Strategic Planning and Replanning Concept Development

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1. Introduction

This report contains three unique sections. The sections are related because of the same underlying topic, namely addressing the inefficiency in the current National Air Space (NAS) associated with airborne flight replanning.

The first section reports on survey work that is a logical extension of the previous work reported by Fan, Hyams, and Kuchar (1997) in which the authors used a World Wide Web-based survey to query pilots on their preferences associated with flight replanning and the inefficiencies they perceive in the NAS associated with replanning. In this report we employ the same WWW-based survey approach to collecting similar opinion data from airline dispatchers (the ones who actually generate flight plans for airline operations).

In the second section of this report an analysis is presented which uses the recently developed Post-Operations Evaluation Tool (POET) to examine the discrepancies between predicted versus actual flight times and fuel burn. POET is a unique analysis tool because it is applied to a data base that contains not only the airline predicted versus actual performance data but also has data from the NAS, in the form of the Enhanced Traffic Management System (ETMS) data associated with each flight.

In the final section, there is the presentation of the "Ultimate Flight Planner" that is intended to reduce or eliminate the inefficiency associated with airborne flight replanning. We've addressed flight replanning at a functional level in order to architect a solution that is applicable both as an airborne decision support tool, or on the ground as an aid to the dispatcher.

2. Preliminary Study of the In-Flight Replanning Performed by the Dispatcher

This section of the Final Report is organized in an identical manner to the report by Fan, Hyams, and Kuchar (1997) that dealt with replanning from the pilot's perspective ("Preliminary Study of In-Flight Replanning Performed on the Flight Deck"). Since NASA-LaRC's AATT personnel were sponsors for both the MIT and the present study, our team was motivated to make the effort at comparing results between the two studies (focused on the Pilot and Dispatcher's role in replanning, respectively) as simple and straight-forward as possible. In the MIT report, the major sections were entitled:

1. Model of the Cockpit In-Flight Replanning Process
2. Survey of Pilot Behavior During In-Flight Replanning
3. Enhanced Cockpit Automation Concepts for In-Flight Replanning
4. Conclusions and Recommendations

This portion of our Final Report is identical in organization to the work of Kuchar and his students. To understand how the two studies compare, the reader can simply replace "Cockpit' with "Airline Operations Center" and replace "Pilot" with "Dispatcher."

In the first section (Model of the Airlines Operation Center In-Flight Replanning Process) we utilize work done under the previous Honeywell activity (Rogers, et. al. 1998) which characterized the flight planning process to model the replanning process.

The next section (Survey of Dispatcher Behavior During In-Flight Replanning) presents data collected from a World Wide Web-based survey completed by more than 50 qualified dispatchers (certified under Part 121 of the Federal Aviation Regulations). This survey, similar to MIT effort, was aimed at understanding and characterizing how replanning is accomplished today with currently available technology.

The next section (Enhanced Airline Operations Center Automation Concepts for In-Flight Replanning) provides insight into what the WWW-based survey respondents would view as improved and desired modifications to automation that support the flight planning and replanning process.

In the final section (Conclusions and Recommendations), some conclusions are drawn regarding improvements to the replanning process based upon specific inefficiencies that plague the National Air Space.

2.1. Model of the Airline Operations Center In-Flight Replanning Process

2.1.1. Tasks Involved in Flight Planning:

There were two classes of tasks, important and support, identified for developing a flight plan at one of the major carriers, see Figure 1:

Important ("attended to first")

- Payload determination and coordination with load planners for weight and balance calculation
- Alternate airport determination
- Route selection
- Re-dispatch point determination for long range flights
- Aircraft minimum equipment verification

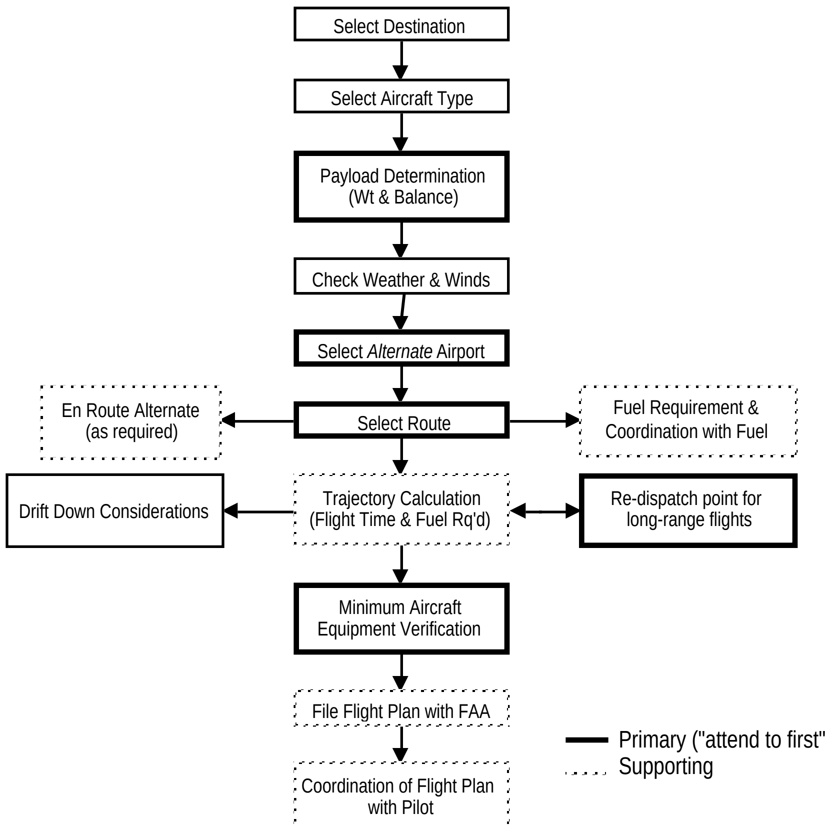


Figure 1 Tasks involved with flight planning (Airline)

Supporting ("necessary to complete, not the first priority")

- Speed and altitude profile calculation, and estimation of flight time
- En route alternate selection (as required)
- Fuel requirement calculation and coordination with fuel loaders
- Coordination of the flight plan with the pilot
- Flight plan filing with the FAA

Historical information is also taken into account when assigning aircraft type and estimating load capacity requirements. One of the major carriers takes into account the last 7 calendar days and the last 7 same-day-of-the-week (i.e., the last 7 Tuesdays) when estimating load/passenger capacity requirements.

The other major carrier listed the key activities in flight planning, although not in any particular order as:

1. Route construction
2. Route initialization
3. Access Upper Air weather
4. Payload input
5. Release calculation
6. ATC Filing

The following as rules that are Federal Aviation Regulations attended to when flight planning:

1. Fuel requirements - Destination weather, alternate criteria, etc.
2. Terrain clearance / Depressurization
3. Route construction - Airways vs. Direct segments vs. LAT / LONG.
4. FAA Pref Routes / NRP Route requirements
5. Communication / Navigation system requirements
6. MEL requirements
7. ATC Filing - Formats and Times
8. ETOPS - Routes and en route alternates
9. Restricted airspace areas, Special use areas
10. Aircraft Performance requirements

That same carrier also listed the following as situations that change the importance of flight planning goals:

1. Airline dependability performance (scheduled block times)
2. Payload capability
3. Airport status / curfews
4. Passenger connections
5. Aircraft status (MEL)
6. Crew legality

2.1.2. Causes for Replanning

One of the major carriers provided the following list as possible causes for in-flight replanning:

- Destination change
- Alternate change
- Reroute (For weather, ATC, or other reasons)
- Significant change from planned en route winds
- New re-release analysis
- Use to provide a better (more accurate) assessment of the flight's performance for flight following
- Search for optimum route / altitude
- On-time performance
- Airport curfew
- Crew legality

2.1.3. Replanning/Information Processing Loop

As a follow up to the previous list, the major airline was asked if there was a sequence, or order to the tasks involved with flight planning within the AOC. The answer follows:

- New route construction
- New route initialization
- Access latest upper air weather data
- Input other desired variables (alternate, fuel load, aircraft weight, current position, etc.) into replanning system
- File with ATC as necessary to forward to international ATC centers

Sometimes the ARTCCs will offer more direct routing to one of the major carrier's flights. The SOC believes that their flight crews have been sufficiently briefed that they no longer categorically accept what is offered, but in fact do coordinate with the SOC to determine if there is an operational gain to be made by accepting the offered route.

One of the major carrier's SOC representatives expressed concern regarding the idea of each aircraft being solely responsible for replanning. The obvious issue is that the flight crew is not aware of "big picture" concerns for the airline; if they accept an opportunity that would take more time than is required for a nominal flight between that city-pair, they could exceed allowable crew duty times. This would have a profound impact on the system, i.e., no crew available to take over the flight at the destination because the in-bound crew cannot fly for 8 hours (the prescribed duty-rest cycle).

When asked about the idea of locating a high-resolution color printer on the flight decks of the fleet, the SOC rep thought that would be enormously beneficial in promoting a shared "world-view" of the routing situation, thereby allowing a better dialog between the flight crew and the dispatcher. Figure 2 shows the participation of the major stakeholders in the replanning information processing tasks for scheduled airline.

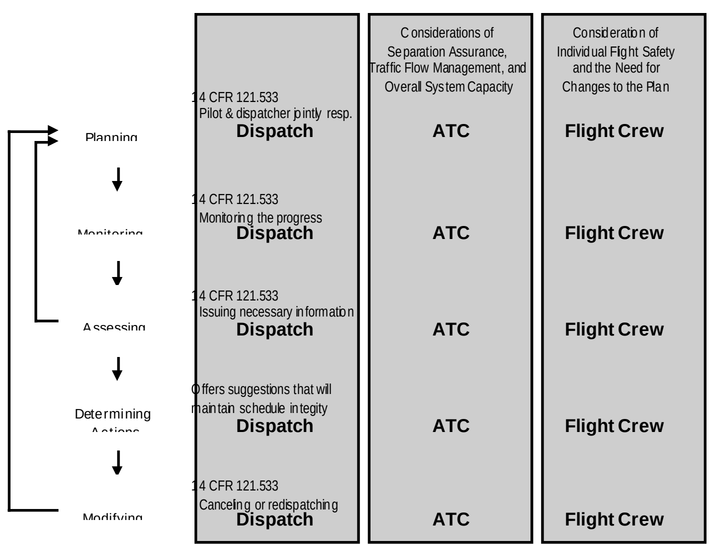


Figure 2 Information processing loop associated with replanning (Airline)

2.1.4. Greatest Existing Inefficiencies

(1) Working with Central Flow Control on rerouting (in reaction to non-normal operations, such as severe weather) is not a well-structured effort. No existing protocol is in place that guides those interactions. Sometimes Central Flow Control will "work with you"; other times they are unapproachable.
(2) Communications during non-normal operations could be improved. Held up as a show case example was a North-East Regional Hotline that is put in place between various ATC facilities (Control Towers, TRACONs, and ARTCCs) when severe weather (i.e., blizzards) disrupts operations. The purpose of the hotline is to facilitate communications, with regards to coordinating traffic flows, between these facilities. The airlines benefit by "eavesdropping" on the conversation because it allows them to anticipate actions that will be taken by ATC personnel, such as:

- closing runways
- redirecting traffic flows (in-bound and out-bound from airports)
- preferred routing that is temporarily put into place

(3) Realistic Holding Times (e.g., "Expect Further Clearance"). With the "tank-limited" flights that one of the major carriers operates, such as DC-9s at the limit of their range, it is important that they receive realistic estimates of airborne delays in order to avoid unnecessary diversions.

In our exposure to the small, niche airline, there were a number of inefficiencies that were unique to the size, scale, and technological sophistication of their operation. For example, the flight crew is completely reliant on voice communication with dispatch and ATC for any information (weather, congested airspace, route optimization calculations, etc.) that would help them replan. Right now, if they had opportunity to choose a different route after becoming airborne, they would not have the tools or information needed to make a choice.

ACARS is a pipe dream for this small carrier. Equipping with any expensive item not mandated is out of the question unless the return-on-investment or increased operating capability is big, quick and obvious.

General view is that kinds of time/fuel efficiency improvements that Free Flight promises are:

(1) unlikely to be realized;
(2) not applicable to their operations (east coast, max FL350);
(3) too costly for them to afford in terms of initial investment in equipment;
(4) too scary in terms of pilot responsibility for self separation; and
(5) of a magnitude that is considered within the "noise" of their operation.

Free Flight advantage for this small airline would be:

(1) reduced delays, both departing and en route; and
(2) better information, particularly to avoid diversions and replans to stop at unscheduled airports because of insufficient fuel due to bad wind data, excessive vectoring, etc.

Unnecessary diversions and delays are much bigger dollar items than the fuel savings of optimal routes.

2.2. Survey of Dispatcher Behavior During In-Flight Replanning

Although survey results continue to trickle in, the current analysis utilizes 51 usable surveys from a total of 55 received. One survey response was eliminated because it was incomplete. One response was sent twice. Three responses were eliminated from the analysis because the respondent ranked *Safety* at the fifth of five concerns when flight planning (either the respondents weren't attending to the question or they were 'having a little fun', in either event the Federal Aviation Regulations require that safety be the foremost concern of a dispatcher as they establish a route of flight).

2.2.1. Demographics

The following questions were intended to obtain data that would allow us to characterize the dispatcher with regards to years of experience, supporting technology at their airline, and sophistication of the automated flight planning tools available to them.

Question from Survey–Number of years as a dispatcher:

Average	Standard Deviation
9.7 Years	8.2 Years

For the purposes of this survey, a Median-Split was performed on the data based upon Years of Experience. This yields two groups labeled "Low Time" and "High Time" for those dispatchers with less than 10 years and those with 10 years or more, respectively.

In order to understand the sort of technology available to the dispatcher to support their flight planning and flight following, the next question was asked.

Question from Survey–Technology available at your operation: (please select all those that apply)

ACARS Data Link	Meteorology Department	Aircraft Situation Display	Graphical Wx Information (current state)	Forecast Wx Information (graphical)
49%	43%	83%	100%	85%

It is important to note than less than half of the dispatchers who responded to this survey did *not* have a data link (ACARS) capability with flight crews under their control. As new technology is envisioned to support Free Flight, it is worth noting that simple VHF data links such as ACARS are not enjoying wide-spread use among FAR Part 121 operations.

The next question was a more specific query of the level of sophistication available in the automation that supports flight planning, and replanning. Not surprising to the authors was the finding that Route Optimization was not found in many existing systems (see Figure 3). We believe that the "Low Time" dispatchers may believe their flight planning automation performs optimization when in fact it does not.

Question from Survey–What level of sophistication does your computer-based flight planner have with regards to replanning? (please select all those that apply)

Point in Space	Allows flight plan (replan) to be developed from where the aircraft is, right now (point in space), to the destination
Actual Weight	Allows modified (actual) weight for the aircraft to be entered during replan
Actual Fuel	Allows actual fuel on-board (at the point that replanning is required) to be entered
Route Optimization	Will search for optimal route at the to-be-replanned point

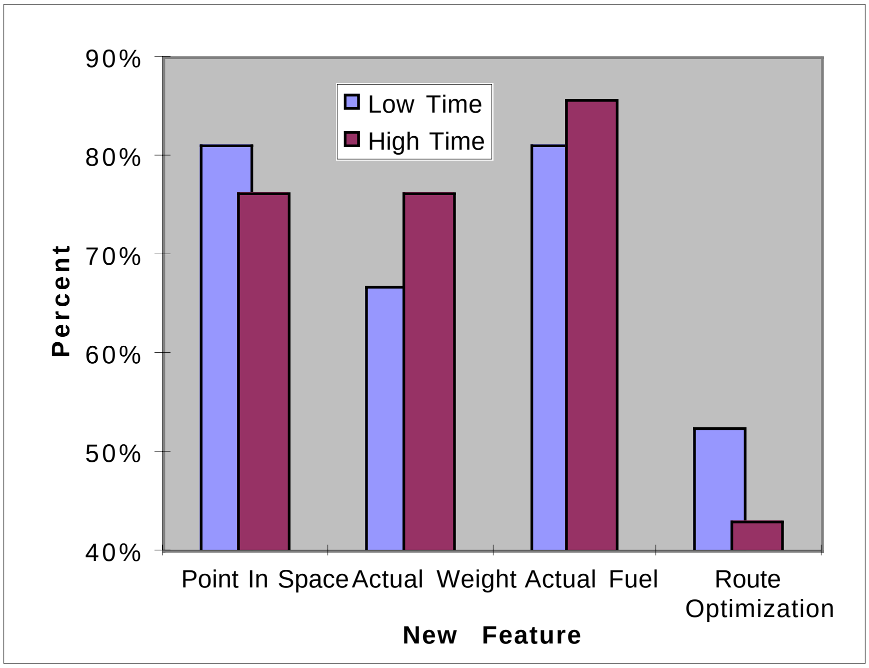


Figure 3 Existing Technology Sophistication in Flight Planning Automation

2.3. Survey of Dispatcher Behavior During In-Flight Replanning

In this section, questions are posed that are intended to characterize the thought processes of the dispatcher as they engage in replanning flights.

2.3.1. Flight Objectives

Question from Survey–Please rank the following flight objectives in order of importance from 1 to 5 with 1 being the most important and 5 being the least important.

Safety	Safety (in terms of severe weather avoidance)
Ride Quality	Ride Comfort
Fuel	Fuel Efficiency
Schedule	Schedule Adherence
Workload	Dispatcher Workload

Dispatcher Experience	Safety	Ride Quality	Fuel	Schedule	Workload
Low Time (<10 yrs)	1.0 (SD 0)	3.18 (SD 1.06)	3.36 (SD 0.87)	3.46 (SD 1.10)	3.86 (SD 1.30)
High Time (>10 yrs)	1.0 (SD 0)	2.64 (SD 0.95)	3.41 (SD 0.91)	3.05 (SD 1.17)	4.33 (SD 0.97)

The next question is intended to determine how frequent is the replanning event for a dispatcher (the authors admit surprise at low response, although it should be noted the wide variation in responses, from 1% to 50%, for both replanned as well as replanned-replanned flights).

2.3.2. Replanning

Question from Survey–What prompts you to evaluate alternative flight plans on your own initiative?

The answers shown below, representative of the more thoughtful responses received, indicate that dispatchers are trying to attend to the two big causes of inefficiencies, namely weather and traffic, as best they can with the available tools.

> From a Dispatcher with 3 years experience: “En route weather such as thunderstorms, turbulence, icing, etc. Possible ATC delays over arrival fixes.”
>
> From a Dispatcher with 14 years experience: “Weather (including: Turb/Weather closed airports affecting driftdown alternates, thunderstorms) Suitable airport available within applicable range for type of aircraft. Possible over load on arrival fixes if notified well enough in advance.”
>
> From a Dispatcher with 15 years experience: “View of the big picture allows the dispatcher awareness of threats to the mission of each flight. This includes safety, economy, efficiency and passenger comfort. Additionally the system perspective allows the dispatcher to amend the mission to achieve system objectives over the basic mission of each flight itself.”
>
> From a Dispatcher with 14 years experience: “Non-operational NAV aids, route restrictions, aircraft equipment restrictions (MEL’s), adverse weather, Fuel/time savings.”

Question from Survey–On average, what percentage of the flights that you handle need replanning? Given a replan occurs, what percentage of the time does another replan become required?

Dispatcher Experience	Percentage of Flights Replanned	Percentage of Replanned Flight that Require Replanning
Low Time (<10 yrs)	10% (SD 9%)	6% (SD 11%)
High Time (>10 yrs)	18% (SD 15%)	12% (SD 15%)

The next question seeks to understand which party (flight crew, ATC, or dispatcher) ‘usually’ initiates the replanning event. There is an interesting interaction between dispatcher experience and initiating party. “Low Time” dispatchers believe they initiate more replanning than do their ATC counterparts, while “High Time” dispatchers believe that ATC initiates more replanning events than they do (see Figure 4).

