case study analyses, which have typically emphasized localized and beneficial air traffic applications, to include objective evaluations of the broader benefits and detriments that likely exist in the coupled NAS network. NAS simulators have been the targeted solution to these challenges, but most models do not have the proper mix of weather intelligence, detailed TMI applicability (for targeted ATM decision analysis), computing speed, and dynamic capabilities to simulate or enforce key parameterizations.

The weather-aware DART NAS simulator is well-suited for evaluating ATM benefits (and shortfalls) of enhanced aviation weather forecasts and decision support. DART can simulate or enforce airport and airspace capacity degradations due to adverse weather (convective and non-convective) – and does so within the structured operations and infrastructure that defines the NAS. DART models individual flight trajectories given available capacity and actual and predicted en route convective weather impermeability – assigning either ground or airborne delays as needed, and developing “good-feasible” reroutes given available resources. DART can explicitly simulate several key TMIs, including GDPs, MIT restrictions, and AFPs – all of which can also be enforced completely or partially (running a NAS simulation in “hybrid mode”) in order to develop targeted ATM scenarios. Even with intricate parameterization options and weather / ATM awareness, DART can complete a “day-in-the-NAS’ simulation, providing detailed flight, flow, and airport delay, cancellation, and diversion results for 50,000 flights in less than three minutes.

DART has been used to evaluate the potential NAS-wide ATM benefits associated with 0-8 hr weather forecast capabilities to be included as part of the FAA NWP. The initial approach and example DART results for one type of NWP application – ATM Playbook reroute decision-making – was presented in this paper.

The opportunities to leverage DART for operationally-relevant aviation weather research and development and shortfall/benefits research are numerous. DART’s terminal capacity degradation models, accounting for both convective and non-convective weather, provide opportunities to evaluate the operational needs, priorities, and requirements of airport weather decision support such as low ceiling and visibility, wind speed and direction, and winter-weather forecasts. Similarly, DART’s advanced en route weather and capacity/reroute modules are well-suited to evaluate the operational needs, priorities, and requirements of en route convective weather forecast initiation, evolution, etc. – as it may vary by ATM decision (and weather forecast) lead time, and the time and airspace for which these forecast elements are needed.

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