

TRACON Controller Weather Information Needs: II. Cognitive Work Analysis

Ulf Ahlstrom, Ph.D., ATO-P

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16. Abstract The main purpose of the present study is to assess the Terminal Radar Approach Control (TRACON) weather information needs. An additional objective is to assess the flow of weather information within the TRACON environment and the impact on controller and pilot operations during adverse weather conditions. The study used the framework of Cognitive Work Analysis where we included both environmental (terminal domain) and operational (controller - pilot) constraints in the analysis (Vicente, 1999). The Mission Need Statement for Aviation Weather (FAA, 2002) served as the foundation for the weather-needs analysis. The Human Factors Group assembled a group with five TRACON controllers and six airline pilots for the collection of weather impact data. During the group sessions, they discussed weather phenomena and the impact on controller and pilot operations. The Human Factors specialist encouraged group members to discuss specific real-life encounters and assessed the topics from both the controller's and the pilot's perspective. They also provided numeric (ordinal) ratings of impact from weather phenomena when appropriate. All ratings were consensus ratings (group ratings) that followed a detailed and complete discussion of each topic. For controller operations, the group provided the highest impact ratings for thunderstorms, snow and ice, and airport reconfiguration due to changing winds. For pilot operations, The group provided the highest impact ratings for thunderstorms, wind shear, microbursts, snow and ice, and mountain wave. The present analysis reveals several information needs for the TRACON controller. Specifically, there is a lack of a graphical display of weather areas with short-time forecast capabilities at the controller workstation. For non-convective turbulence and adverse winds, there is a shortfall in the accuracy of available tools.					
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Table of Contents

	Page
Executive Summary	v
1. INTRODUCTION	1
1.1 Cognitive Work Analysis.....	1
1.2 Adverse Weather Phenomena	3
1.3 Approach.....	5
1.4 Purpose.....	5
2. METHOD	5
2.1 The Weather Working Group	6
2.2 Development of Categories for Adverse Weather Phenomena	6
2.3 Procedure	6
2.4 Analysis.....	7
3. RESULTS	7
3.1 Pilot Operations	7
3.1.1 The Relative Impact of Adverse Weather Phenomena on Different Aircraft Types. 7	
3.1.2 The Impact of Adverse Weather Phenomena on Pilot Operations	9
3.1.3 Weather Phenomena and Aircraft Type As Determinants of Pilots' Go/No-Go Flight Decisions	9
3.2 Controller Operations.....	11
3.2.1 The Impact of Adverse Weather Phenomena on Controller Operations	11
3.2.2 Control Task Analysis.....	12
3.2.3 Strategies Analysis.....	17
3.2.4 Current Weather Information Flow in the TRACON Domain	18
3.2.5 Weather Information Requirements.....	20
4. DISCUSSION.....	20
5. CONCLUSIONS	22
References.....	25
Acronyms.....	27
Appendices	
A - TRACON Weather Display Description	

List of Illustrations

Figures	Page
Figure 1. Pilot impact ratings for nine weather phenomena and five aircraft types.	8
Figure 2. Pilot impact ratings for 11 weather phenomena and three types of pilot operations.	9
Figure 3. Pilot go/no-go ratings for 10 weather phenomena and five types of pilot operations.....	10
Figure 4. Controller impact ratings for 11 weather phenomena and three types of pilot operations.....	11
Figure 5. The current terminal weather information flow.	19

Table	Page
Table 1. Control Tasks for TRACON Controllers during Adverse Weather Phenomena.....	13
Table 2. TRACON Controller Strategies for Eight Adverse Weather Phenomena.....	17

Executive Summary

This is the second in a two part study on weather information needs. The main purpose of the present study was to assess the Terminal Radar Approach Control (TRACON) weather information needs. An additional objective was to assess the flow of weather information within the TRACON environment and the impact on controller and pilot operations during adverse weather conditions.

The present study used the framework of Cognitive Work Analysis (CWA) (Vicente, 1999) where both environmental (terminal domain) and operational (controller - pilot) constraints are included in the analysis. This framework is as an ecological approach to human factors. An ecological approach begins with, and gives primary importance to, the environmental constraints (e.g., runway configuration and aircraft characteristics) that impose limitations on operators' behavior. Environmental constraints are of primary focus because they impose constraints on goal-directed behavior (i.e., they limit the achievement of certain job tasks). By identifying constraints the CWA can point to instances where weather information is lacking or insufficiently distributed.