Question from Survey–Of those flights that require replanning, indicate the relative percentages associated with who initiates the replanning activity. (It is vital to ‘think’ about this in terms of initiating the change, the dispatcher will likely make the final acceptable tweaks to the to-be-flown plan, but who initiated the replanning process?)

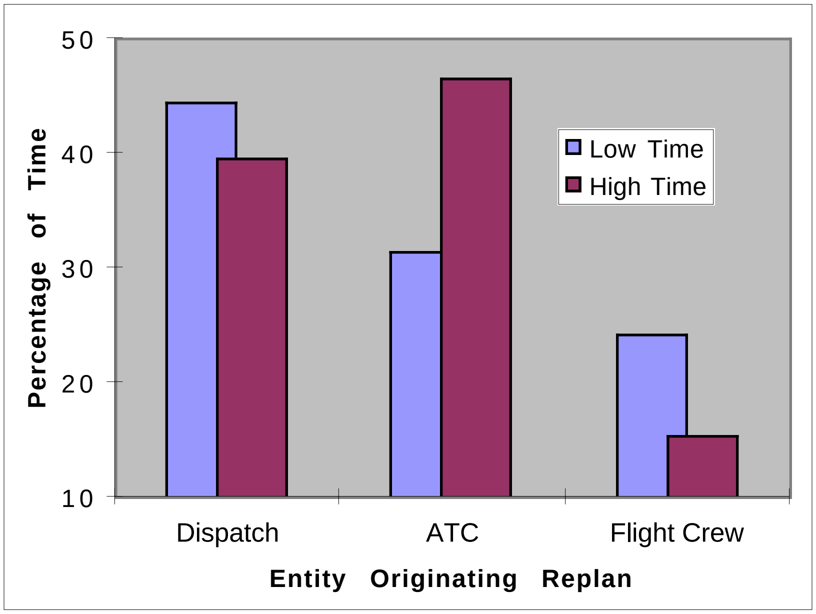


Figure 4. Which Party Initiates the Replanning Event

The next question is intended to assess relative success between the two parties with the best “Big Picture” view of the variables associated with replanning, namely ATC and the dispatcher. Although not statistically significant, it is interesting to note that the High Time dispatchers believe they are more successful, on average, than is ATC at replanning successfully on the first attempt.

Question from Survey–If the dispatcher is the ‘creator’ or the replan that is actually used, what percentage of the time is the replan accepted AS-IS (no further replanning efforts are required, PLEASE use integers only)? If ATC is the ‘creator’ or the replan that is actually used, what percentage of the time is the replan accepted AS-IS (no further replanning efforts are required)?

Dispatcher Experience	Percentage of Successful Replanned Flights (Dispatcher)	Percentage of Successful Replanned Flights (ATC)
Low Time (<10 yrs)	80% (SD 22%)	80% (SD 25%)
High Time (>10 yrs)	76% (SD 27%)	67% (SD 30%)

The next question is intended to determine “how far into the future” the dispatcher is trying to consider events that will might effect the flight. There seems to be general agreement between the dispatchers of varying experience level that 20-40 minutes into the future is the correct perspective for replanning purposes (see Figure 5).

Question from Survey–What is the TIME-DISTANCE "event horizon" that you consider a cutoff for dispatcher intervention, as opposed to letting the flight crew (and/or ATC) handle the matter as a tactical situation avoidance issue. For example, a flight that is 500 miles away from a thunderstorm front (tops to FL500) would appreciate being notified of the impending obstacle by dispatch because their on-board systems (i.e., Wx radar) can't sense problems that far in the future. Please select a representative event horizon from the list below (assuming an aircraft that has a ground speed of 480 mph).

5-to-10 Min	40 miles / 5 minutes -to- 80 miles / 10 minutes
10-to-20 Min	80 miles / 10 minutes -to- 160 miles / 20 minutes
20-to-40 Min	160 miles / 20 minutes -to- 320 miles / 40 minutes
40-to-60 Min	320 miles / 40 minutes -to- 480 miles / 1 hour
More than 1 Hr	Greater than 1 hour

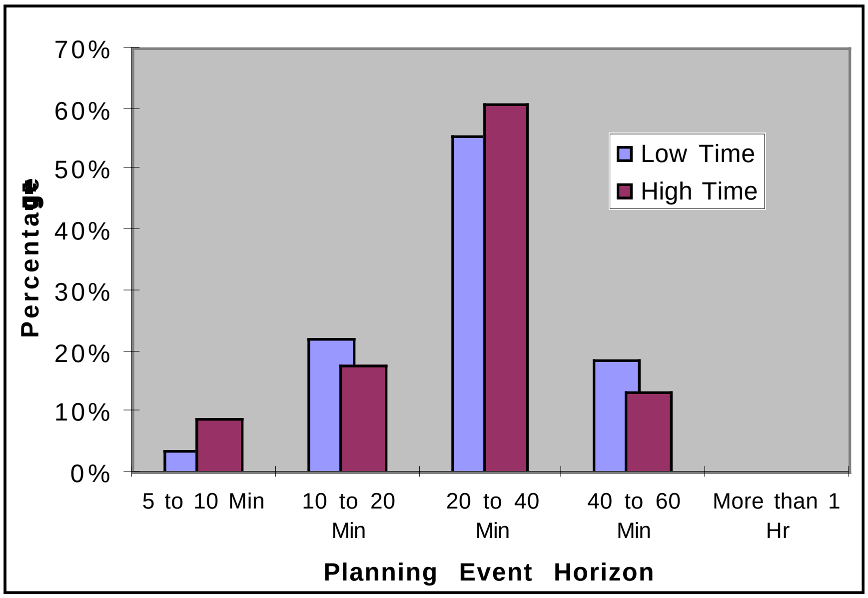


Figure 5. Dispatcher Event Horizon

Question from Survey–When someone else (i.e., the Flight Crew or ATC) initiates replanning, what considerations, other than those mandated by FAR (e.g., adequate fuel), do you concern yourself with?

> From a Dispatcher with 12 years experience: "Additional impact to the rte...i.e., is there something else 500 miles further up the line? ATC often will reroute flights around their weather, but right into weather in another center's airspace."

> From a Dispatcher with 13 years experience: "Is the Re-route safe such as ride and weather en route and the question why an ATC re-route when there is no evidence to warrant one. Why does a crew blindly accept an ATC re-route with out checking with his dispatcher especially when the flight is over one hour.'

> From a Dispatcher with 15 years experience: "System objectives. Given a change initiated by other parties the base question for the dispatcher is: Should I change the overall mission of this flight given the present disruption to the original plan. Beyond that

the dispatcher brings the longer view (event horizon) of the implications of the change. Example - Captain are you aware that we will now need priority handling at destination since the airborne holds are averaging 25 min and we have use 15 of our 30 min contingency in this reroute. Or ATCSCC IND center's reroute was great for the weather in their airspace but we are now on a route that will put us directly in the path of a line of TRW activity in KS which is building rapidly."

From a Dispatcher with 1 year of experience: "Can the aircraft do what it's being asked to do? Are there any MEL items that won't permit the operation requested? Is it the wisest course of action from a customer service standpoint, considering weather and fuel factors?"

The next question is intended to assess the degree to which dispatchers are vested in the outcome of replanning event being correct on the first pass (see Figure 6).

Question from Survey–Indicate your level of concern that the replan will WORK, meaning you've taken into consideration the constraint that caused the original plan to need replanning and as much relevant information you can to assure that you won't have to replan this flight again.
(Please select JUST one answer)

High	High level of concern
"OK"	I feel that it is 'okay' to replan again, stuff happens
Not Concerned	Not concerned in the least, that's why I'm here

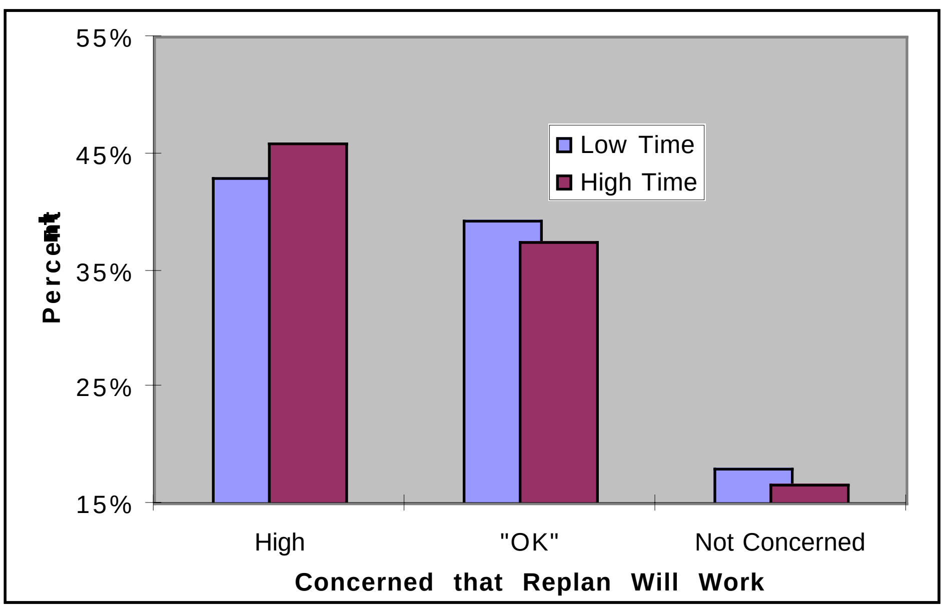


Figure 6. "First-Time Quality" Concern for Replanning Event

The next question was aimed at determining along what axis of control the dispatcher will initially seek a replanning solution. The responses are consistent with deviation around weather as the to-be-solved problem (see Figure 7). (It would be interesting to ask the question again with traffic/congestion as the cause of the replanning event to determine if a different axis of control might compete with lateral path changes.)

Question from Survey–Please indicate what type of replanning you consider first, acknowledging that many times the FINAL replan contains a combination of all three changes.

Lateral	Lateral course change
Altitude	Altitude change
Speed	Speed change

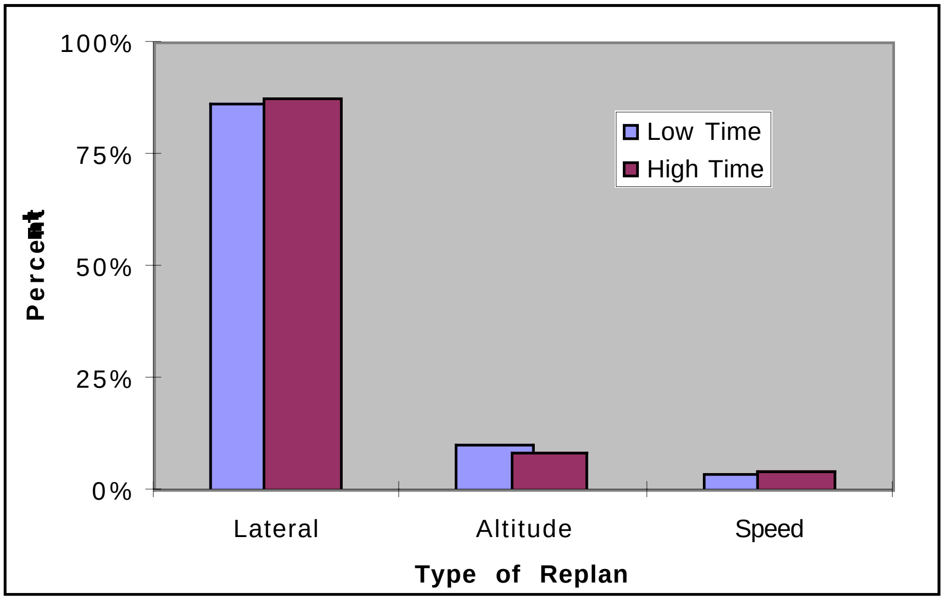
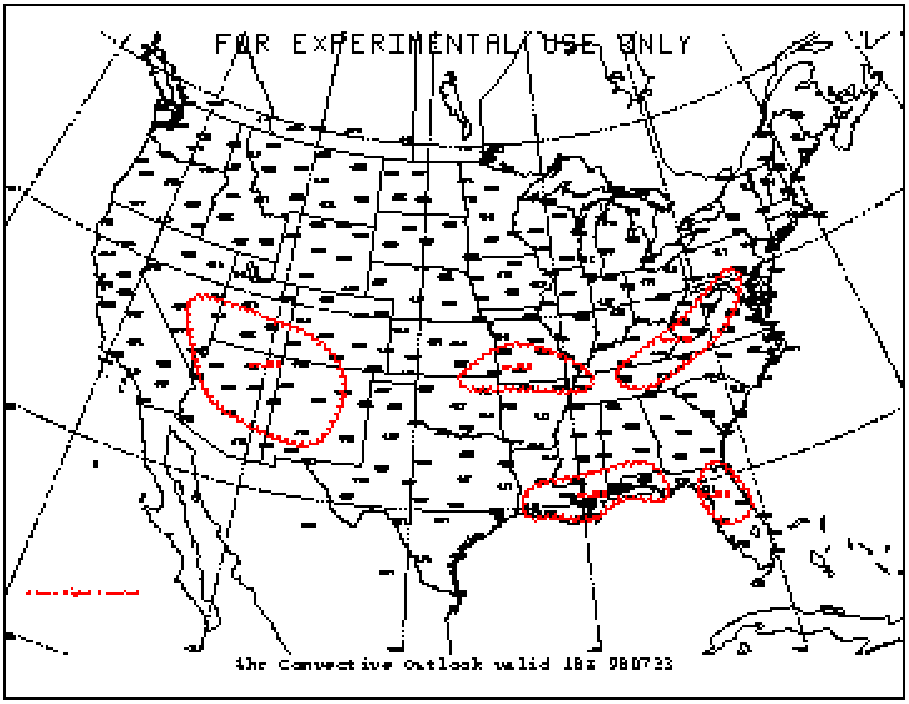


Figure 7. Axis of Control for Path Replanning

2.3.3. Scenario

Verbiage from Survey (in order to provide context for questions)–Below is an experimental Wx product being offered by the National Weather Service on their website:

http://www.awc-kc.noaa.gov/awc/246exp.html



This Wx product is a forecast of convective weather for the domestic U.S.. The intent will be to allow dispatchers and air traffic controllers to proactively route aircraft around convective weather that will develop sometime in the future, as opposed to waiting for severe weather to develop and then react with Severe Weather Avoidance Plans (SWAP).

Imagine that you have such a forecast available to you for a flight that has departed Chicago for a flight to Los Angeles. The situation is currently as follows: it is currently 16:00 Zulu, the flight is 30 minutes out of Chicago (just reaching Top of Climb), the image below is a forecast for 2 hours in advance (18:00 Zulu), the forecast tops for the severe weather, directly along the originally filed route, in the 'four corners' area is FL450 (well above the service ceiling of the aircraft).

The series of questions that follow are intended to gain insight into how dispatchers might use this information. What would be your reaction to these unfolding events? (Figure 8)

Question from Survey–I would do the following:
(please select ALL that apply, although some options are mutually exclusive)

New Route	I'd develop a new route and inform the crew
Inform & Ask	I'd inform the crew of the Wx forecast and ask what they want to do
Wait & See	I'd wait until the crew got MUCH closer and deal with the diversion in real-time
Seek Info	I'd go seek additional information from Wx service providers available to our company

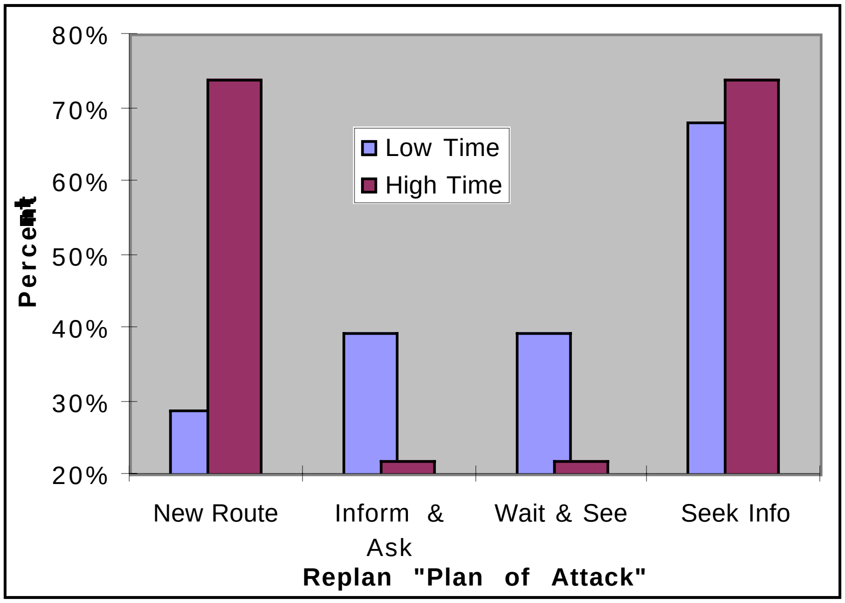


Figure 8. Dispatcher Replanning Strategy

From a Dispatcher with 15 years experience: "The results of the reanalysis would determine how I would approach the crew. If the alternate flight plan was very little impact on the time and burn I would present the new route more forcefully than in the case that the new route say puts completion the flight in jeopardy. In other words if I can change the route without affecting the crew's comfort level with the dispatch parameters of the flight I expect the crew to follow my lead just as they do an original release (Capt's rarely amend dispatchers release) In the case that the comfort level of the crew is impacted I will present the reroute."

From a Dispatcher with 1 year of experience: "If I had the forecast product during the flight planning process, I would not have routed the flight through the area of forecast convective activity to begin with. Prior to contacting the crew, I would have already determined the new routing and calculated the fuel numbers ahead of time. I'd also take a moment to analyze present conditions in the forecast area using various "official" sources such as constant pressure charts, lifted index charts and surface observations to determine if the forecast actually seems valid. Only then would I actually contact the crew and reroute them. If the forecast was not "panning out" in the forecast area, I would probably leave well enough alone and just monitor the area more closely and watch for signs of convective activity."

2.4. Enhanced Airline Operations Center Automation Concepts for In-Flight Replanning

2.4.1. Variation On Previous Scenario

Imagine the previously described scenario, and imagine for a moment, that there are an unprecedented number of technologies available to you to communicate the unfolding weather situation with the flight crew (Figure 9).

Question from Survey–I would do the following:
(please select ALL that apply, although some options are mutually exclusive)

Graphics	I'd ship the same graphical image of the Wx forecast up to the display/printer in the aircraft so the flight crew would have the same information in order to facilitate a dialog
Interactive Graphics	I'd use the interactive capability available to both the aircraft and myself to draw, in real-time, candidate routes around the Wx (a 'virtual' white-board shared between the air and ground where candidate routes can be drawn and viewed by both parties at the same time)
Wait & See	I'd wait until the crew got MUCH closer to the forecasted convective Wx region and deal with the diversion in real-time
Seek Info	I'd go seek additional information from Wx service providers available to our company

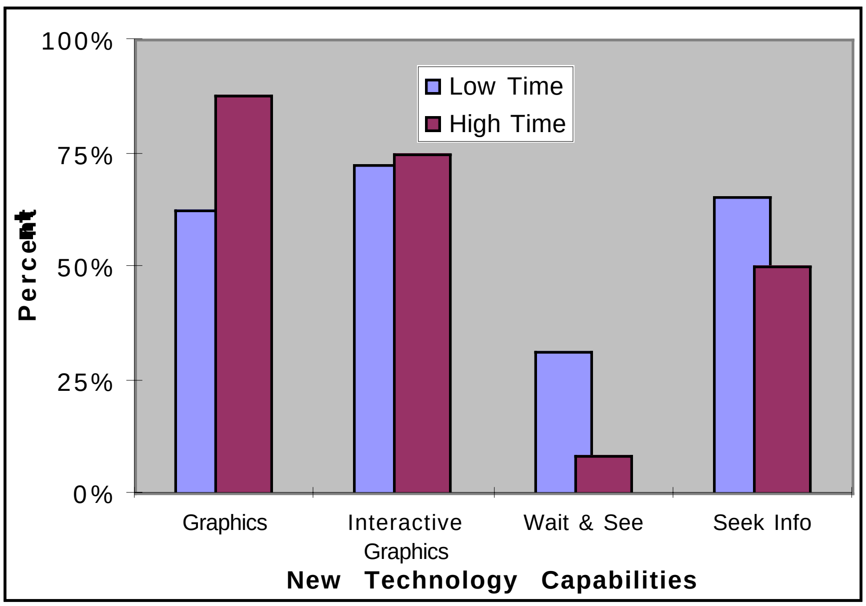


Figure 9. What New Technologies Would Do to Dispatcher Replanning Strategy

The next question is intended to address the desired features for a point-in-space replanning capability (Figure 10).

Question from Survey–Imagine the previously described scenario, and imagine for a moment, that there is a route replanning capability that would allow you to take the aircraft's present position and determine a new route to the destination. What would be the following characteristics of such a replanning tool that you'd like to see implemented. (please select ALL that apply)

Fuel	Fuel Consumption for Old route vs. New route
Time	Predicted Flight Time for Old route vs. New route

Traffic	Determine traffic along new route of flight to determine congestion constraints
Fuel at Alternate	Automatic recalculation of fuel impact on previously Filed Alternate
Actual Weight & Fuel	Ability to accept ACTUAL weight and fuel remaining in replan calculation
Special Use Airspace	Automatic highlighting of Special Use Airspace considerations for New route (i.e., the proposed route crosses SUA)

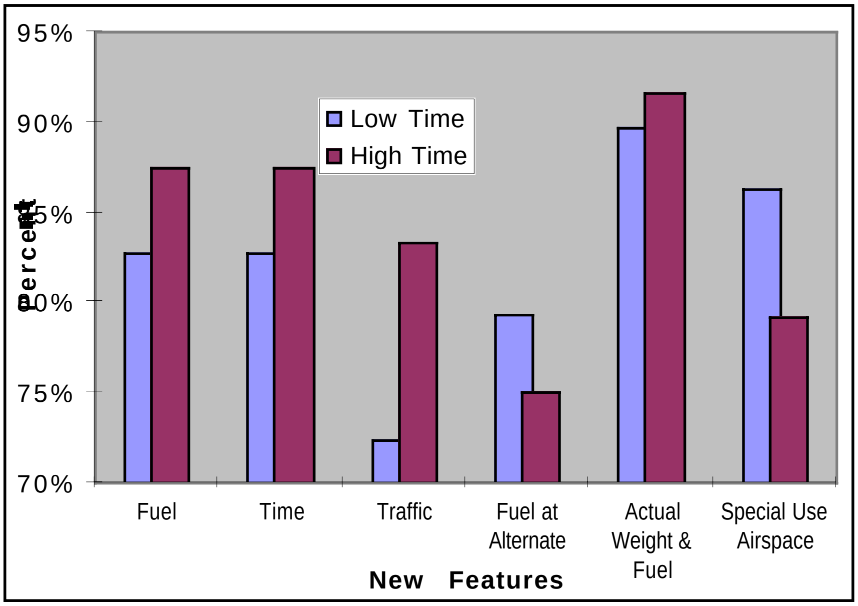


Figure 10. Desired Point-In-Space Replanning Capability

From a Dispatcher with 15 years experience: "ATC intent included in the congestion picture. This way we can create and maintain predictivity which keep actions of ATC and Carrier in synch - very important. Current aircraft fuel state and performance parameters of the flight in progress. This way I do not suggest we climb to FL350 when the crew has already done that."

From a Dispatcher with 1 year of experience: "Maybe it would be nice if it could also show ATC preferred routes and any active traffic management programs in place."

From a Dispatcher with 20 years experience: "Three-dimensional display of the NAS with aircraft... Come on, it can't be THAT hard to do!"

The next question is intended to address the desired features for any new replanning functionality that would be added to the dispatcher's flight plan automation capability. It is clear that dispatcher's are seeking integration among the various pieces of automation they currently use. If they have access to information about weather and traffic (as with many ASD products) it is reasonable to think that a graphic representation of a flight plan could be overlaid on this display and then 'cut & paste' and 'dragging' capabilities (using a mouse or other cursor control device) could be provided.

Question from Survey–If some form of automation could be made available to assist you in the replanning process, what function(s) would it provide to you?
(Please answer in the text box provided)

From a Dispatcher with 3 years experience: "Fast point to point replanning capabilities without restriction taking into account fuel on board and actual ZFW of A/C."

From a Dispatcher with 21 years experience: "A completely integrated display using data derived from ASD, Flight planning programs, NEXRAD weather."

From a Dispatcher with 13 years experience: "The ability to input actual fuel and wind values at any given point. To have the same features as a FMS but using actual en route winds beyond the point of replanning."

From a Dispatcher with 4 years experience: "FAST method of creating new routings (connecting airways, SIDs/STARs, etc) and pumping that into the flt planning system. Current method requires extensive use of charts or solid familiarity of area."

From a Dispatcher with 15 years experience: "(1.) Real-time air traffic demand by fix and airway including airspace which is presently saturated. Real-time display of all ATC restrictions and display of ATC INTENT. (2.) Automatic real-time fuel state and present performance of the aircraft fully integrated into the dispatch flight planning tools. (3.) Ability to uplink dispatch replan directly into the FMS for Captain approval and seemly execution by flight deck."

From a Dispatcher with 1 year of experience: "Real-time aircraft position, actual fuel onboard, altitude, outside air temp, ATC data relating to traffic volume and preferred routings and traffic management programs displayed graphically in real-time."

From a Dispatcher with 20 years experience: "I want the ability to graphically display my flight then click a new route and have the display draw that route, and spit out a new flight plan, based on the original input parameters, with optional entries if I so choose. Need to be able to tell the flight planning computer "this flight must overfly ABC" or "this flight must AVOID ABC...".

From a Dispatcher with 1 year of experience: "Being able to forecast ATC bottle necks (graphical) and a user friendly replanning system. Currently I need to assure fixes are "tied together" or the replanning entry will not be accepted. Being able to point and click to selected VOR's and automatically performing an analysis for time sensitive replanning would help a great deal."

2.5. Conclusions and Recommendations

The interesting point to note is that all the respondents currently have graphical weather information available to them. In addition, more than 4 out of 5 have forecasted weather information, in some graphic format. Also interesting to note is that greater than 4 out of 5 have some form of an Aircraft Situation Display. It should be noted, however, that many indicated an interest in a graphic indication of ATC or ATCSCC traffic flow initiative be presented on the same display.

As is the case in most tasks involving Command and Control, the sample of dispatchers that responded to this survey are indicating a strong desire for integration among the various software elements that support their job. They would like to see weather and traffic integrated, in a graphical format, on a flight planning tool which allows modifications (*replanning*) to be made by simply "clicking and dragging" segments of the flight plan to avoid problematic areas..

3. Post Operations Evaluation Tool Assessment of Actual vs. Predicted Fuel Burn and Airborne Delay

CDM is a joint FAA/industry initiative aimed at improving Traffic Flow Management. Through increased information exchange and improved collaboration, CDM promotes the principles of collaborative problem-solving and consensus-based decision making between the various components of aviation transportation, in both government and industry.

As part of CDM, Metron has been involved in the development of the Post Operations Evaluation Tool (POET). This tool allows an analyst to explore what happened in the National Airspace System (NAS) using a combined database of information from the FAA and the airlines. This database includes what the airlines originally intended and what actually transpired. At the time of this writing POET exists as a working prototype with a sample database consisting of information on over 142,000 domestic flights operated by a major airline between April and June of 1998.

Using the POET prototype, the sample database, and other tools we have conducted a study to explore aircraft routing inefficiencies in the NAS. This study was done under contract to the Honeywell Technology Center as part of NASA's Advanced Aviation Technology Transfer (AATT) program. This report documents the results of this effort.

The remainder of this paper is organized into three sections in which we summarize the results, discuss the details of our analyses, and make specific recommendations for follow-on efforts.

3.1. Summary of Results

The goal of this study was to explore aircraft routing inefficiencies in the NAS. To do this we:

- Defined a straight-forward quantitative metric based on the difference between planned and actual fuel burn and airborne delay
- Applied it to a recent data set of over 142,000 flights
- Looked for relationships within the data that identify where inefficiencies are occurring and possibly what may be causing them

There are several limitations that apply to our analysis:

- The current data set encompasses only a single major airline.
- Some data are incomplete or inaccurate, but we have attempted to filter these out as best as possible.
- We do not have data on winds aloft that impact the efficiency metric as defined in this paper.

3.1.1. Two Major Findings

Eastbound vs. Westbound Flights

In our analysis we found that *eastbound flights were inefficient significantly more often than westbound flights*. This trend appears to occur throughout the NAS, and not in specific regions. One possible explanation is that westbound flights want to avoid the jet stream (headwinds) which is easier to do and less affected by reroutes (because there is more space outside the jet stream). In contrast, eastbound flights trying to take advantage of the jet stream (tailwinds) may be more sensitive to reroutes taking them out of the favorable wind pattern. This explanation is tentative and requires further investigation.

Reroutes vs. Inefficiency

We looked at the correlation between inefficient flights and flights that were significantly rerouted and found that *the significant rerouting of a flight is not a strong predictor of its inefficiency*. We found that over half of the inefficient flights were not significantly rerouted. Conversely, we found that only fifteen percent of the rerouted flights were inefficient compared to thirteen percent for all flights. Significant reroutes do appear to be a contributing factor to inefficiency, but not the primary cause.

3.1.2. Summary of Other Results

In addition to the two major findings above we also found the following:

- We analyzed inefficiency as a function of time of day, and found that it appears to track with the frequency of operations. That is, as the number of departures per hour goes up so does the number of inefficient flights. Additionally, we observed no cumulative effect. This suggests that inefficiencies occur on a flight-by-flight basis.
- When we analyzed inefficiency as a function of day of the week, we found no significant correlation other than to reinforce the previous result.
- In analyzing inefficiency as a function of city pair, we found that flights into the Northeast (e.g., BOS, LGA, etc.) and flights from the West Coast into ORD had a larger percentage of inefficient flights than elsewhere in the NAS.
- In analyzing inefficiency versus cruise-altitude changes, we found that more inefficient flights had cruise-altitude changes than did efficient flights. These changes tended to involve lower altitudes for the inefficient flights. We did find, however, that a large percentage of inefficient flights were neither significantly rerouted nor had cruise altitude changes. This reinforces the second major finding above.

3.2. Analysis Details

In this section we discuss the details of our analyses and their results. It is divided into six primary sub-sections. First, we describe how we measure inefficiency, and discuss the limitations that apply to our results. The remaining four sections look at inefficiency as a function of time of day, day of the week, city pair, and significant reroutes.

3.2.1. Measuring Routing Inefficiency

High-level Metric

With hundreds of airlines and general aviation users operating in excess of 40,000 flights a day the NAS is a very complex place. There are many conceivable methods for measuring the efficiency of routing within the NAS ranging from the theoretically ideal to operationally specific. These measures can get pretty complex and are not always easy to understand as they delve into concepts such as predictability, flexibility, availability, delays, workload, equitability, profit, traffic counts, traffic flows, capacity and demand. For this analysis we wanted a simple, intuitive, and quantitative measure.

As the service provider, the FAA strives to provide safe and efficient use of the NAS to its users. The scheduled air carriers attempt to fly their published schedules and minimize their expense in doing so. For individual flights this translates into operating on time without incurring additional cost. *Thus, from a routing perspective, we can say that a flight that remains in the air longer than planned and/or burns more fuel than planned is inefficient.* This assumes that airlines plan their flights to be as efficient as possible under the given circumstances of prevailing winds, weather, air traffic control/management restrictions, schedule impact, market decisions, etc.

Figure 11 shows graphically how inefficiency is defined in this study. The vertical axis (fuel delta) is the difference between actual and planned fuel burn, while the horizontal axis (airborne delay) is the difference between actual and planned flight time. The diagonal line shows an arbitrary threshold that marks the boundary between inefficient and efficient flights.

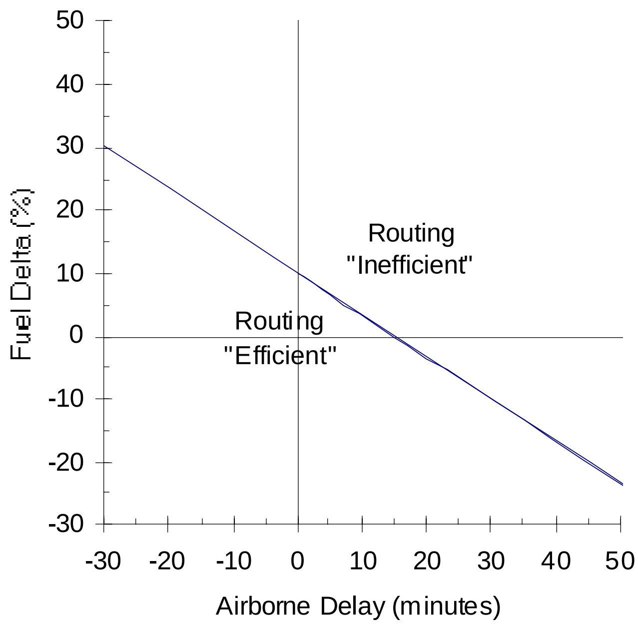


Figure 11: Definition of Routing Inefficiency

Using this approach, we have plotted data from 142,172 flights that operated between April–June 1998, as shown in Figure 12. This figure shows that the bulk of the flights are near the origin, meaning that the actual fuel burn and flight time are close to what was planned. It is important to note that many of the data points in the middle overlap, which causes the chart to misrepresent the distribution somewhat. In fact, more that 95 percent of the data have fuel deltas between ± 20 percent and airborne delays between ± 20 minutes. However, the figure does show that a significant number of the flights both burned significantly more fuel and were delayed in the air. For example, 2243 flights burned more than ten percent extra fuel and were delayed more than 15 minutes in the air.

Also note that we chose to plot the fuel difference as a percent to normalize the differences due to different equipment types' fuel efficiencies and differences in the total fuel burns. Conversely, the airborne delay is not plotted as a percent. After doing some statistical analysis, we found a strong correlation between airborne delays and arrival delays, and we felt that these delays are more meaningful in absolute terms (i.e., actual minutes delayed) vice relative terms (i.e., a percentage of planned airtime).

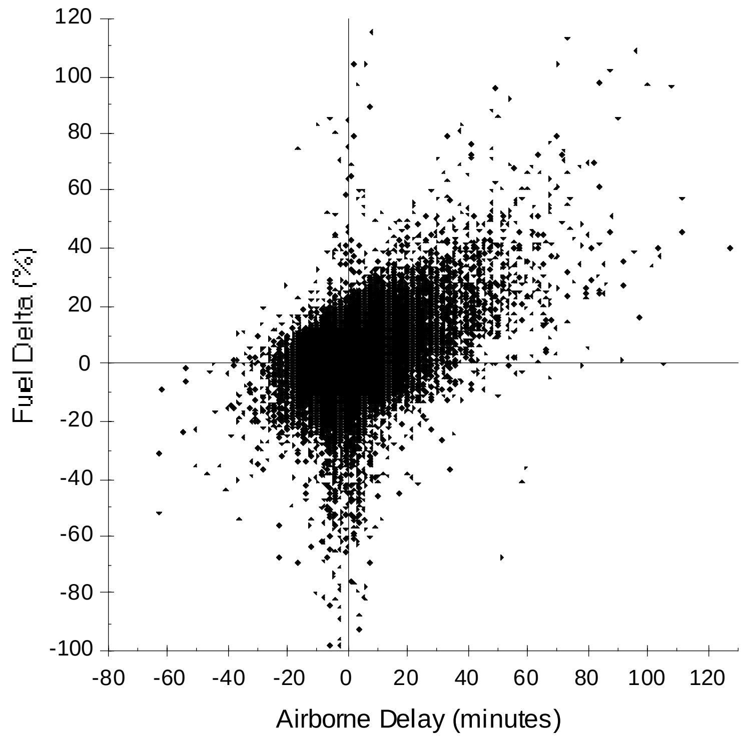


Figure 12: Fuel Delta% ((actual – planned)/planned) vs. Airborne Delay (actual - planned) for 142,172 flights

Threshold Considerations

The selection of a threshold to distinguish whether an individual flight is inefficient is somewhat arbitrary. From conversations with several airline dispatchers we understand that there can be an intentional tradeoff between fuel efficiency and flight time. For example, an airline may want to fly at a faster, less fuel-efficient speed to make up for departure delays. Therefore, we chose the threshold to be a function of these two variables. Specifically, we chose a straight-line boundary with a y-intercept of 10 percent more fuel burned than planned, and an x-intercept of 15-minutes airborne delay (see Figure 11). Using this threshold function, 18,462 (13%) of the 142,172 total flights in our data set are inefficient, as illustrated in Figure 13.

Are there other reasonable threshold functions? Yes, but it is beyond the scope of this analysis to explore them. We did, however, briefly look at two additional threshold functions to see how sensitive the results are to the choice of threshold. We found that number of inefficient flights varied with the different thresholds; however, the distribution of inefficient flights among the different groupings (e.g., time of day, day of week, by city pair) we examined did not appear to vary significantly.

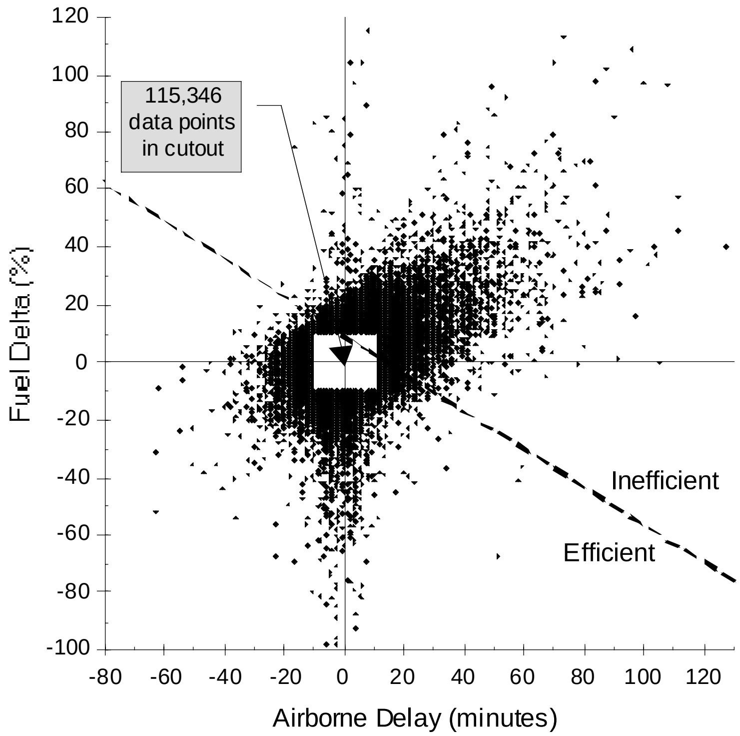


Figure 13: Inefficient vs. Efficient flights

3.3. Study Limitations

There are several limitations that apply to this study. We do not believe that the results would change significantly if these limitations were removed, but we feel their possible effects warrant further study. Below is a brief discussion of these limitations.

3.3.1. Single Airline

The airline[1] whose data we used has a very large domestic operation, and we feel they provide a representative sample of NAS operations; nevertheless, our data set encompasses information for only one major airline. This impacts the study in two important ways. First, there are routes that are not represented (or under-represented) in the data because this airline does not fly them. Second, because our inefficiency metric is partly based on planned values, any unique characteristics of the airline's planning process could potentially influence the results.

[1] We refrain from identifying the airline in this report at their request.