The Mission Need Statement for Aviation Weather (Federal Aviation Administration [FAA], 2002) served as the foundation for this weather needs analysis. This FAA document outlines the weather phenomena causing most of the safety and delay problems throughout the National Airspace System. Eight adverse weather phenomena are summarized in the FAA analysis: thunderstorms, in-flight icing, obstruction to visibility (low ceilings and poor visibility), wind shear (microbursts), non-convective turbulence and winds aloft (mountain wave), snow and ice, airport reconfiguration in response to wind changes, and wake vortex.

In July 2003, the Human Factors Group assembled a group with five TRACON controllers and six airline pilots for the collection of weather impact data. During the group sessions, they discussed weather phenomena and the impact on controller and pilot operations. Researchers encouraged group members to discuss specific real-life encounters and assessed the topics from both the controller's and the pilot's perspective. The group also provided numeric (ordinal) ratings of impact from weather phenomena when appropriate. All ratings were consensus ratings (group ratings) that followed a detailed and complete discussion of each topic.

As expected, an analysis of the ratings showed that the degree of impact from adverse weather phenomena is contingent upon aircraft type. Light single engine and light twin aircraft have the highest impact rating, followed by turbo prop, small turbo jet, and, finally, commercial jet showing the least impact of all aircraft types. Regardless of aircraft type, the highest impact ratings are for thunderstorms, microbursts, snow, and ice. The group provided the highest impact ratings for pilot operations for thunderstorms, wind shear, microbursts, snow, and ice, and mountain wave. These two constraints (aircraft type and pilot operations) affect pilot decisions regarding flying in areas of adverse weather. Pilot ratings showed a trend where the go/no-go decision ratings for light single engine and light twin aircraft have fewer clear-cut go decisions compared to turbo prop, small turbo jet, and commercial jet. For controller operations, the highest impact ratings were for thunderstorms, snow and ice, and airport reconfiguration due to changing winds.

The present analysis also revealed several information needs for the TRACON controller. Specifically, there is a lack of a graphical display of weather areas with short-time forecast capabilities at the controller workstation. This information is especially important for the controller during thunderstorms. There is also a lack of weather information from adjacent airports. During conditions of low ceiling and poor visibility, controllers must often divert Visual Flight Rules flights to satellite airports. Without accessible information regarding the conditions at these airports, controllers experience increased workload due to an increase in communications and poor weather situation awareness. For non-convective turbulence and adverse winds, there is a shortfall in the accuracy of available tools. Deployment of runway-specific sensors, winds aloft detection systems, and turbulence warning algorithms would mitigate these deficiencies.

1. INTRODUCTION

There are many deficiencies in the weather information flow within the National Airspace System (NAS). A Mission Need Statement (MNS) for Aviation Weather by the Federal Aviation Administration (FAA) (FAA, 2002) found many capability shortfalls throughout the NAS. Systems for the detection and forecasts of adverse weather conditions such as thunderstorms, icing, and adverse winds lack accuracy and resolution. Dissemination of weather information is another problem; some users never receive available information.

Although these kinds of analyses are informative about NAS-wide information flow, few studies have systematically assessed weather needs within the Terminal Radar Approach Control (TRACON) domain (Ahlstrom & Della Rocco, 2003). Specifically, what are the weather information needs for TRACON controllers in support of operations that reduce delays and increase the safety of operations? Is it possible to optimize the flow of weather information within the TRACON domain? In addition, what can be done to optimize the communication of weather information between pilots and controllers?

Adverse weather conditions cause delays and promote safety hazards. These conditions also increase the workload for both terminal controllers and pilots. During these strenuous conditions, there is an increased demand on the availability, accuracy, and timeliness of important weather information. Controllers and pilots need a veridical mental model of airspace and weather constraints for safe and efficient operations (i.e., their knowledge of the weather situation must correspond to the external reality of the weather situation) (St-Cyr & Burns, 2001b). The knowledge of the location and spatial distribution of adverse weather areas are necessary components for the realization of these models.

The TRACON domain is a complex and dynamic environment with highly coordinated work patterns among operators. Because of these environmental demands, there is a need for an efficient and accurate dissemination of weather information. Furthermore, one must also consider domain constraints that affect controller behavior when assessing weather information needs. Accurate and timely weather information is a necessary, but not a sufficient condition, for safe and efficient TRACON operations during adverse weather conditions. An ecological approach to work analysis with an emphasis on both environmental and operational constraints will provide insight into both information needs and information flow shortages.