3.3.2. Bad or Missing Data

Looking at our data set on a day-by-day basis, four days stood out as having far fewer flights than the rest (see Figure 14). We believe that there were problems with the data collection on these days. Therefore, we removed these days from our day-of-the-week investigation and any other investigations requiring an entire day's traffic. There is no reason, however, to suspect that the data on the flights that were collected on those days is inaccurate. Thus, we did use those flights in our flight-by-flight comparisons.

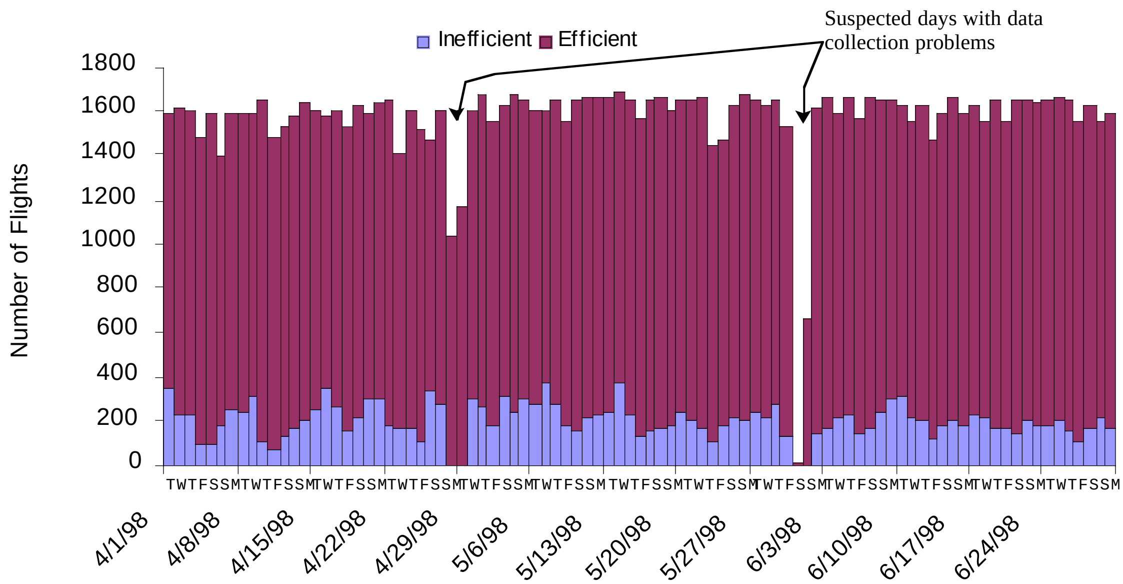


Figure 14: Inefficiency by Day (Dates shown are Tuesdays)

We also found instances where the data for individual flights appeared to be inconsistent or inaccurate. For example, some of the actual fuel burns were extremely low compared to the planned fuel burn. Also, some of the FAA position reports (i.e., TZ messages) that make up the actual flown track data were clearly wrong when plotted on a map. In these cases, we attempted to filter these data out of our computations.

Additionally, the in-air fuel burn data is derived from the total fuel burn (gate-to-gate) and modeled taxi fuel burns. In cases where the taxi times were much longer than expected, such that the pilot may have shut down an engine resulting in a lower taxi fuel burn, the in-air fuel burn may be somewhat understated. This may result in a few flights being considered efficient when they are actually inefficient.

Finally, we found several cases where portions of the actual track data were missing. In our analysis of significantly rerouted flights we did not use these flights.

3.3.3. Ground Delay Programs (GDP)

We performed some analysis checking for a correlation between ground delay programs (GDPs) and inefficiency, but an investigation to properly address this issue was beyond the scope of this study. The information we had on ground delay programs allowed us to look at days with and without such programs, but did not allow us to segregate individual flights by whether or not they were directly affected by a ground delay program.

In the top quartile of days with the most inefficient flights, there were several days on which there were no ground delay programs. Conversely, there were days with ground delay programs in effect in the bottom quartile of days (days with the fewest inefficient flights). However, the worst 10% of the days for inefficient flights did have ground delay programs in effect, so we believe that this is an area that warrants further study.

3.3.4. Unexpected Winds

Unexpected winds can have an impact on inefficiency as we have defined it. If the winds (or other weather phenomena) change from what was predicted at the time a flight is planned, then the (in)efficiency of that flight may have little to do with the factors that we have studied. However, in looking at large numbers of flights we would expect the impact on our results to average out unless there is a systemic problem in the wind models being used to plan flights (e.g., if the position of the jet stream was always incorrectly modeled). In any case, analysis of weather data was beyond the scope of this study.

3.4. Inefficiency by Time of Day

In Figure 15, we separated the data into one-hour groups based on scheduled departure times. As the number of departures increased, the number of inefficient flights also increased at a very similar rate. When the number of departures decreased, the number of inefficient flights also decreased. This indicated that there was no buildup of inefficiency in the airspace causing an increasing number of inefficient flights over time. Rather, the number of inefficient flights was directly related to the number of flights. This suggests that inefficiency occurs on a flight-by-flight basis instead of as a cumulative effect of what happened to the NAS prior to a flight's departure.

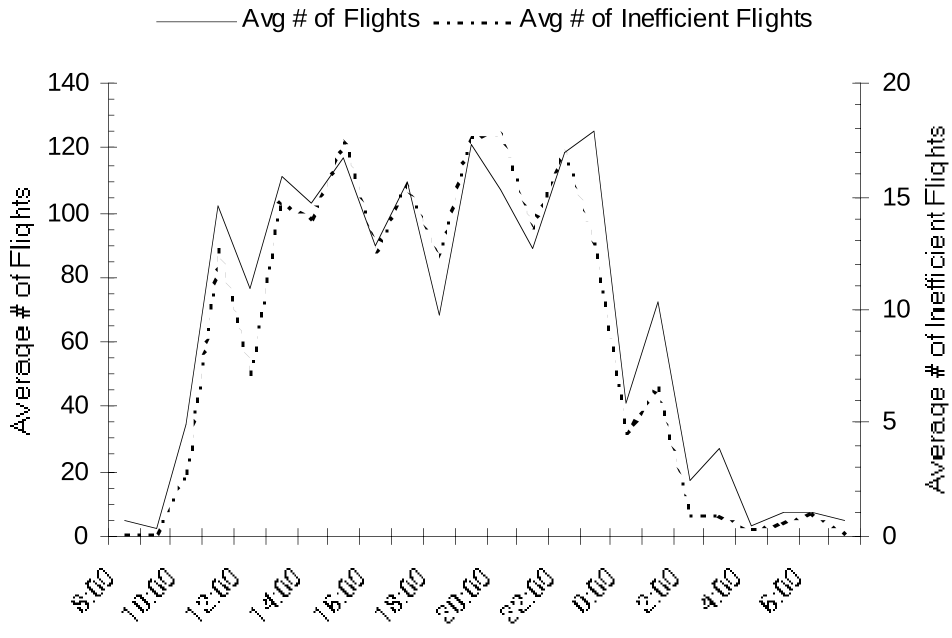


Figure 15: Inefficiency by time (GMT) of day

3.5. Inefficiency by Day of Week

In Figure 16, we plot the average number of flights for each day of the week and compare that to the average number of inefficient flights. The figure shows the number of inefficient flights is about the same on different days of the week except for Saturdays and Sundays where the number of inefficient and efficient flights is slightly less.

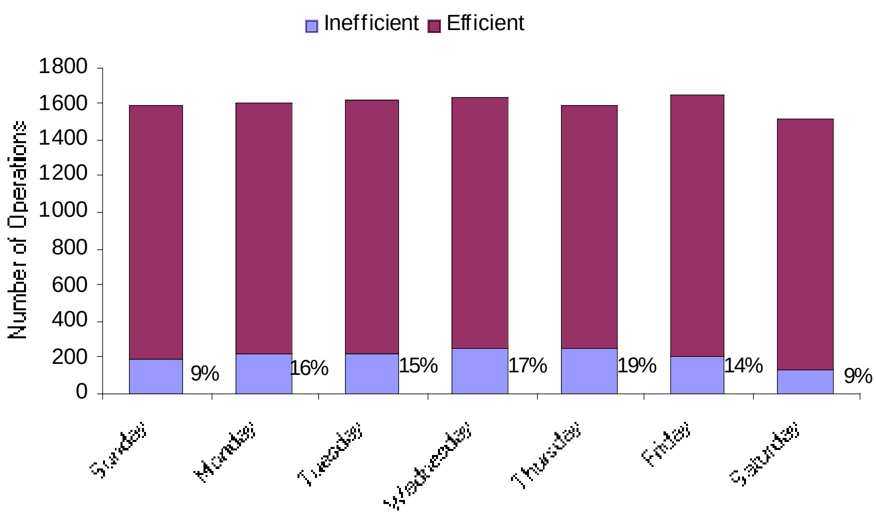


Figure 16: Inefficiency by day of week

3.6. Inefficiency by City Pair

3.6.1. Inefficient Routings

To get an idea of where the inefficient flights are occurring we computed the percentage of inefficient flights by city pair. Looking only at those city pairs that average two or more flights per day, Table 1 lists the top twenty city pairs with the highest percentage of inefficient flights. The table shows that for those city pairs approximately one to two thirds of the flights are inefficient. As perhaps expected, it shows that flights into the northeast airports (EWR, LGA, BOS, JFK) are a problem, as well as flights from the west coast (PDX, SJC, SAN, SNA, SEA) into ORD.

Table 1: Inefficiency by city pair—Top 20

Departure Airport	Arrival Airport	Inefficient Flights	Total Flights	Percent Inefficient
ORD	EWR	650	1028	63
PDX	ORD	137	229	60
SJC	ORD	221	408	54
ORD	LGA	624	1217	51
DFW	EWR	407	808	50
SJC	BOS	124	253	49
ORD	BOS	539	1126	48
ORD	PHL	376	908	41
DFW	ATL	495	1203	41
LAX	EWR	99	243	41
DFW	BOS	295	788	37
DFW	STL	206	584	35
DFW	PHL	198	580	34
MIA	EWR	86	252	34
SFO	JFK	141	417	34
ORD	ATL	154	468	33
SAN	ORD	135	427	32
SNA	ORD	126	415	30
LAX	JFK	242	826	29
SEA	ORD	128	442	29

To better visualize the geographic distribution of inefficient flights we plotted an arc on a map between each city pair in our data for which there was more than five instances. The color of each arc represents the percentage of inefficient flights. It ranges from white to red, where white means zero inefficient flights and red means 50 percent or more inefficient flights for that city pair. The width of each arc is proportional to the total number of flights between a particular city pair. Note that these arcs do not represent the actual or filed route of flight, merely the origin and destination. Figure 17 shows an example of one of these plots.

In this figure we have excluded those city pairs with less than 10 percent inefficient flights to better reveal where the inefficient flights are occurring. Figure 17 shows what we noted earlier in Table 1: the flights into the Northeast tend to be more inefficient than the rest of the country. The next two figures further reveal details of where the inefficient flights are occurring. In Figure 18 we show arcs only for city pairs with more than 20 percent inefficient flights. Likewise, in Figure 19 we show arcs only for city pairs with more 30 percent inefficient flights.

Figure 17: City pairs with greater than 10% inefficient flights (white = 0% inefficient, full red = 50% inefficient)

Figure 18: City pairs with greater than 20% inefficient flights (white = 0% inefficient, full red = 50% inefficient)

Figure 19: City pairs with greater than 30% inefficient flights (white = 0% inefficient, full red = 50% inefficient)

3.6.2. Eastbound vs. Westbound

One limitation of the plots above is that it is hard to see the difference between flights going different directions between two cities (e.g., LAX to DFW versus DFW to LAX) because one arc tends to overwrite the other. To check if there were any differences we looked at the differences between flights arriving and departing selected airports. When we did this we noticed a very definite bias against eastbound flights. That is, eastbound flights have a greater tendency to be inefficient than westbound flights. The following figures illustrate what we found:

Figure 20 and Figure 21 show flights going to and from California, respectively. Notice that the arcs in the Figure 21 are redder that in Figure 20 indicating that the eastbound flights are more inefficient.

Figure 22 and Figure 23 show similar data for the New York and Boston airports. Again the eastbound flights show more inefficiencies.

Figure 24 and Figure 25 show flights going to and from DFW, respectively. In Figure 24 the flights coming from the west tend to be redder (more inefficient) than the flights coming from the east. Figure 25 shows the eastbound bias is consistent for flights leaving DFW. In addition, these two figures refute the idea that this bias is just a byproduct of the inefficiencies noted earlier in the northeast.

Figure 26 and Figure 27 show flights going to and from ORD, respectively, and further illustrate the points made for DFW.

Figure 20: Westbound flights to CA airports (white = 0% inefficient, full red = 50% inefficient)

Figure 21: Eastbound flights from CA airports (white = 0% inefficient, full red = 50% inefficient)

Figure 22: Eastbound flights to NY/BOS (white = 0% inefficient, full red = 50% inefficient)

Figure 23: Westbound flights from NY/BOS (white = 0% inefficient, full red = 50% inefficient)

Figure 24: Flights into DFW (white = 0% inefficient, full red = 50% inefficient)

Figure 25: Flights from DFW (white = 0% inefficient, full red = 50% inefficient)

Figure 26: Flights into ORD (white = 0% inefficient, full red = 50% inefficient)

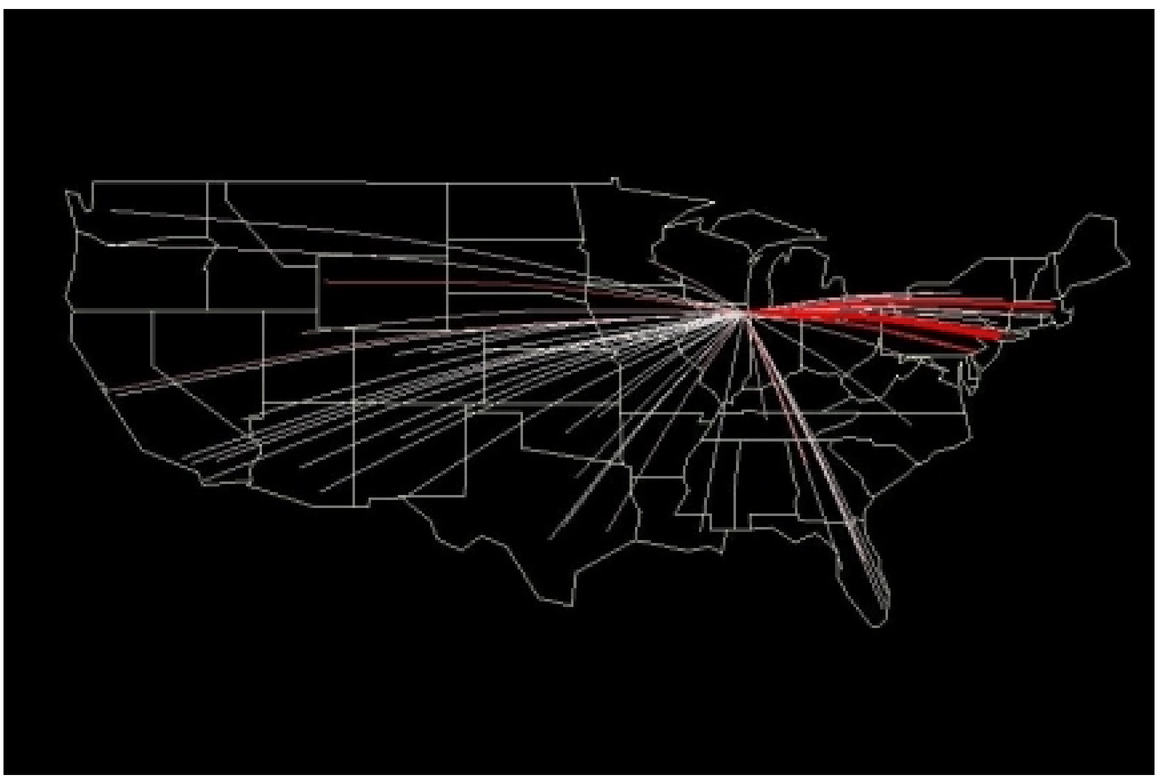


Figure 27: Flights from ORD (white = 0% inefficient, full red = 50% inefficient)

To understand the magnitude of the difference between the eastbound and westbound flights we looked at the flights between the 20 cities with the most operations (within the single airline data set), and we categorized each city as being in one of three regions: east, west, or central. Table 2 lists the percentage of inefficient flights between these three groups. It shows that there are roughly two to three times more inefficient eastbound flights than westbound flights. Furthermore, the "East to East" line shows that this phenomenon is not simply a result of inefficiency in the Northeast.

Table 2: Inefficiency by general direction of flight

		Percent Inefficient
Eastbound	West to Central	18%
	West to East	26%
	Central to East	31%
Westbound	East to Central	9%
	East to West	8%
	Central to West	3%
Neither	East to East	10%
	Central to Central	12%
	West to West	N/A

West = LAX, SFO, PHX, SJC, SAN
Central = DFW, ORD, AUS, IAH, DEN, BNA, MCI
East = MIA, LGA, BOS, DCA, EWR, ATL, JFK, PHL

What is the cause of this bias? One possible explanation is that westbound flights want to avoid the jet stream (headwinds) which is easier to do and less affected by reroutes (because there's more space outside the jet stream). In contrast, eastbound flights trying to take advantage of the jet stream (tailwinds) might be more sensitive to reroutes taking them out of the favorable wind pattern. How valid is this idea? Without further analysis we cannot say, but it seems reasonable.

3.7. Inefficiency vs. Reroutes

3.7.1. Identifying Significant Reroutes

During a flight there are many actions that can cause it to deviate from its filed flight plan. These include reroutes, vectoring, changing speed, changing altitude, holding, etc. To explore the impact that reroutes may have on a flight's efficiency, as defined in this paper, we need to determine which flights were significantly rerouted from their filed flight plans.

We first looked at the number of flight plan amendments (i.e., AF messages) that were received for each flight after departure. Unfortunately, when we examined the proposed versus actual tracks for many individual flights we found no correlation between the number of flight plan amendments and whether a flight was significantly rerouted. A single amendment might completely change the flight path, or seven separate amendments might only alter the flight path slightly, leaving it very similar to its originally filed flight path.

Our next approach was to algorithmically compare the length and the spatial similarity of the proposed flight track in the filed flight plan with the actual track for each flight. To compare the track lengths we computed the sum of the distance between each waypoint in the proposed flight track and, similarly, the sum of the distance between each position report that comprises the actual track. Excluding those flights with incomplete or clearly inaccurate actual track data, we found that the distance actually flown ranged between about 15 percent less to over 50 percent greater than the length of the proposed route. We then grouped the flights into four categories of track-length similarity:

short—actual track more than 5% shorter than proposed track
same—actual track within ± 5% of the proposed track
long—actual track between 5-15% longer than proposed track
longer—actual track more than 15% longer than proposed track

Next we calculated the spatial similarity of the proposed flight track with that actually flown using Metron's Spatial Similarity Algorithm (SSA). The SSA quantifies the degree of similarity between two ground tracks with the same starting and ending points, but different intermediate points. It returns a small number for tracks that are very similar and a large number for tracks that are very dissimilar. This is accomplished by measuring the lateral displacement between selected points along the tracks, summing, and normalizing the total displacement at these points by the average length of the two tracks. This procedure is somewhat similar to determining the area enclosed by the two tracks and dividing that area by the average length of the two tracks, thus obtaining a measure of the average separation between the tracks.

Figure 28 through Figure 30 show some examples of the spatial variance parameter (SVP) that is returned by the SSA for several pairs of proposed (thicker line) and actual tracks (thinner line). After visually examining many track pairs we grouped flights into two categories of spatial similarity based on whether the SVP was greater or less than 0.5:

- spatially similar—SVP less than 0.5
- spatially dissimilar—SVP greater than or equal to 0.5

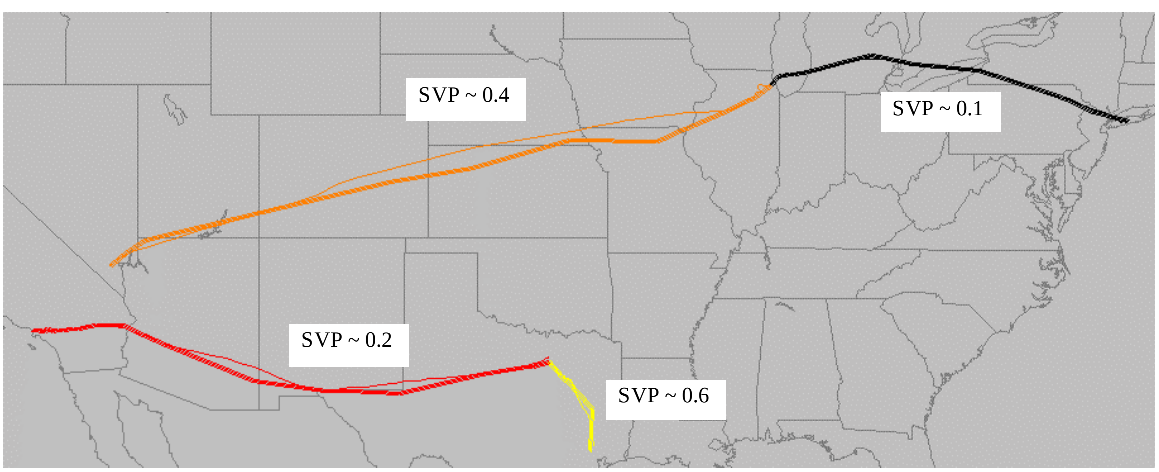


Figure 28: Spatial variance examples (SVP = 0.1 to 0.6), thick line = filed route, thin line = actual route

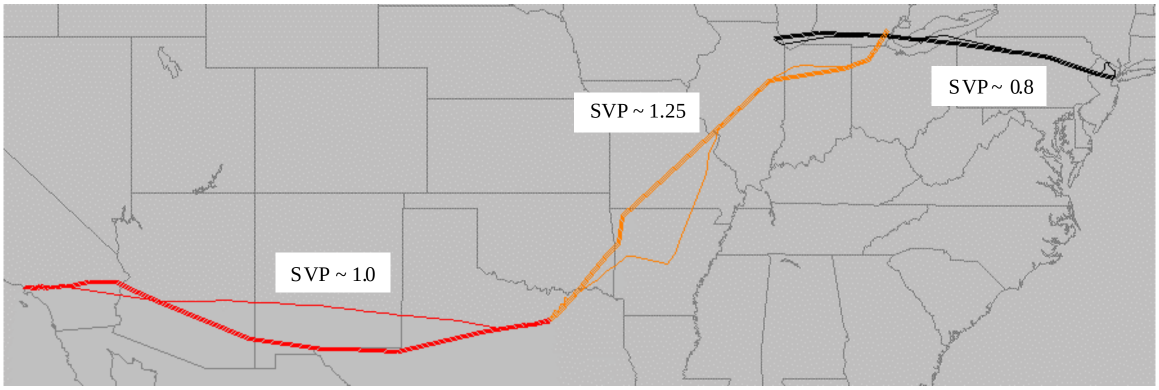


Figure 29: More spatial variance examples (SVP = 0.8 to 1.25), thick line = filed route, thin line = actual route

Table 3 summarizes the results of the track length and spatial comparison of the proposed versus actual flight tracks.

We next visually examined representative flights from each of the eight groups in the table and determined that the shaded cells represent those flights that were significantly rerouted from their originally filed flight plan. Overall, a total of 14.9 percent (41, 997 out of 129,367) of the flights that we looked at were significantly rerouted. The total number of flights used in this analysis differed from 142,172 because some of the flights had missing or inaccurate actual flight track data.

Table 3: Rerouted flights categorized by track length and spatial similarity of actual routes versus proposed routes. Shared cells show significantly rerouted flights.

	Spatially similar		Spatially dissimilar	
Track length similarity	Flights	% of Total	Flights	% of Total
short	3,151	2.4%	3,282	2.5%
same	78,811	60.9%	31,226	24.1%
long	5,408	4.2%	5,265	4.1%
longer	537	0.4%	1687	1.3%

Note that we excluded 12,805 of the 142,172 total flights from this table due to missing or inaccurate actual flight track data. Also, percentages were rounded to one decimal.

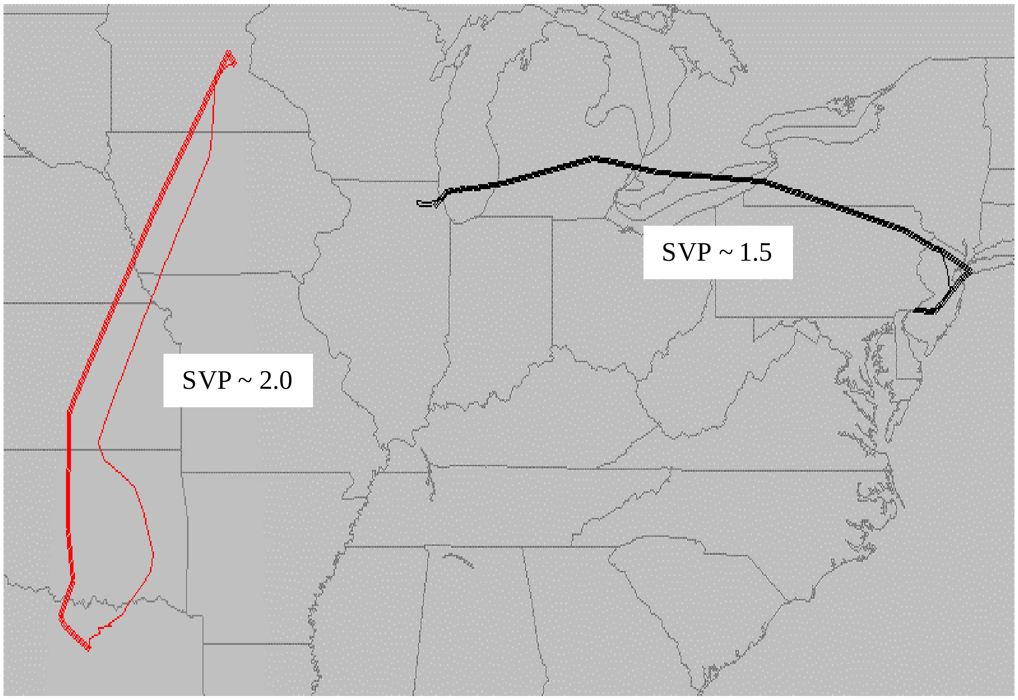


Figure 30: More spatial variance examples (SVP = 1.5 to 2.0), thick line = filed route, thin line = actual route. (Large value of SVP for the ORD/PHL route caused by significant difference close to ORD.)

3.7.2. Inefficiency and Significant Reroutes

After determining which flights were significantly rerouted, we then looked at the relationship between these flights and inefficient flights. Table 4 and Table 5 list the breakdown of efficient and inefficient flights into the spatial and track-length comparison categories. The first table shows that while the majority of efficient flights (68.4%) were not significantly rerouted, a large fraction (31.7%) were. Similarly, the second table shows that while many of the inefficient flights were significantly rerouted (37.9%), the majority of them were not (62.1%). In fact, almost half (48.1%) of the inefficient flights appear in the same-similar category.

Table 5 does show that in the population of inefficient flights there are relatively fewer flights in the same-similar category and relatively more in the long-dissimilar category as compared to the population of efficient flights (Table 4). Also, Table 4 shows that a significant percentage of the efficient flights (2.8%) appear in the short-dissimilar category (i.e., the received a "beneficial" reroute or shortcut) whereas very few of the inefficient flights (0.5%) appear in this category.

Table 6 summarizes the relationship that we found between inefficiency and significant reroutes. This table and the two previous ones show that significant rerouting appears to be a contributing factor to flights being inefficient; however, it does not appear to be the primary cause.

Table 4: Efficient rerouted flights

Track length similarity	Spatially similar: Number	Spatially similar: % of Tot. Efficient	Spatially similar: % of Grand Total	Spatially dissimilar: Number	Spatially dissimilar: % of Tot. Efficient	Spatially dissimilar: % of Grand Total
short	2,916	2.6%	2.3%	3,201	2.8%	2.5%
same	70,856	62.8%	54.8%	28,631	25.4%	22.1%
long	3,329	3.0%	2.6%	3,008	2.7%	2.3%
longer	209	0.2%	0.2%	687	0.6%	0.5%

Note that we excluded 10,873 of the 123,710 total efficient flights from this table due to missing or inaccurate actual flight track data. Also, percentages were rounded to one decimal.

Table 5: Inefficient rerouted flights

Track length similarity	Spatially similar: Number	Spatially similar: % of Tot. Inefficient	Spatially similar: % of Grand Total	Spatially dissimilar: Number	Spatially dissimilar: % of Tot. Inefficient	Spatially dissimilar: % of Grand Total
short	235	1.4%	0.2%	81	0.5%	0.1%
same	7,955	48.1%	6.1%	2,595	15.7%	2.0%
long	2,079	12.6%	1.6%	2,257	13.7%	1.7%
longer	328	2.0%	0.3%	1,000	6.0%	0.8%

Note that we excluded 1,932 of the 18,462 total inefficient flights from this table due to missing or inaccurate actual flight track data. Also, percentages were rounded to one decimal.

Table 6: Summary of inefficiency vs. significantly reroutes

	# Flights	# Inefficient	Percentage
Sig. rerouted	41,997	6,261	14.9 %
Not sig. rerouted	87,370	10,269	11.8 %
Total	129,367	16,530	12.8 %

Note that we excluded 12,805 of the 142,172 total flights from this table due to missing or inaccurate actual flight track data. Also, percentages were rounded to one decimal.

3.7.3. Inefficiency & Altitude Changes

In the previous sub-section we saw that a large number of inefficient flights were not significantly rerouted. A possibility is that these flights were inefficient due to altitude changes even though they were not significantly rerouted. While a thorough investigation of this possibility is beyond the scope of this study, we did perform some analysis of this issue. Specifically, we examined all the flight-plan amendment data to determine if each flight's cruise altitude was changed from that originally proposed in the flight plan. In many cases, the cruise altitude was changed several times either higher, lower, or both. Note these are not necessarily the actual altitudes at which the aircraft actually flew.

Table 7 and Table 8 list the number of flights that had amended altitudes by the spatial and track-length comparison categories. Notice that in each category the inefficient flights had a greater percentage of flights that had altitude amendments. It is also interesting to note that about 40 percent of the inefficient flights in the same-similar category did not receive any amended altitudes. Thus, there were many inefficient flights that were neither significantly rerouted nor given changes in cruise altitude.

Table 7: Efficient flights that received amended cruise altitudes categorized by track length and spatial similarity category (Percentages are relative to same category in Table 4)

	Spatially similar		Spatially dissimilar	
Track length similarity	Number	% of Efficient	Number	% of Efficient
short	1516	52.0%	1711	53.5%
same	36936	52.1%	16260	56.8%
long	1101	33.1%	1583	52.6%
longer	68	32.5%	327	47.6%

Percentages were rounded to one decimal.

Table 8: Inefficient flights that received amended cruise altitudes categorized by track length and spatial similarity category (Percentages are relative to same category in Table 5)

	Spatially similar		Spatially dissimilar	
Track length similarity	Number	% of Inefficient	Number	% of Inefficient
short	186	79.1%	53	65.4%
same	4818	60.6%	1701	65.5%
long	1061	51.0%	1415	62.7%
longer	113	34.5%	517	51.7%

Percentages were rounded to one decimal.

Finally, we grouped these flights according to whether their altitudes were amended higher or lower. In the case of multiple amendments, we added a third group for those flights that were amended both higher and lower. Figure 31 shows this grouping for flights in the same-similar spatial and track-length comparison category. It shows that cruise altitudes for the efficient flights were amended lower somewhat more often than they were raised (1.2:1). In contrast, for the inefficient flights the cruise altitudes were lowered much more often than they were raised (2.7:1). This is significant because typically aircraft burn more fuel at lower altitudes, which would contribute to a flight being inefficient as we have defined it.

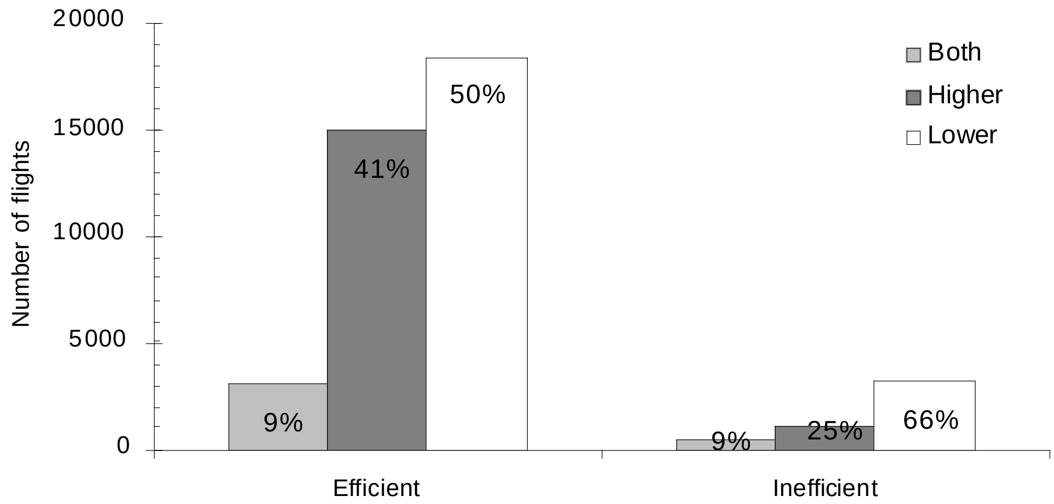


Figure 31: Number of flights with amended cruise altitudes in the same-similar category

3.8. Recommendations for Future Analyses

This analysis developed a useful, quantitative methodology to explore routing inefficiencies within the NAS. In addition it provided a first look at these inefficiencies and found some interesting results. We feel that more needs to be done to expand our understanding of NAS routing inefficiencies, and based on our results, there are several important areas ripe for follow-on analyses. Specifically, we recommend the following should be pursued:

- Repeat/expand this study using data from additional airlines.
- Explore the validity of the jet-stream hypothesis as an explanation for the inefficiency differences observed between eastbound and westbound flights.
- Determine if a better, more appropriate threshold function should be used in these analyses.
- Further investigate the effect of altitude changes on routing inefficiency.
- Obtain winds-aloft data and explore the effects of winds on the inefficiency metric as defined in this paper.
- Investigate the impact of speed changes on inefficiency.
- Explore the role of ground-hold initiatives (e.g., GDPs) on routing inefficiency.

4. Model for a Dynamic Flight Re-planning System

4.1. Flight Planning vs. Flight Re-planning

What's the Problem?

Information about changing conditions for weather, wind, turbulence, etc. is currently available for much of the world for those of us residing on the ground.

Abundant tools and services exist to provide detailed flight plans prior to departure. These tools and services include sophisticated AOC support (for airlines), Flight Service Stations (for all US domestic operators), flight planning services, and personal PC tools.

However, once an aircraft becomes airborne, the planning capability is greatly diminished. Even with sophisticated ground support, the in-flight re-planning problem is fundamentally different from pre-flight planning:

- Since the aircraft has departed, there is no opportunity to change the aircraft initial state by, for example, loading more fuel or fewer passengers.
- Re-planning is usually needed from the aircraft present position or from a nearby fix, not from the departure airport.
- In general, a re-plan is urgent. It is no longer possible to wait for conditions to change and it's too late for a no-go decision. If the destination airport is closed for example, another one must be found *soon*.
- While the original flight plan may have been generated entirely by a ground-based service, a re-plan necessarily involves the flight crew in some way.

What's being done about it?

Assuming a definition of *tactical* as dealing with a time horizon of under 30 minutes, and *strategic* as more than 30 minutes, quick review of a few of current FAA and NASA initiatives shows that much of the Free Flight focus is on tactical tools:

- **Arrival/Departure Management Tools** enhance efficiency of arrivals and departures:
  CTAS - Center-TRACON Automation System and its components:
  TMA (Traffic Management Advisor),
  FAST (Final Approach Spacing Tool)
  EDA (En route Descent Advisor)
  EDP - Expedite Departure Path

- **Airport Surface Management Tools** help solve the ground controller's problem:
  SMA - Surface Movement Advisor
  ASMT - Active Surface Management Tool
  Plus numerous other efforts utilizing ID/position broadcast and squitter technologies to track movement of all vehicles on the airport.

- **Conflict Management Tools** assist in assuring airborne separation.
  CPTP - Conflict Prediction and Trial Planner (CTAS component)
  CDTI - Cockpit Display of Traffic Information
  ICP/URET - Initial Conflict Probe/User Request Evaluation Tool

In the *strategic* arena, the FAA is clearly interested in US traffic flow management, and has sophisticated tools using ETMS (En route Traffic Management System) data to anticipate and control traffic congestion. The System Command Center (SCC) in Herndon, Virginia is devoted to strategic traffic control. However, the operative word is *control.* The Ground Delay Program, instituted following the 1981 air traffic controller's strike to manage traffic flow, is an example of a successful control initiative. While this program has prevented long holding pattern delays, it is unpopular because it conveys bad news (kill the messenger) and extorts airline control. Traditionally the SCC (and ATC in general) has made decisions without regard or knowledge of airline business priorities. Recent significant advances with Collaborative Decision Making and Collaborative Routing programs and tools like the Flight Schedule Monitor have shifted some of this control to the airlines and promoted sharing of information.

The Free Flight paradigm emphasizes freedom from traditional FAA control. At a minimum, this implies strategic *flexible routing* - flexibility to fly routes defined by lat/long points free from published fixes and airways, and *free filing* - the ability to file and re-file as needed (*free-flying* using tactical self-separation may also bear fruit, but is likely a longer term prospect). In support of this new freedom, RTCA working groups are presently discussing, among other topics, User-Preferred Routes and Arrival Time Based Traffic Management. Exploitation of these concepts will require real-time planning tools.

This section proposes a scaleable air/ground flight planning model that facilitates planning for all users, and collaboration required by high-end fleet operators. An overview is provided giving planning tool requirements, followed by a description of the infrastructure required to support such a tool.

A pilot or a dispatcher often must mentally integrate information from a variety of sources to devise a new plan. Current information sources target only one piece of the re-planning puzzle - ATC voice comm, cockpit map and weather displays, for example. Computer and communication technologies now exist to greatly enhance the re-planning process. The key questions are:

1. How can these technologies be integrated to achieve decisions that meet the needs of all stakeholders?
2. Assuming you “can't have it all”, what technologies and infrastructure support will provide the best value?

The approach used to answer these questions is to specify an “ideal” flight planning/re-planning system, given current technology but without regard to cost. From this set of requirements the salient features may be distilled and tested in a simulation environment.

4.2. Overview of Existing Flight Planning/Re-planning Tools

The requirements for flight planning vary significantly across the range of aviation. Whilst all flight plans are usually predicated on a safe and efficient journey, there are many other aspects of the flight plan which are more or less important to the user. With easy access to portable computers and easy telecommunications links to data sources and agencies, there has developed a multitude of software packages and agencies providing a full spectrum of flight planning services. However none of these appear to extend meaningfully to an in-flight re-planning service. For this service it takes the resources of the major AOCs with their specialized computer facilities to achieve a replanned flight plan which is more efficient than the most simplistic re-route. Research projects (e.g. CASSY, DIVERTER etc.) which have delved into the in flight re-planning problem have not yet moved into the real aviation world.