TRACON domain constraints affect goal-directed behavior. They set the boundaries for controller actions. TRACON domain constraints include local aspects such as runway configuration, obstacles, system components, control procedures, and aircraft characteristics. Aircraft characteristics are especially important for controller operations. Heavy precipitation, adverse winds, and the ability to perform certain aircraft maneuvers affect controller operations and constrain available control options. Therefore, it is important to consider domain constraints when assessing controller weather information needs.

1.1 Cognitive Work Analysis

The TRACON domain is a dynamic environment with automated systems and highly coordinated work patterns. As such, it fits the description of a complex sociotechnical system

(Vicente, 1999). Complex sociotechnical systems are usually composed of many different elements and forces. They also require clear and effective communication among many operators in a highly dynamic environment. For the most part, these environments are highly computerized and automated and require mediated interaction (i.e., interaction via an interface). Furthermore, complex sociotechnical systems usually provide a high degree of potential operating hazards. As more and more technological inventions control the work domains, new difficulties arise in the analysis and design of complex sociotechnical systems. How do researchers analyze complex systems to make sure they fully understand worker demands and the necessary support systems needed for safe and efficient operations? Similarly, how do researchers elicit domain information from any expert group in order to gain insight for system design and system evaluation?

The framework of Cognitive Work Analysis (CWA) (Vicente, 1999) has proven fruitful for analysis and design of complex sociotechnical systems. The CWA puts great emphasis on the process by which designers and researchers uncover information necessary for the creation of computer-based support systems. First, the explicit study of work and the design of computer-based information systems should be concurrent. Second, researchers should use an ecological approach to work analysis. An ecological approach gives primary importance to the domain constraints that impose limitations on operator' behavior.

As outlined by the CWA, researchers need to focus on five dimensions of complex sociotechnical systems. First, the work domain (i.e., the system being controlled) should be analyzed independently of any goals, operators, tasks, or interfaces. The goal is to describe the constraints (relationships or limitations) that the work domain imposes on operators' actions. This description should be of the constraints, not of the actions. Second, researchers need to represent the control tasks (e.g., a controller issuing an altitude change) used in the work domain to achieve system goals. This control task description should be independent of operators and specific solutions. Third, there should be a description of the strategies (cognitive task procedures) used to perform control tasks, independently of who is performing them. The strategies are process descriptions of how something can be done, compared to control tasks that describe what an operator has to do. Fourth, social organization and cooperation deals with relationships among operators. Included in this description are operator responsibilities and task allocation in the work domain. Finally, worker competencies deal with the human capabilities necessary for effective performance.

TRACON domain constraints are multifaceted because of facility differences in local aspects such as runway configuration, physical obstacles like mountains and high buildings, hazardous weather patterns caused by the specific geographic location, local control procedures, TRACON and tower staffing (are not always collocated), and aircraft performance characteristics (e.g., the different aircraft types using an airport). Furthermore, the TRACON environment itself differs across the NAS. For example, there is a huge difference in the physical layout of TRACONs and towers, and there is variation in automation and available information systems. In fact, not even the Terminal Controller Workstation (TCW) is the same in every TRACON.

1.2 Adverse Weather Phenomena

The *Mission Need Statement for Aviation Weather* (MNS) (FAA, 2002) served as the foundation for the weather needs analysis. This document outlines the weather phenomena causing most of the safety and delay problems throughout the NAS. Furthermore, the document presents an analysis of NAS capability gaps and outlines a strategy for weather mitigation initiatives.

FAA (2002) summarizes eight adverse weather phenomena in their analysis: thunderstorms, in-flight icing, obstruction to visibility (low ceilings and poor visibility), wind shear (microbursts), non-convective turbulence and winds aloft, snow and ice, airport reconfiguration in response to wind changes, and wake vortex. Although wake vortex is not a true weather phenomenon, winds and other weather conditions can affect the locality and spatial coverage of vortices and, thereby, increase the operational impact for terminal controllers.

Thunderstorms are the most significant weather phenomenon that contributes to NAS flight delays. They also affect flight safety but to a lesser degree due to advances in thunderstorm detection and forecast. Among the thunderstorm attributes, we find lightning, tornadoes, hail, turbulence, icing, wind shear, and microbursts (Nierow, 1999). Thunderstorm activity affects the controller by constraining the usable part of the airspace. It also affects the controllers' decision-making by causing pilot requests for deviations and alternate routings. Among planned improvements for future thunderstorm detection and forecast is the fielding of Integrated Terminal Weather Systems (ITWSs) with automated thunderstorm tracking (FAA, 2002).

In-flight icing is predominantly a problem for General Aviation (GA) (Maynard & Sand, 1999), but it also affects Air Taxi and commuter planes due to operations at altitudes where conditions are favorable for icing. It affects the controller because pilots will request changes in altitude or routes to avoid icing conditions. In-flight icing also constrains the use of parts of the airspace for aircraft that lack deicing systems. Planned improvements for the future NAS (FAA, 2002) consist of an enhanced detection with the new Current Icing Potential (CIP) tool deployed for en route operations. This tool will enhance the detection of conditions that are favorable for icing. There will also be enhanced information to pilots regarding Super Cool Liquid Droplets (SLD) from the Forecast Icing Potential (FIP) tool developed by the National Center for Atmospheric Research (NCAR). Planned enhancements to the Next Generation Weather Data (NEXRAD) include a dual polarization feature that, among other things, will enhance the detection and identification of the atmospheric conditions that cause severe aircraft icing.

Obstructions to visibility are weather conditions that in some way obscure the pilot's ability to perceive the layout of runways, surrounding terrain, or the position of other aircraft. Also included in this category are restrictions on airport operations that are due to ceilings and visibility below what is required for normal operations. Ceilings below minimums can effectively close an airport or prevent operations of certain aircraft types. For future enhancements of the detection of obstructions to visibility, the FAA (2002) proposes the use of slant visual range (SVR) sensors and an implementation of new weather sensing systems (visibility forecast algorithms and products) related to visibility detection.

Wind shear is a convective and non-convective phenomenon that includes gust fronts and wind shift lines. Wind shear affects approach and departure routings, especially pilot landing

decisions on final approach. To mitigate the effects of wind shear (FAA, 2002), FAA proposes an expansion of the wind sensor network to provide wind shear coverage 3 miles out from runway thresholds. The FAA also proposes an expansion of the microburst prediction capability for the Airport Surveillance Radar-Weather System Processor (ASR-WSP). Research efforts are also under way to improve the wind shear prediction algorithm used in the ITWS.

The FAA MNS (2002) merges non-convective turbulence and winds aloft into one package. Non-convective turbulence is a serious aviation hazard because every type of aircraft is vulnerable to its effects. It can occur in almost any weather condition and at almost any altitude. Non-convective turbulence also affects flight operations due to re-routes around reported areas of turbulence. These re-routes often result in flight delays. Upper-level forecasts of winds aloft are usually beneficial to traffic managers for optimization of flight routes; however, these same high winds can also indicate the presence of clear air turbulence. For non-convective turbulence and winds aloft, there is an ongoing effort to use the wind profiler network (NPN) to detect this phenomena. Research is also ongoing to examine the possibility of using the airborne meteorological data collection and reporting system (MDCRS) for the detection of both non-convective turbulence and winds aloft. Additionally, there are ongoing developments of an auto-Pilot Report (PIREP) system and algorithms for the measurement of in-situ turbulence.

Snow and ice can have a major impact on airport operations. Surface icing affects controller decisions regarding acceptance rate, metering, and runway selection. It also affects the braking distance and in some cases, icing will cause ground holds or a complete stop of operations. Another problem with snow and ice is the added delay due to de-icing procedures needed for safe takeoffs. Ongoing research is exploring ways to mitigate the effects of snow and ice on ground operations. For example, current research is exploring ways to develop 2, 4, and 12 hr forecasts for surface icing. There is also an effort to improve liquid water content algorithms and to determine the number and locations for additional runway-condition sensors (FAA, 2002).

Unexpected and sudden changes in wind direction at airports are causing operational disruptions and delays. Controllers have to reposition aircrafts for landing and takeoff and turn the airport around (use a different runway configuration). The result is a lower acceptance rate that induces delays throughout the NAS. To support efficient airport reconfiguration, FAA (2002) concludes that new sensors need to be developed for the detection and tracking of surface wind discontinuities. Furthermore, new algorithms need to be developed that can detect and track wind shifts and process multiple sources of wind data. There is also a need for a new algorithm output format for the creation of end user products.