4.2.1. Current Pre-flight Planners

Low end:
The stakeholders here are the pilot, any passengers, and ATC, and the prime goal is simply a safe flight. Low priced software exists for portable computers that can be used by the pilot alone and typically provide:

- A database of the public-use airports in the U.S.
- The ability to enter one's own airport information.
- The ability to enter specifications for one's own aircraft (including performance and weight and balance information).
- A means to quickly describe the flight manifest, and determine the weight and balance for the flight.
- The generation of a flight plan that is ready to file.
- Zulu Time conversion, and sunset and sunrise times.

High end:
Here the stakeholders change to include the cabin staff, AOC. Now the passengers become much more influential, and their comfort and timetables become a higher priority.

The major domestic airlines have developed comprehensive computer applications, databases and networks and procedures, that allow individual flight plans to be developed to optimize the health and efficiency of the whole fleet while respecting the passenger's needs (primarily schedule integrity). This form of flight planning can include aircraft specific aerodynamic, fuel usage and thrust models for greater information about a candidate flight plan. To see this type of operation we visited American Airlines and observed the dispatchers for several hours. We noted:

The dispatchers are responsible for pre-departure planning of flights in their area. American Airlines organizes dispatchers basically by geographical area. For example, the dispatcher at our station managed flights between Miami (an AA hub) and the Northeastern US. His job is to plan fuel, routes, equipment, crew, etc. for flights in this area, release each flight, the provide fight following while airborne. This was described as "running a little airline" - minimal crew and equipment mixing occurred with other "little airlines". While continuous geographical movement of resources throughout the entire system would be optimal, the "little airline" concept simplifies the problem for dispatchers and makes disruptions more manageable and confinable. About 5 flights were in progress during our stay.

The dispatchers sit at stations dominated by two Macintosh systems with large 21-inch screens. Each station deals with up to about 20 aircraft either on a "linear" basis (sequential tail numbers) or area of operation. Positions of aircraft are updated every 5 minutes on the display. A window shows a list of flights the dispatcher is responsible for. This list contains flights in progress as well as future scheduled flights. A flight's status parameters are green if all is going to plan; any other color means that flight needs attention.

A window shows textual details of any given flight, and the dispatcher uses this to see why the disposition line is not green. For example it may be that a future flight has a problem with the cabin crew not being available at the time expected, or maybe a aircraft has become unavailable. The dispatcher now uses his "tribal" knowledge to contact other facilities and resources to resolve the problem. He may try several solutions before he sees one that he thinks not only solves the problem, but does so in a "best" way, considering the whole operation. Any system based on individual's knowledge, initiative, and experience, whilst being effective in one instance, is usually neither scalable nor consistently reproducible elsewhere.

The mainframe computer (software is Flight Operating System - FOS) provides an aircraft trajectory prediction capability that considers many performance characteristics and initial conditions (e.g. takeoff gross weight). Its lateral routing capability is based on established company routes between city pairs with the facility for a dispatcher to make modifications (e.g. add lat/long points) to form a “Dispatcher’s Temporary Route”. This route is sent to the flight deck via ACARS (printer) and is known as a “Miscellaneous 14” after its ACARS annotation. An interesting side effect of this is that there is no facility in the planner to propose great circle legs. In the case where a pilot is given a clearance for a “direct to” the dispatcher has to obtain and add to the planner a couple of lat/long waypoints along the “direct to” route so that the new trajectory can be predicted and tracked.

At this time some third party software application developers (e.g. Koppel, AVOPS, and Jeppesen’s suite of services) are offering medium size airlines this same kind of operation for use on UNIX and NT platforms, typically offering:

- Flight planning
  - ✓ ETOPS and EROPS handling
  - ✓ Cost index based vertical flight path optimizations
  - ✓ Dynamic random routing
  - ✓ Use of ARINC 424 Jeppesen databases
  - ✓ SIDS and STARS
  - ✓ Fuel tankering analysis
- Weather information and NOTAMS
  - ✓ Use of Bracknell weather data.
  - ✓ High resolution, full-color weather graphics
- Flight following
- Integrated crew management
- Weight and balance data
- Passenger reservations systems
- Revenue management
- Inventory and maintenance management

4.2.2. Airborne Re-planning

Surveys [1] have shown that the dominant reason for airborne re-planning is to avoid bad weather.

<u>Low End:</u>
Once airborne data communications are not available and so the pilot relies on PIREPs and ATC (flight watch) for advice. Re-planning of the route involves little more than choosing an alternate, fuel feasible, candidate route from the available charts and confirming its suitability via flight watch. (Sometimes, even in airline operations, the charts are not readily available and so are not consulted, and the pilot just accepts whatever ATC recommends).

<u>High End:</u>
With the aircraft in the air, the ground based planning tools are still available to find a new route, but with certain obvious constraints such as fuel-on-board and aircraft-in-flight. Typical additional restrictions for this form of re-planning are

- The planner is not capable of autonomously creating great circle routes, and so is restricted to established, predefined routes.
- The planner can only act on city pairs, and cannot be initialized at current aircraft position.

If the dispatcher needs to replan he studies a monitor with map display and weather superimposed. He then selects a company route (or a combination of company routes) which takes the aircraft more or less along the new desired route. This route-selection process is illustrated in Figure 32, although today's dispatcher has no graphical display of company routes; he must use his knowledge and experience to mentally superimpose routes on the map screen. As in the pre flight planning, “Dispatcher’s Temporary Flight plans” are available.

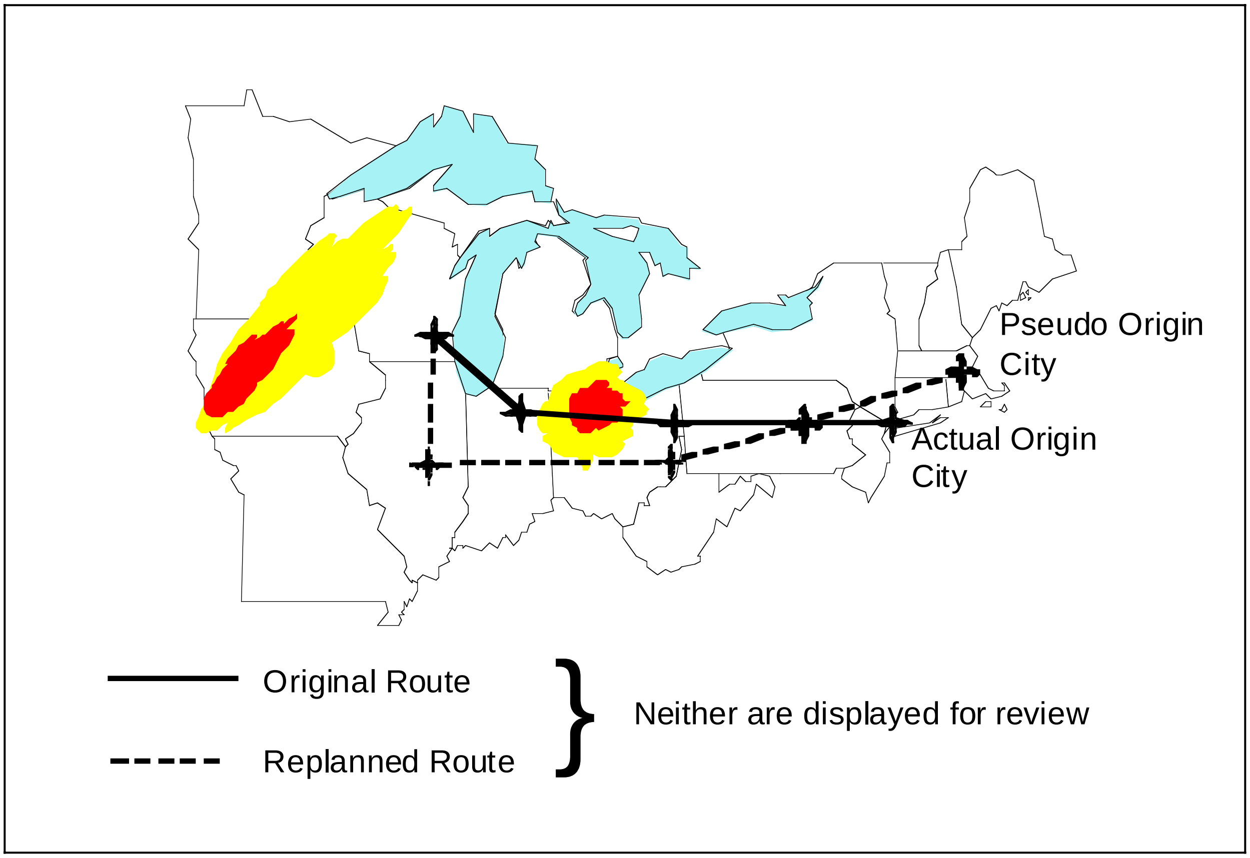


Figure 32. Re-planned Route (dispatcher's *mental* image)

The effect of the second restriction can be mitigated by having the FOS planner use another route between city pairs which is more or less collateral with the candidate route, at least downpath from current aircraft position. Fuel usage is synchronized by having the pilot report actual fuel-on-board at the next reporting waypoint; the FOS planner’s initial fuel is corrected to make its trajectory predictions more accurate.

Speed is used to recover schedule. FOS apparently will automatically sacrifice fuel efficiency in the planning process if a departure is late. Early arrivals also cause problems - gate or personnel availability for example, particularly in hub-and-spoke operations. Integrity of schedule is critical.

Note that for local weather disturbances, a pilot can negotiate with his air traffic controller to find his own way around the problem, and may not even inform the dispatcher.

A personal opinion voiced by the dispatcher was that although pilots seem to want much more information about what is going on and why, when things are really hot, they are grateful just to be told what to do!

This dispatcher was not particularly concerned with ATC communication inefficiencies, as others have indicated. However, he said that when a flight is re-routed (re-filed), and a plan is already filed for that flight, he must manually phone ATC to remove the old route - it isn't automatically replaced. Otherwise ATC keeps both plans active and the two get confused.

Flight Management Systems

Aircraft equipped with a full capability FMS have facilities to make and view on the navigation display provisional routes. This re-planning process usually has the following characteristics:

- The replanned route can be constructed from
  - ✓ waypoints selected from an onboard NDB (Navigation database).
  - ✓ company routes, also stored in the NDB.
  - ✓ lat/long positions entered by the crew.
  - ✓ bearing and distance offsets from existing waypoints.
- The provisional route can be viewed on the navigation display.
- Predictions of aircraft state (speed, time, fuel-on-board, altitude) are displayed on the MCDU.
- All legs are computed (and eventually flown) as great circle segments.

Some FMS have the facility to receive new routes in the air, via ACARS data link. The new route is sent up and loaded by the FMS into a provisional buffer, allowing the pilot to view and confirm the plan. When appropriate, the pilot activates the plan as the active flight plan. So it is possible for a dispatcher to replan on the ground and link the route to the aircraft en route. However, at present, no airline AOC has integrated this facility into its operation.

Weather

The facility also exists for uplink of textual wind and temperature data via ACARS. At pilot initiation, the downwind waypoints are downlinked and ground processing uplinks each waypoint's wind and temperature at a specified altitude. The data is sent to the ACARS printer and the pilot can transcribe them into the FMS provisional route. Again, at present, no airline AOC has integrated this facility into its operation.

Note that the FMS airborne re-planning process does not automatically modify lateral routes to optimize for wind or any other effect (e.g. avoidance of SUA), it will use the wind, temperature, and altitude data to evaluate cost-optimal speeds, and it may also find best altitudes and "step at" altitudes.

4.2.3. Current Technology Summary

In general, the current state of the art for ground-based *pre*-flight planning is quite sophisticated. High-end corporate users and commercial airlines either possess or have access to, tools and services that are capable of providing detailed flight plans from departure to destination. The plans generated may account for weather, wind, terrain, alternate airports, and other planning constraints. Plans often include accurate aero models that estimate arrival times and fuel at multiple fixes.

Current technology may be exploited to improve flight planning/re-planning in two key areas:

1. <u>Connectivity</u>. Availability of relevant data to the cockpit, dispatcher, re-planning service provider is no longer a technical barrier. Timely distribution of weather data or ATC restrictions for example is entirely possible, as is data sharing among the relevant decision-makers. What are the attributes of this data and what equipment is needed to move and display it?

2. Collaboration. Given wide availability of current data, what procedures will provide a robust re-planning capability?

4.3. Requirements for an "Ideal" Flight Re-planning System

Previous work (Rogers, 1998) included interviews with assorted dispatchers, pilots, and ATC personnel. The study highlighted awkward and inefficient re-planning processes due to compartmentalization, non-sharing of information, and conflicting goals among the primary stakeholders - aircraft, AOCs, and ATC. Solving this problem with a re-planning "tool" is challenged by the wide variety of wants and needs from the aviation community. Availing all information to all parties is unnecessarily confounding at best, and dangerous at worst. All agree that both the air and ground re-planning operations could benefit from technology advances, but opinions differ on the extent and cost benefits of new equipment.

Figure 33 shows the three principle agents in the flight planning/re-planning process with a generalized view of their goals and information flow. The AOC component is shown with a dashed line because it isn't always present. Worldwide, aircraft operations actually show a continuum in the level of AOC involvement. At one extreme, a highly developed AOC is sufficiently informed and connected to make nearly all strategic decisions and communicate them to the aircraft. At the other, AOC does not exist and re-planning decisions are made entirely in the cockpit, often only using information from ATC. In the middle, strong AOC *pre*-planning support leaves crews to fend for themselves once airborne. Weak support from home is often an inevitable consequence of flying to remote destinations in foreign airspace. A comprehensive re-planning model is needed which covers the full range of needs.

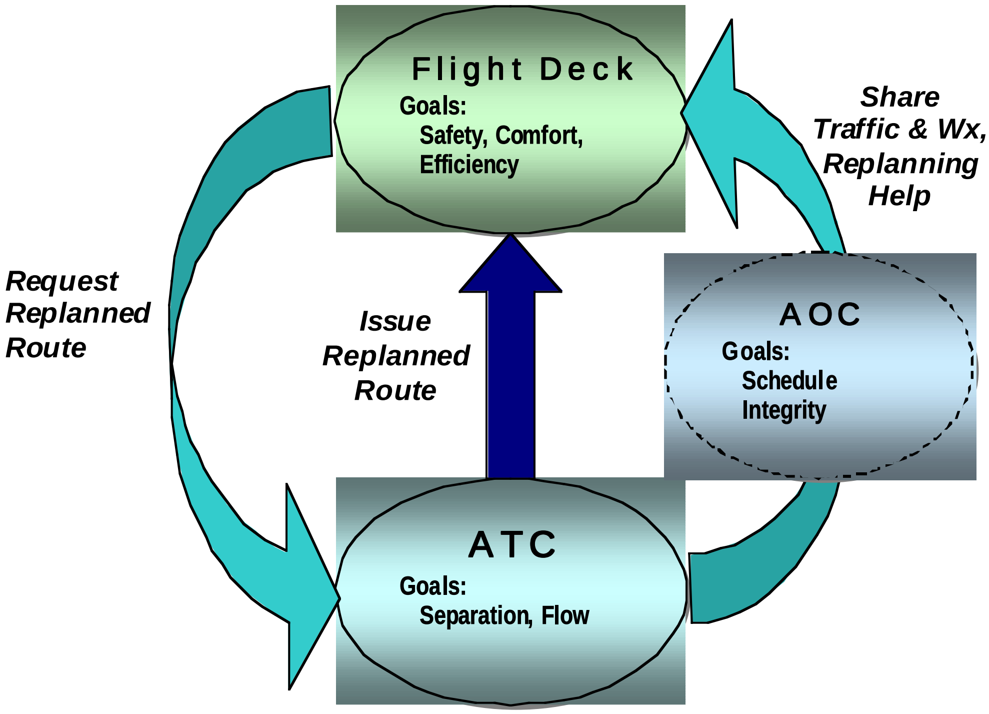


Figure 33. Goals, Roles, and Information Flow

The following examples illustrate the range of this continuum:

- A corporate jet with no ground decision-making support. Numerous data provider services enable informed choices, but the flight crew makes those choices. In general, the goal is to reach the destination quickly. Fuel efficiency is a low priority. Post-flight scheduling of crews and equipment is not a consideration.
- A regional airline serving one primary airport employs a minimum dispatch and flight following operation as required by FAR part 121. Once released, flight crews are generally on their own to complete their mission safely. The impact of late or diverted flights is geographically contained and recoverable in one day. Re-planning is performed as needed by the crew en route.
- An airline serving international travelers provides one outbound and one returning flight per day to several distant cities. Profitability is sensitive to fuel management, which balances efficiency (carry and burn the least) with range (avoid refuel stops). Wind-optimum routes are essential. Late or early arrivals have little downstream impact. The US information network is generally not present. While dispatcher involvement with re-planning is highly desirable, the crew is more directly responsible for strategic decisions.
- An airline operates a hub-and-spoke route structure to move payload around a wide geographic area. All payload moves from its departure point (spoke), through the hub, then on to its destination (spoke). In theory, this model maximizes load factors by breaking the payload movement problem into smaller parts. Compared to a direct departure-to-destination route structure, fewer airplanes, smaller airplanes, and fewer flights are required to move payload if many geographically dispersed cities are served. However, the high number of connections makes this model extremely sensitive to schedule disruptions. Late, canceled, or diverted flights create effects that may take days to recover. AOC involvement with strategic re-planning is essential to maintain schedule.

4.3.1. Basic Requirements and Overview

The following assumptions are made about a useful Planner:

1. It allows conventional flight routing in today's domestic US environment. This implies full support of waypoints, airways, SIDS, STARS, flight levels and other published routing structures. A planner that depended on the promises of free flight would be a flop. This basic requirement insures the planner is useful regardless of which Free Flight initiatives actually materialize.

2. It supports planning that *doesn't* require adherence to conventional published routing structures (flexible routing). Flexible routing is defined here as the freedom to fly a route defined by user-specified lat/long waypoints.

3. It permits mixing of conventional structured routing and flexible routing. This allows, for example, strict 3D compliance with assigned or published routing for some portions of a flight, but flexible routing for the remainder. It assumes flexible routing will be phased in with structured routing, but some structured routing will always exist.

4. A flight plan must be definable by a string of lat/long/alt waypoints, with optional time (4D). This allows interfacing with existing navigators, and supports sharing of intent information for ADS-B or Air Traffic Management Partnership (ref Lockheed) models.

5. Its function is strategic, meaning it deals not only with the present but with multiple time horizons in the future, using predicted conditions.

6. Its user interface is graphical, with a map display, keyboard entry, and cursor control.

This discussion considers re-planning problems both with and without AOC support. The Planner described here is only intended to aid in an individual aircraft's *route* re-planning, not the much larger dispatcher's problem. Within an AOC, the influence of business and regulatory control on the re-planning process is extensive and well documented (see "AOC Overview", ADF and Seagull, 1995).

The following component definitions will be used throughout this discussion:

Flight Planner - A tool that aids the user in assessing and implementing flight plan scenarios. A pilot or dispatcher may use it to either make an initial plan to re-plan a flight in progress. It has knowledge of all factors and constraints that are normally known or knowable to devise the "best" plan, and may compute suggested plans. It can illustrate the plan, store it, and communicate it to other equipment for implementation. It does not control the aircraft. The flight planning function of a modern FMS contains a small subset of these capabilities - basically an FMS user is permitted to enter a plan if one is already known. This document describes the Flight Planner (Planner).

Navigator - An airborne utility that executes the flight plan. By this definition, a "Navigator" is an abstraction of the FMS Navigation and Guidance functions coupled with an Autopilot.

Aircraft Model - A tool that uses aircraft-specific aerodynamic data, engine performance data, and state data to model an aircraft's behavior. Both the Flight Planner and the Navigator require an Aircraft Model. The Flight Planner needs the aircraft model to estimate flight times, fuel used, speeds, etc. The Navigator needs the Aircraft Model to implement the flight plan, manage energy, and manage control surfaces (autopilot). Ideally, all components requiring the Aircraft Model have access to the same model and state information.

Figures 34 through 36 illustrate the basic components of the flight re-planning system in three different instances.

Figure 34 assumes cockpit autonomy for the re-planning task. In this instance the Planner is an airborne tool to gather and display relevant data, and assist in planning an optimum route given a potentially large set of constraints. It features an interface to the Navigator, to receive aircraft position and state data, and to send plans to be flown.

Figure 35 depicts a model where a dispatcher has primary re-planning authority, and

Figure 36 shows how the crew and dispatchers may collaborate with distributed authority.

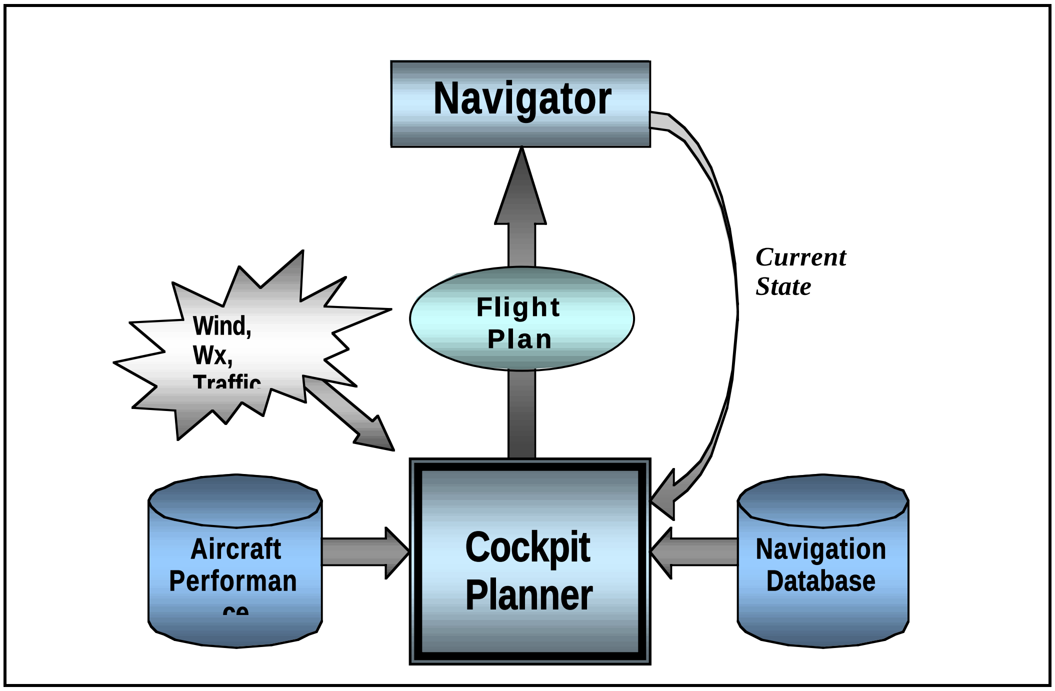


Figure 34. Cockpit Planner Context

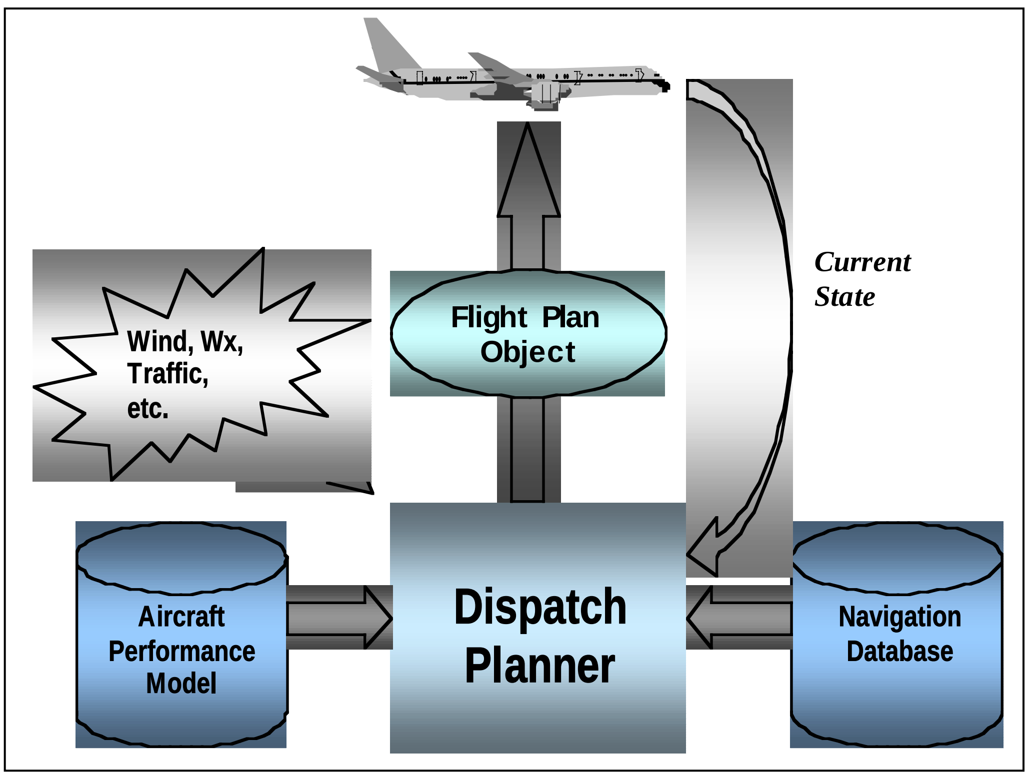


Figure 35. Dispatch Planner Context

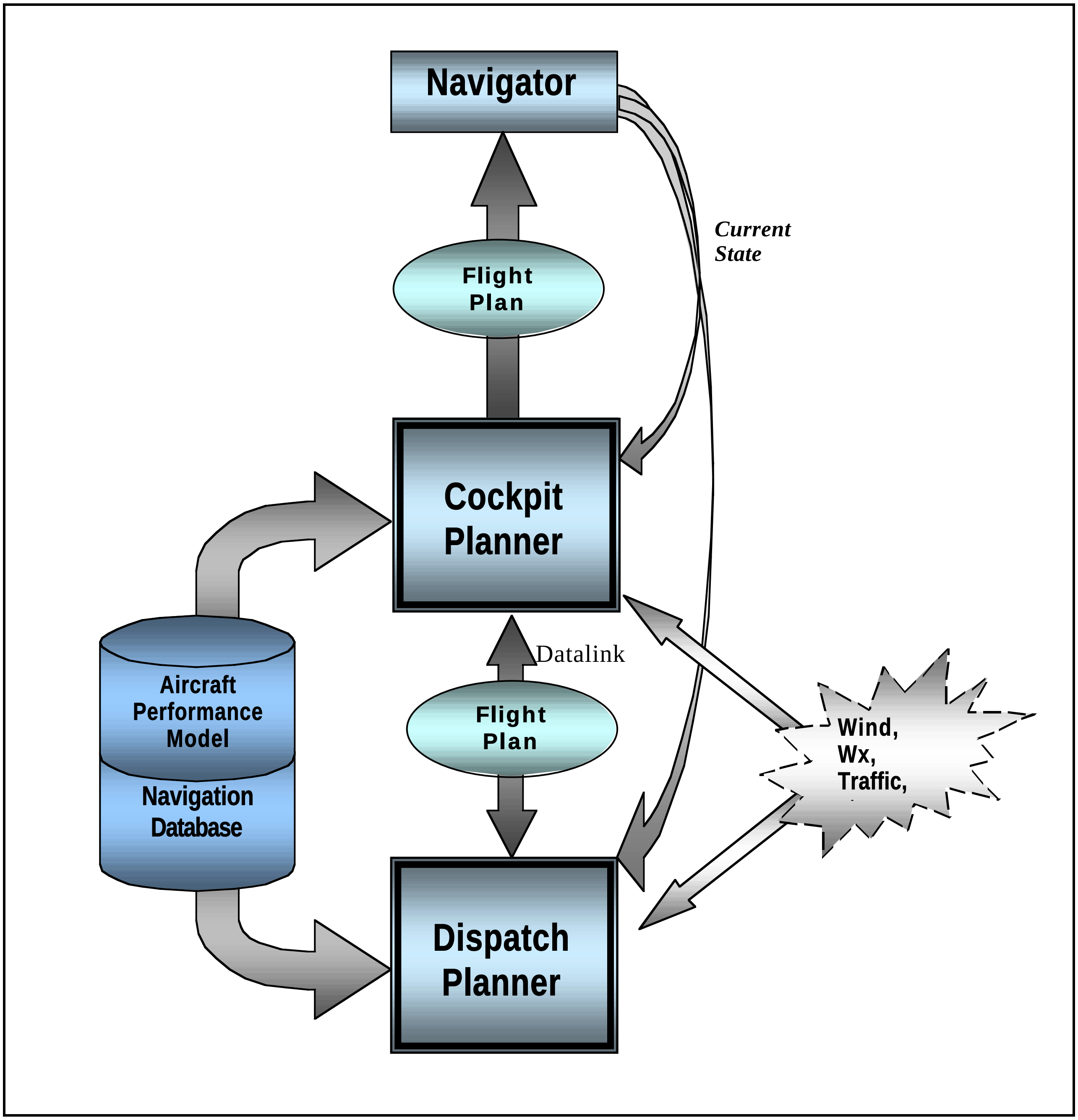


Figure 36. Shared Planner Context

4.3.2. Operational Scenarios

The model for a Planner proposed here is best illustrated through scenarios. These scenarios examine the use of a Planner either in the aircraft, on the ground, or both. A Planner may also exist on the ground in support of one or more airborne Navigators. The Planner, wherever it resides, is connected to the world for periodic receipt of real time data. It communicates with one Navigator if we're assuming a Planner in an aircraft, and with many Navigators if it is on the ground.

In order to be useful in the real world and meet the basic requirements given above, the scenarios assume the existence of flight plan route templates. The templates may be simple departure/destination pairs, or complete routes using published waypoints, airways, and procedures, or anything in-between. The templates represent constraints, or plan data that is not alterable by any automated optimization function of the Planner, and may be stored in either the Planner or the Navigator. Within the constraints, the planner is free to build a good plan. For example, a template for a PHX-JFK route may simply consist of departure airport PHX, St Johns Two SID, JFK. ATC-assigned compulsory altitude blocks and route segments determined at release time are added as needed. This concept is similar to "canned" company routes supported today with an FMS. Company routes - detailed templates - are useful when routes are inflexible and frequently used.

Planner in an Aircraft - No AOC Support (Figure 34)

1) Prior to departure, the pilot uses the Planner to retrieve canned or previously entered flight plan, including SID, STAR, and route with published airways/waypoints. The Planner graphic display shows the full route with selected current and predicted weather/SUA/wind/turbulence (or whatever). Also shows Planner-calculated state data at progress points, ETA, ETE, fuel remaining, etc. Pilot reviews the conditions on Planner display. Since the route shows no problems, the Planner's function is primarily for situational awareness. If desired, the pilot can use the Planner to modify the route. For example, the Planner may be requested to produce a wind-optimized route between two waypoints at a specified altitude or block of altitudes. The waypoints might define the ends of the en route portion of flight - after the SID and before the STAR, during which flexible routing may be permitted. Effectively, the Planner fills an intentional flight plan discontinuity with the best route. When satisfied, the pilot transmits the plan to ATC. Upon ATC approval, he 'activates' the plan, sending it to the Navigator.
2) While en route, the Planner receives new weather prediction data. The pilot is automatically alerted to a conflict with surprise weather on the planned route (predicted for the time the aircraft traverses the area). The pilot enters or selects a waypoint that he believes will take him on a route that avoids the weather, and re-optimizes. Basically he has entered the new waypoint as a template item. As with the original plan, the new plan is coordinated with ATC, the activated. The same steps are followed when a re-plan is needed for any reason.
3) 2 hours from destination, the Planner receives information regarding new ATC delays at the arrival airport and annunciates the problem. At this point, the pilot uses the planner to review the fuel and time situation to determine if an alternate is needed.

Planner at an AOC - no Planners in Aircraft (Figure 35)

1. As part of periodic daily planning, the dispatcher reviews the flight plans for flights due to depart in about 4 hours. The plans have been generated automatically given the best current and predicted information available. Each flight is reviewed independently by the dispatcher on a graphic map display. Since these plans are fresh, no changes are required - this is a preliminary check.   Equipment assignments have already been made, but may be changed. The Planner associates the correct aero model with the equipment.
2. Each flight plan is re-checked no earlier than 1 hour prior to final release. The dispatcher makes flight plan and fuel adjustments as needed, then posts the plan for automatic uplink either on pilot request or a fixed time prior to departure.
3. Upon reaching top-of-climb, each flight reports position, weight, and fuel. At the dispatcher's desk, the flight plan is recomputed to refine the destination ETA. Unless a serious mismatch occurs from the original flight plan now loaded in the aircraft, no plan changes are uplinked.

4. The Planner continuously monitors multiple flights for conflicts as each flight progresses and new dynamic data is received (weather, turbulence, ATC restrictions, etc.). The dispatcher is automatically alerted when any re-planning is required. The dispatcher may review progress and the planned route for any aircraft.
5. The planner alerts the dispatcher to new turbulence expected along the route of a flight in progress. The dispatcher reviews the current plan along with a graphic depiction of the turbulence, and devises a clean route. The new route is uplinked and marked as pending until accepted by the crew. The crew then makes the ATC re-route request. Following ATC approval the crew relays acceptance to dispatcher and the route now becomes the new plan.

Planner in both Aircraft and AOC (Figure 36)

This scenario is a superset of the previous two, assuming Planners in the aircraft and in it's supporting AOC. Regardless of an aircraft's dependence on an AOC or company decision-making policies, the crew has the ultimate responsibility for the flight, and occasions will always arise where planning must occur only in the air.

The crew reports directly to the aircraft and downloads the dispatch-planned company route to a European city. The crew reviews the route on the display, loads it into the Navigator, and the flight departs after a 30-minute ATC delay.

1. At top-of-climb, the airborne Planner automatically downlinks position, fuel, and new ETA information to the AOC Planner. The dispatcher is alerted that the new ETA is outside this airline's acceptable on-time limit. The dispatcher recomputes a new plan using a higher en route speed, and uplinks the plan for crew review. The crew accepts the new plan, and following ATC approval, loads it into the Navigator. This action causes the airborne Planner to automatically relay acceptance to the ground planner.
2. Over the Atlantic, new weather data shows newly predicted convection tops 30 minutes ahead at the aircraft altitude. Both the ground and airborne planners annunciate the new conflict, and dispatch uplinks a plan to avoid it. The crew however, viewing the developing weather out the window and on weather radar, decides that it will not be a factor at the current altitude and elects to remain on the original plan.
3. In European airspace, large unplanned re-routes are required for late-breaking ATC flow restrictions and avoidance of weather in areas with poor weather monitoring. Since the AOC has little re-routing control, the crew reverts to a planning mode that avoids the AOC approval cycle, entering ATC re-routes as required.

4.3.3. Requirements

Planning Support Functions

Formal requirements specifications often use the word “shall” to define each detailed requirement. To avoid this tedium, high-level requirements are specified here in bold italics as the rest of the sentence: “The Planner shall…”

support routes defined by existing published data.
Comment:

> This is to meet basic requirement 1. Regardless of advances made toward Free Flight, some route structure will always be needed and the planner must support it.

compute optimized route segments defined by user-entered start waypoints, end waypoints, and altitude blocks for each optimized segment.
Comment:

Use of optimized routing is assumed to be restricted to certain route segments. The user must be able to bound the flexible routing area.

compute optimized sections based on relevant <u>predicted</u> conditions.

Comment:

Dynamic data products have a time attribute that must be considered during planning. One way to simplify this complexity is to break the route of flight into route-tailored "time zones". Each zone contains information along the route of flight, predicted for the time at which the aircraft will be in that zone. This concept is illustrated in Figures x-6 and x-7. The illustration may form the basis of a planner display, but more importantly shows how the data set used for route optimization may be constructed. This data set must include the constraints that normally go into route planning. While the planner display may look similar, displaying all constraint and optimization information at once is impractical.

Construction of a data set for strategically planning or re-planning a route could be performed as follows:

1. As a first approximation of the geographical area of interest for the route of flight, draw a great circle route between departure and destination.
2. Locate the points along this route that represent where the aircraft is expected to be at cardinal hours after departure. This is illustrated as 1500Z, 1600z, etc., and is assumed for this purpose to represent hourly weather forecasts.
3. Construct a set of lat/long bounding boxes centered on the hourly route points. The boxes should cover an area wide enough to contain the worst-case deviation from the great-circle route after optimization. Figure 37shows an approximation of this process.
4. Collect predicted wind, weather, and constraint data for each box for the appropriate time frame as shown in Figure 38. This data set should be used for planning the strategic route. A weather system shows up first over Oklahoma, but is a factor further east in subsequent hours as it grows and moves. Figure 38 also illustrates SUA in southern New Mexico and turbulence in the Great Lakes area.

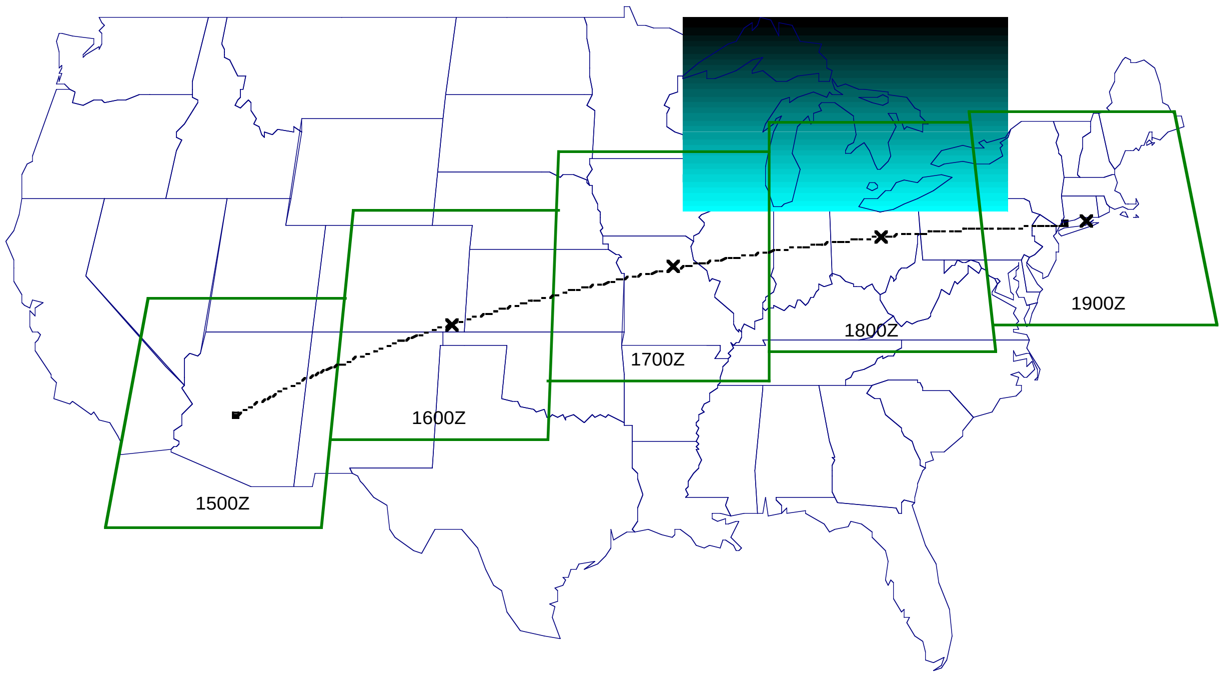


Figure 37. Determine The Area and Time of Interest

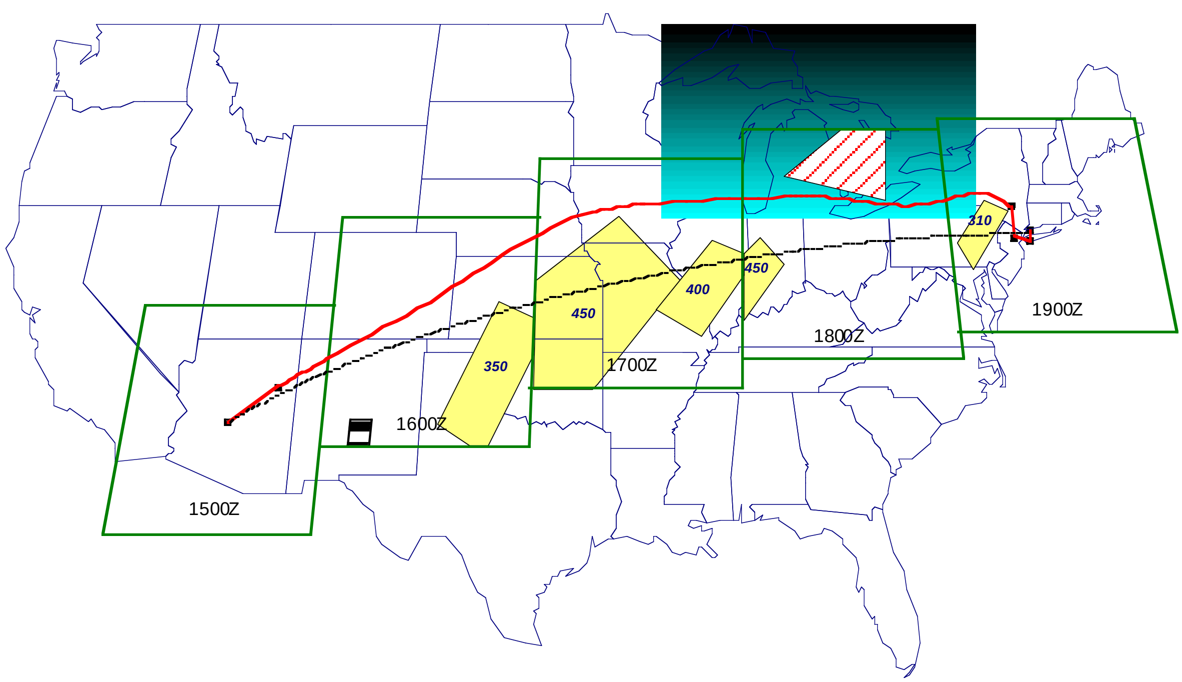


Figure 38. Add Predicted Weather and other Constraints, Compute Route

compute optimized sections based on all known constraints.