Wake vortices can be a serious safety hazard for in-trail aircraft during landings and takeoffs. Due to unfavorable wind conditions (especially light wind conditions) vortices can drift away and affect other runways in close proximity. Wake vortices also constrain airport acceptance rate and capacity. To mitigate the effects of wake vortex, research is underway to create 3D atmospheric models for prediction of 3D vortex attributes and new ways to sense the presence and behavior of vortex. The National Aeronautics and Space Administration's (NASA) Aviation Vortex Spacing System (AVOSS) is a part of this research effort. Once these vortex data are available, they will be fed into dynamic separation tools (Center TRACON Automation System [CTAS] / Active Final Approach Spacing Tool [aFAST]) that will assist controllers with departure and arrival operations (FAA, 2002).

1.3 Approach

In this study, the domain constraint analysis focused on adverse weather phenomena and the weather information flow across the TRACON domain. What types of weather phenomena mostly affect pilot and controller operations? What types of weather information and displays are available? Who is the recipient of this information? The present study also included the pilot side in the analysis. Pilot go/no-go decisions and aircraft characteristics, together with adverse weather phenomena, impose certain constraints on the terminal controller's actions.

The control task analysis focused on what needs to be done by terminal controllers for safe approaches, take-offs, and so on, during adverse weather. We aimed at defining a general class of control tasks and the associated weather information needs. The strategies analysis describes how the controller can perform certain control tasks. For example, to ensure aircraft separation a controller can use a) speed, b) altitude, or c) heading, to accomplish the same system goal. However, depending on the weather information available and aircraft characteristics, certain strategies are not applicable and, therefore, constrain the controller's options.

The analysis of social organization and cooperation is restricted to weather-related communication between the controller and the pilot and the weather information flow between the controller, supervisor, and Traffic Management Unit (TMU). Specifically, in the present study, we assessed TRACON controller weather information needs. The present study does not incorporate an analysis of worker competencies.

1.4 Purpose

The present study assessed TRACON controller weather information needs that are based on environmental (TRACON domain) and operational (controller/pilot) constraints in order to establish an empirical foundation to examine changes to the current display of weather.

2. METHOD

The Human Factors Group applied CWA methods to the TRACON environment for an analysis of weather information needs and weather information flow in the following manner. First, we analyzed adverse weather phenomena and the relative impact on different aircraft types, the impact on pilot operations, pilot's go/no-go flight decisions, and the impact on controller operations. Second, we analyzed the operational impacts of weather on control tasks, strategies, and the current weather information flow in the TRACON domain. The group used data collected from the Weather Working Group, which met over a 2-day period at the William J. Hughes Technical Center Research Development and Human Factors Laboratory.

2.1 The Weather Working Group

The working group included five experienced TRACON controllers ($M=15.6$ years, $SD=8.6$) that also had experience in tower, en route, military, and Flight Service Station (FSS) operations. Six experienced commercial airline pilots also participated in the working group ($M=14.7$ years, $SD=6.5$). In addition to the airline experience, the pilot group also had experience in GA and Military Aviation.

2.2 Development of Categories for Adverse Weather Phenomena

In this analysis, we kept the general classification of adverse weather phenomena presented in the MNS (FAA, 2002) rather than dividing phenomenon into their attributes. For example, thunderstorms are multi-faceted phenomena and can include hazards like lightning, tornado activity, hail, turbulence, and wind shear. Lightning and hail could potentially have a different impact on pilot operations but are less likely to modify the TRACON controller's actions. Because our analysis aims at defining behavior-shaping constraints for TRACON controllers, there is no further gain by dividing major weather phenomena into their attributes.

In addition to the MNS (FAA, 2002) weather phenomena, the group expanded the categories to include other adverse weather conditions that affect pilot and controller operations. For example, mountain waves can impose a serious problem for pilots when they occur. Similarly, braking actions also have an adverse effect on both pilot and controller operations. For some of our analyses, we differentiated between forecasted and reported weather phenomena and whether the phenomenon is moderate or severe in nature. For pilots, this important distinction affects their decision-making and route planning. For example, the distinction between moderate and severe for reported non-convective turbulence could translate to a go and no-go decision respectively.

The resulting categories were: thunderstorms, in-flight icing, obstruction to visibility, wind shear (forecasted and reported), microbursts, non-convective turbulence (moderate and severe), snow and ice, airport reconfiguration due to changing winds, wake vortex, mountain wave, and braking action.

2.3 Procedure

The weather analysis and data collection took place in a group setting over the course of two days. During these sessions, the Weather Working Group discussed weather phenomena and the impact on controller and pilot operations. All discussions followed a structured plan that the Human Factors Group set up prior to the sessions.

Researchers led this group and encouraged members to discuss specific real-life encounters. They provided numeric ratings (on a 1-5 scale) of impact from weather phenomena, when appropriate. All ratings were consensus ratings (group ratings) that followed a detailed and complete discussion of each topic.

2.4 Analysis

We present a summary and analysis of work group data for pilots in three key categories in the Results section. The first category shows group ratings for the impact of adverse weather on five aircraft types, the second group ratings reflect the impact of adverse weather on pilot operations, and third, we present group ratings on the effect of adverse weather on pilot go/no-go flight decisions.

We present work group data for controllers in five key categories. First, we show group ratings for the impact of adverse weather phenomena on controller operations. Second, we provide a summary of the control task analysis that shows what controllers have to do during different operations in adverse weather. Third, we outline the results of a strategies analysis that reveals possible ways for the controller to handle different aircraft/weather situations. Forth, we summarize an analysis of the flow of weather information within the TRACON environment that captures limitations in the dissemination of weather information to the controllers. Finally, we use the results from the control task analysis and the strategies analysis to capture weather information requirements.

3. RESULTS

3.1 Pilot Operations

3.1.1 The Relative Impact of Adverse Weather Phenomena on Different Aircraft Types

An important constraint that affects pilot and controller operations, especially during adverse weather, is aircraft characteristics (i.e., aircraft type, on-board equipment, and aircraft performance). Therefore, researchers expected that adverse winds, reduced visibility, heavy precipitation, and certain aircraft maneuvers (e.g., climb and descend) had a different impact depending on the aircraft type. We aimed at a general categorization of the impact from adverse weather phenomena on different aircraft types. The focus here is on the impact on the aircraft unit as such, not on pilot task demands. We used five aircraft types in this analysis: light single engine, light twin, turbo prop, small turbo jet, and commercial jet. The working group rated the impact on a 5-level scale that ranged from one (low impact) to five (high impact). Figure 1 summarizes the group ratings of aircraft type and weather phenomena in a bubble chart.