Comment:

In addition to meteorological conditions, other constraints which are a normal part of planning should be considered, such as:

- Terrain
- Special Use Airspace
- Overflight fees
- ATC flow restrictions

For route calculations, weather conditions and all of the items listed above may be considered "constraints" with different weighting. Each constraint category/severity can be assigned a weight which may change depending on user preference or optimization goal. For example, terrain and severe convection must always be avoided, but overflight fees or light turbulence may not be significant if optimizing for time. Turbulence may be weighted high (avoid it) for passenger operations but lower for cargo operations.

optimize for one of the following user-selected goals (reference Bob Simpson):

Fuel - Least Fuel Plan

Time - Least Time Plan

Cost - Least Cost Plan

Comment:

In general, Cargo and Corporate flights are most concerned with time, while passenger airlines must manage fuel and tradeoffs between fuel and time (cost) to meet schedule. Regardless, the concept of Free Flight is that the users manage flights to meet their own goals.

annunciate constraint changes affecting the route.

Comment:

This requires monitoring meteorological updates, as well as monitoring the destination airport for restrictions, closure, braking action reports, IFR vs. VFR, and NOTAMS. Events that may affect the current plan should be annunciated. In Figure 39 new data indicates a predicted turbulence area near the Great Lakes has moved south since the last optimization.

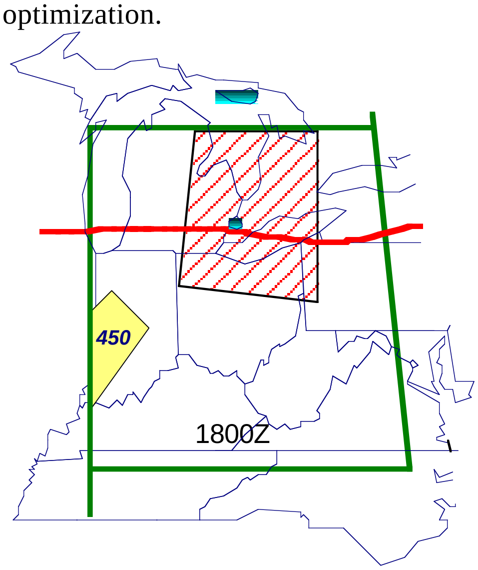


Figure 39. Change in Turbulence Prediction Alerts to Re-Planning

display the following for user-selected future points en route:

Estimated Time of Arrival
Distance from Present Position
Time from Present Position
Fuel Remaining at Selected Point

display the following for the destination:

Estimated Time of Arrival
Scheduled Time of Arrival
Estimated Time En route
Fuel Remaining

display the following for the present position:

Fuel Remaining
Distance Remaining
Time Remaining

display the route of flight and significant constraints.

Comment:

The purpose of this (high-level) requirement is that the plan be displayed *graphically* for easy review. Displaying all of the 4D constraints for a plan may be difficult since the number and type of constraints is potentially large. Perhaps different display products can be displayed on request - don't show SUA for example, unless requested. Design of a display that is flexible and usable requires detailed application of Human Machine Interface (HMI) rules and is not the subject of this paper.

Communicate the flight plan to other equipment, including:

- load the flight plan TO the Navigator on user request.
- load the Flight Plan FROM the Navigator on user request (possibly).
- downlink the Flight Plan to another ground-based Planner.
- load the Flight Plan FROM another ground-based Planner.
- downlink the Flight Plan to ATC.

Comment:

Establishment of a standard flight plan format is critical.

Support storage and manipulation of at least one "provisional" flight plan.

Comment:

This requirement is needed to support trial planning and review of a new plan while the other is active.

User Interface

The following are minimum requirements on the Planner user interface. The basic Planner consists of a map display showing the flight plan, and a method of user input-keyboard, mouse, touch screen, or other.

- All display products hide-able
- Enter departure and destination
- Select aircraft type or tail number (if not in aircraft)
- Select canned flight plan template
- Enter additional constraints to template
- Allow two stored routes, current and alternate
- Allow mods to stored routes, save when ready
- modify alternate route by rubber banding
- enter cruise alt, block alt, alt constraints

- select segments for optimization

Database Requirements

Static data is locally contained in a database and used for display and calculations.

- Airspace maps including current ARINC 424 NDB content
- Significant terrain
- SUA static info
- Overflight fees
- Other data as needed

Display of Dynamic Data for Selected Geographical Area

The following data should be displayable in some form to allow sufficient planning and explain route optimization strategies. Since most information has 4 dimensions (location/alt/time), designing an effective user interface will be challenging.

Graphical Data

- wind vectors at selected altitudes (time stamped)
- convective weather by severity
- air traffic density
- ATC flow restrictions
- Temperature
- Icing
- Turbulence
- SUA

Textual Data

- RVR and runway condition for destination and alternates
- Airport configuration
- braking action reports
- crew log information
- aircraft equipment constraint information (MELs, CDLs)

4.3.4. Interface Definition for Dynamic Data

Even if the “Ideal” flight planner was built today, the required dynamic data (weather and other changing constraints) isn't globally available. An environment where one or more service providers periodically broadcasts all data for the entire planet is obviously impractical. For weather, services in place or in development today mainly broadcast a single weather attribute - satellite view or weather radar - for a geographical 'footprint'. While quite useful, the data represent current conditions. For strategic planning it is more reasonable to envision a two-way request/response model where planners establish a connection with a single service provider and obtain the requested 4D data. For example, an LA to NY flight needs NY weather now and LA weather four hours from now, whereas NY to LA flight leaving now needs the opposite. Regardless of how smart the planner is, this requires a sophisticated capability on the part of the service provider.

Referring again to Figure 38, an airborne planner may request all relevant data defined by the respective times and spaces given in the illustrated boundary boxes. A ground-based service provider will act as a collection point for worldwide (or wide area) data and respond with a tailored data package of manageable size. Shortly prior to arrival, the requested data may take a more detailed form appropriate for the arrival area.

A dispatcher's planner would use the service provider in exactly the same manner, except the geographical area would be larger.

A standard communication format and protocol is essential. Due to the diverse attributes and ownership of the data, multiple service providers may be required, and should be considered in the comm model. A small set of request/response types may be defined to service different needs and phases of flight.

General content of request:

Requestor's ID (unique address)
Request Type (see below)
Request ID (to associate response with request, possibly just a number)
Request Area/Time (varies with request type)

General content of response:

Requestor's ID
Request ID (to associate response with request)
Requested Data

For the purpose of flight planning, the following response message types are proposed:

En route Weather
Terminal Weather
Airport Data
ATC Data

En route Weather Message
To simplify protocol and ground processing for meteorological information, a grid with numbered sections may be used to identify any area of entire earth. The grid may have multiple levels, allowing large areas to be quickly identified. A requestor would indicate which areas/altitudes/times were needed. The service provider would continuously maintain a database of grid information using all available sources of data. Upon receiving a request, data could be quickly extracted and packaged for response. Convective weather and turbulence information shown in Figure 38 for example, could be communicated in “pixels” with a TBD size. For route planning purposes, the pixels needn't be so small as to render a crystal-clear display; granularity should simply reflect the precision of the prediction. Various grid overlays currently exist for communicating weather for various geographical areas, but a single worldwide standard would be necessary for worldwide application.

Terminal Weather Message
To be useful during arrival, terminal area weather should be current and detailed. Geographic boundaries may be pre-determined as given by a terminal area identifier. This function is more tactical than strategic.

Airport Data Message
Airport data is the equivalent of today's ATIS data - active runway, wind, NOTAMS, etc. While most of the data is tactical in nature and most useful just prior to arrival, some information, such as braking action and RVR, may be used by the planner in monitoring for conditions affecting the plan. The crew could be alerted, for example, that their non-functional reverse-thrust system prohibited landing due to reports of poor braking.

ATC Data Message
ATC Data consists of arrival restrictions, flow management programs, Special Use Airspace (SUA) advisories, NOTAMS, and other information which generally has a time and location. However, much of this data is difficult to automate and standardize for use in a planner. Flow management programs for example, are often ad-hoc and frequently changed. Further, the diversity and fragmentation of worldwide ATC systems precludes any model that is highly dependent on strong ATC participation.

One way to manage this problem is to use the model proposed for weather data, where a single service provider maintains a database of consolidated ATC data. Participating ATC organizations could periodically report a summary of current or expected arrival management (or other) programs in a standard format including details about time, area, and type of program. A request for ATC data would contain the same geographical/time definition as a weather request. Relevant data would be filtered out on the ground and sent up to the requestor.

4.3.5. Ground Support - Data Collection and Dissemination

Despite a single Planner's capabilities, any plan is only as good as the data that goes into it. The wide range of data sources and types suggests a data flow model where a single flight planning advisory service provider with a broad network of information sources maintains a 4D worldwide database of airspace state data. Such a model is illustrated in Figure 40. This “super service provider” is the aviation analogy to worldwide news organizations such as CNN or Reuters. As communication paths develop linking airports, ATC service providers, weather service providers, and other sources of aviation data, this model becomes a more practical solution than requiring each flight crew and dispatch operation to maintain multiple redundant communication channels.

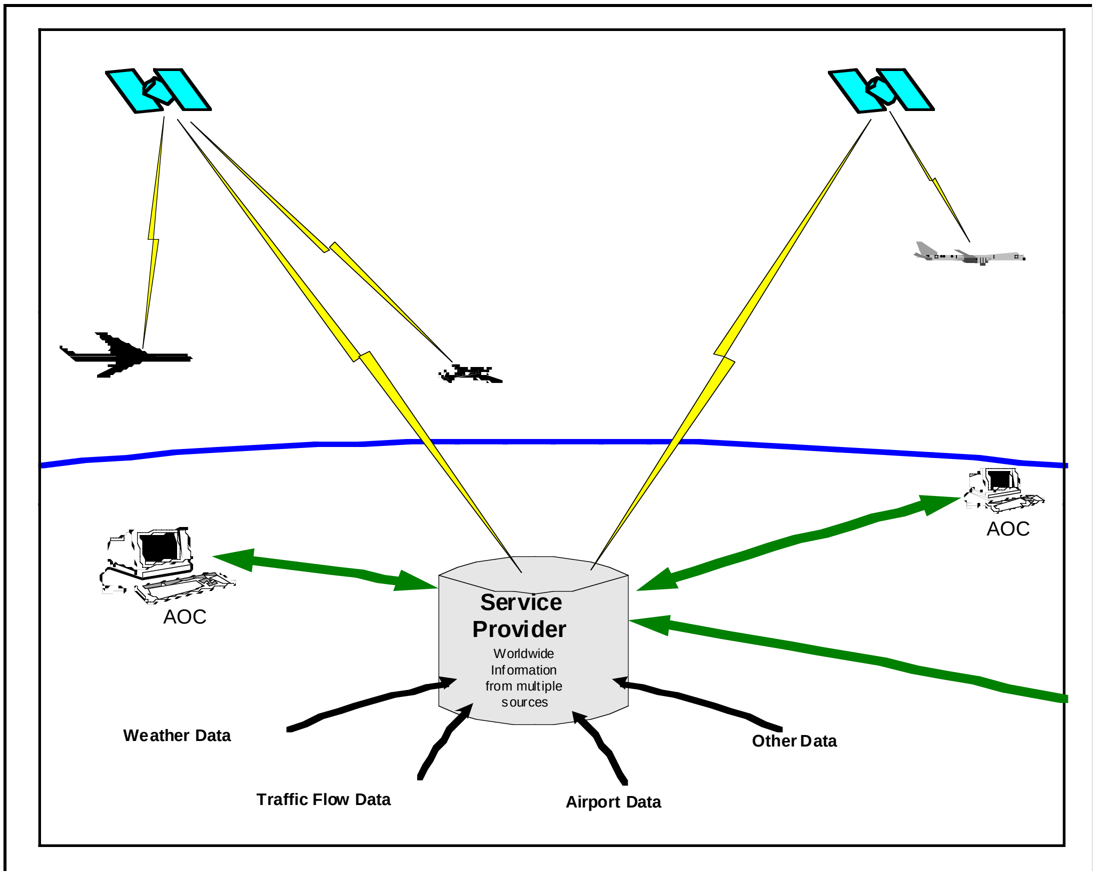


Figure 40. Central Service Provider

4.3.6. What To Do First?

The ambitious Planning model described needs to be tested for economic merit. The technology to build it is here today, but is expensive. The process of building the services to support it requires time for tuning and trust-building. What are the benefits in order of payback?

1 - Provide situational awareness. For both the cockpit and the ground, graphical display of current and predicted weather, ATC flow constraints, etc., is the obvious first choice. If the Planner did nothing else, improving situational awareness for the area of interest would provide immediate benefits. Current efforts giving over-the-horizon weather displays are an excellent first step. In fact, this area is receiving much attention from avionics vendors, since equipment can be built which use public meteorological broadcasts and installed with minimal aircraft system impact. Services providing other relevant data (turbulence, SUA, traffic density), and *predictive* data will add tremendous value.

2 - Automate the planning process. With knowledge of the aircraft model and operator goals, functions may be provided which and optimize the planning/re-planning job. Inclusion of the automated flight planning functions described in this write-up is the next logical step.

3 - Share Flight Plans and Intent - Collaboration, and management of fleets and airspace as a system, requires sharing of flight plans. A standard definition of a 4D flight plan object would facilitate the implementation of the collaborative flight planning suggested by Figure x-4. ATC coordination could also greatly benefit from the use of a standard flight plan object. Establishment of standards for flight plan objects, procedures for their use, and equipment to support them is a very difficult step. The current representation of flight plans on paper clearances, controller strips, and voice communication has been standardized for the same reasons - the need to communicate the plans. However, flight plans based on airways, fixes, and discrete altitudes are much simpler to represent than flexible 4D plans.

4.3.7. Certification Considerations

The basic model for the Planner described here includes significant overlap with the FMS and NAV Display in a modern glass aircraft. These components have been tested and certified at great expense to insure reliability and safety of flight. Realistically, the actual design of a Planner to meet requirements described here must separate the critical, essential, and non-essential functionality to be cost effective. Care must be taken to avoid involving the Planner in flight-critical functions by relying on pilot-confirmation of all Planner decisions and by backup by trusted legacy equipment. For example, if the Planner loads a plan into an FMS and the FMS warns of inadequate fuel or unable to make an altitude, the FMS warning needs to be considered by the pilot.

4.3.8. Simulator Assumptions

The same planner software will be used for an airborne planner process or a ground planner process. Each planner process will use a configuration file to define its particular instance (ground or air, ID, connection rights, etc). The objective is to build one software object, and to be able to turn planner capability on and off.

Navigators periodically transmit their ID, position, and if needed, request for a flight plan (when they don't have one, as possibly on powerup).

Planners will be connection oriented. One connection will occur at a time, either to a Navigator or another planner. An airborne planner will be configured to connect with only its ownship Navigator or its ground planner. A ground planner will be configured to connect with all fleet airborne planners.

> *The 'connection rights' concept may be needed in the real world but be overkill in the simulator. Perhaps FASTWIN and two planners will be the only players in any collaboration experiments we want to run. The connection security could be deferred to comm software to be added later.*

5. Conclusions

This report has taken an eclectic approach to addressing the issues associated with inefficiencies in airborne replanning. A survey of airline dispatchers has indicated that the replanning event is somewhat rare less than 20% of flights (although there is a wide range for the responses received, so there is less than unanimous agreement on this point), and that replanning previously replanned flights is even rarer, less than 15% of flights (with even more disagreement on this point). While perhaps not the most pressing need for automation upgrade among the tasks they're requested to perform, we learned that dispatcher's are anxious for better tools to support the replanning activity. Specifically, dispatchers are anxious to have replanning tools that take into account the situation as it currently exists, with regards to traffic constraints, weather constraints, and actual aircraft state (both fuel and weight). In addition, the dispatcher's expressed an interest for an integration of this information on a single workstation so that they we serving in the role of information integrator.

The data-driven examination of the issues associated with replanning, the work reported by Klopfenstein and his associates at Metron, provides a glimpse of the outcome of replanned flights with the recently developed Post Operations Evaluation Tool (POET). The finding that the direction of traffic is a predictor of delay, Eastbound traffic suffers more delay than Westbound traffic might be somewhat predictable if one assumes that flying into airspace along the eastern seaboard of the United States is some of the most congested in the world. What is not so intuitive is the finding that rerouting is not a strong predictor of delay or greater than predicted fuel burn. Additional analyses should be performed on this finding as quickly as possible to uncover the nature of greater than predicted fuel burn, specifically "if it isn't happening among aircraft being rerouted, where is excessive fuel burn happening?"

Finally, the functions associated with the "Ultimate Flight Planner" are dissected and addressed. The unique aspect of this planner is that the functions are addressed independent of the party performing the replanning activity (dispatcher vs. the flight crew). This yields an independent assessment of "how-to" implement these functions in the most effective manner.

Honeywell is prepared, based upon the research reported in Rogers et. al. (1998), the present effort, and as part of the work currently being conducted integrating an airborne Conflict Probe into NASA's FASTWIN aircraft simulation (RTO#5b), to combine the functions of strategic route planning with that of a nominal, Free Flight, airborne Conflict Probe. Honeywell has been developing a route planning software capability and we are prepared to work with NASA to add this functionality to the Conflict Probe in order to provide the self-separation assurance function in a manner that is consistent with the airlines' ultimate goal of cost-effective routing.

6. References

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