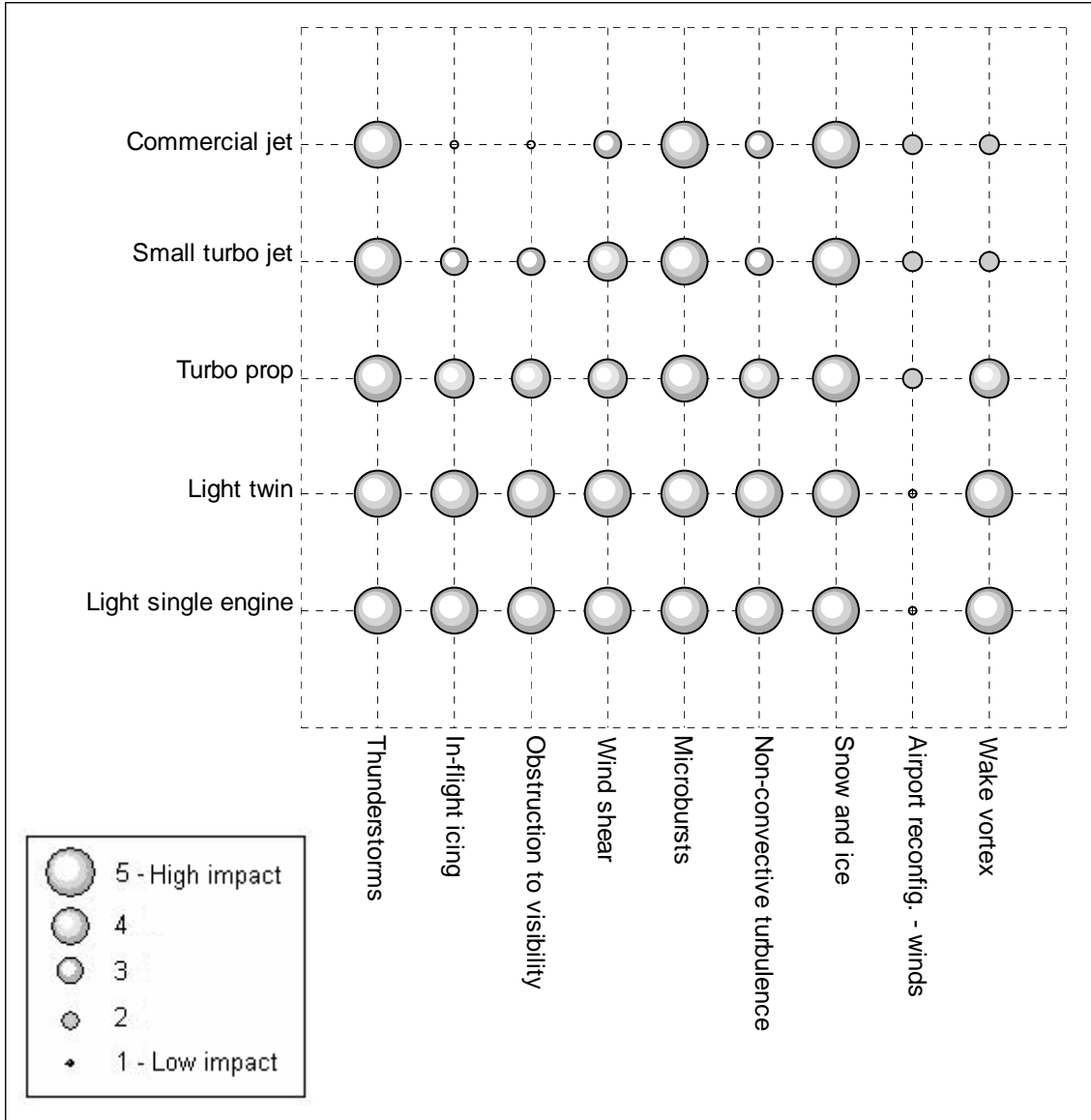


Figure 1. Pilot impact ratings for nine weather phenomena and five aircraft types. The figure depicts a bubble chart (x-y chart) where the size of the bubble indicates the rating value (1=low impact, 5=high impact). Each bubble represents a value from a group rating (i.e., consensus rating) and is therefore shown without a standard deviation. Note: The ratings for light aircraft types under Obstruction to visibility are for non-equipped aircraft only. It relates to situations where a lack of equipment prohibits certain aircraft maneuvers (landings etc.).

Concerning weather phenomena, the highest impact ratings (5) are for thunderstorms, microbursts, and snow and ice, regardless of aircraft type. Conversely, the lowest impact rating is for airport reconfiguration due to changing winds. Figure 1 also shows a trend where light single engine and light twin aircraft both have the highest impact rating, followed by turbo prop, small turbo jet, and, finally, commercial jet showing the least impact of all aircraft types.

3.1.2 The Impact of Adverse Weather Phenomena on Pilot Operations

We used three aircraft types for the rating of pilot operations: GA, air taxi, and air carrier. For these ratings, the GA category is restricted to smaller and less equipped aircraft. Figure 2 summarizes the group ratings of the impact of aircraft type and weather phenomena on pilot operations. As can be seen in the figure, the highest impact ratings (5) are for thunderstorms, wind shear, microbursts, snow and ice, and mountain wave. Figure 2 also shows that there is a somewhat higher impact rating for GA. However, the impact rating from non-convective turbulence, airport reconfiguration, and braking action are the same for all three aircraft types.

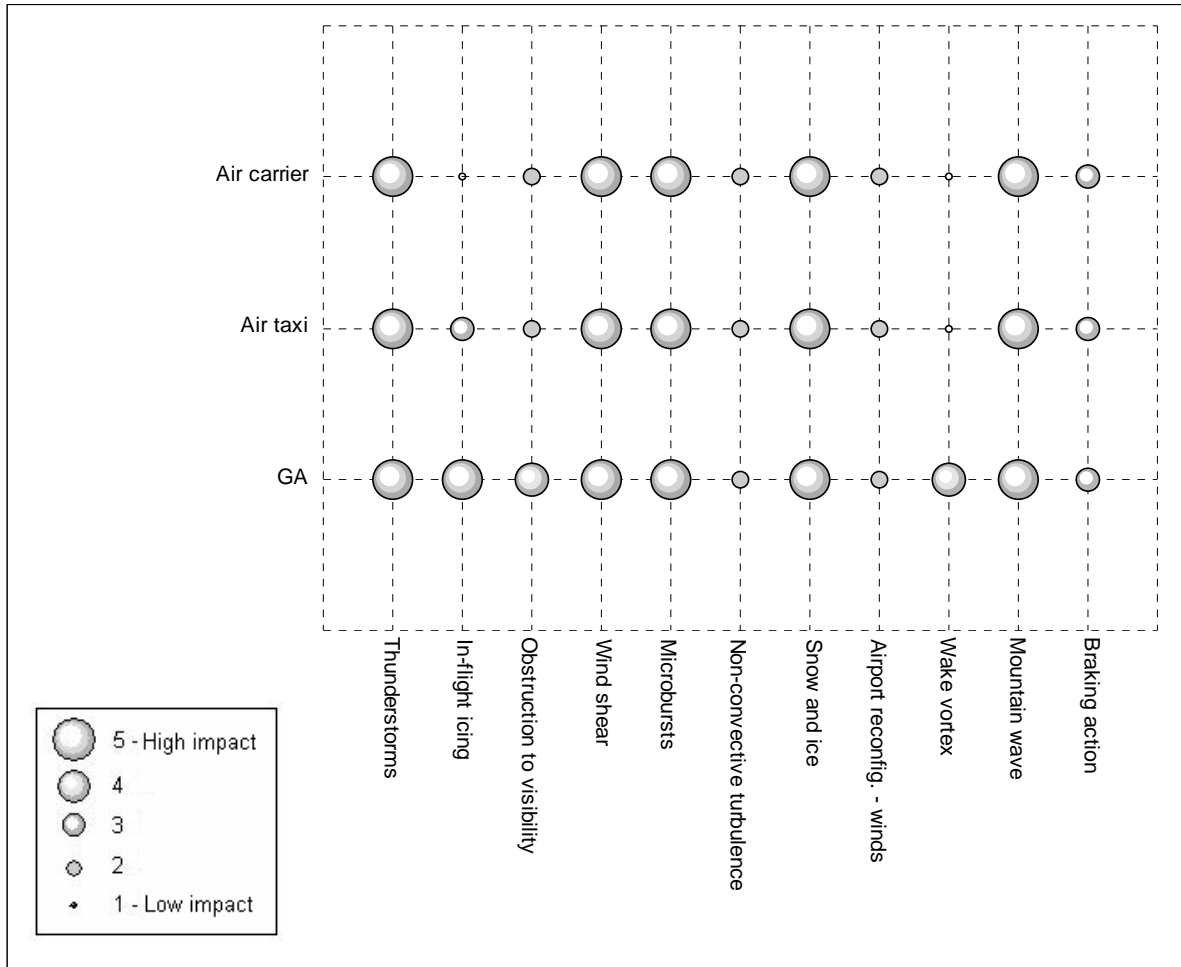


Figure 2. Pilot impact ratings for 11 weather phenomena and three types of pilot operations.

3.1.3 Weather Phenomena and Aircraft Type As Determinants of Pilots' Go/No-Go Flight Decisions

The Human Factors Group assessed pilot go/no-go flight decisions as a function of weather phenomena and aircraft type. We used five different aircraft types in the analysis: light single engine, light twin, turbo prop, small turbo jet, and commercial jet. For the analysis, we used a

discussion scenario where pilots have weather information prior to flight, and based on the particular weather phenomena and aircraft type, make a go/no-go flight decision. The following is an example of a question presented to the pilots: “If you know the weather conditions along your flight path, would you fly through an area with thunderstorms in a light single engine plane?”. The working group rated the pilot go/no-go decisions according to a 5-level scale with one representing never (no-go) and five representing always (always a go decision).

Figure 3 summarizes the group ratings of pilot flight decisions for the five aircraft types and 10 weather phenomena. As can be seen in the figure, only one weather phenomena, reported severe non-convective turbulence, yields a no-go decision regardless of aircraft type. Pilots do not fly through an area with reported severe non-convective turbulence. However, they will do so for reported moderate turbulence, albeit to a lesser extent with single engine and light twin aircraft.

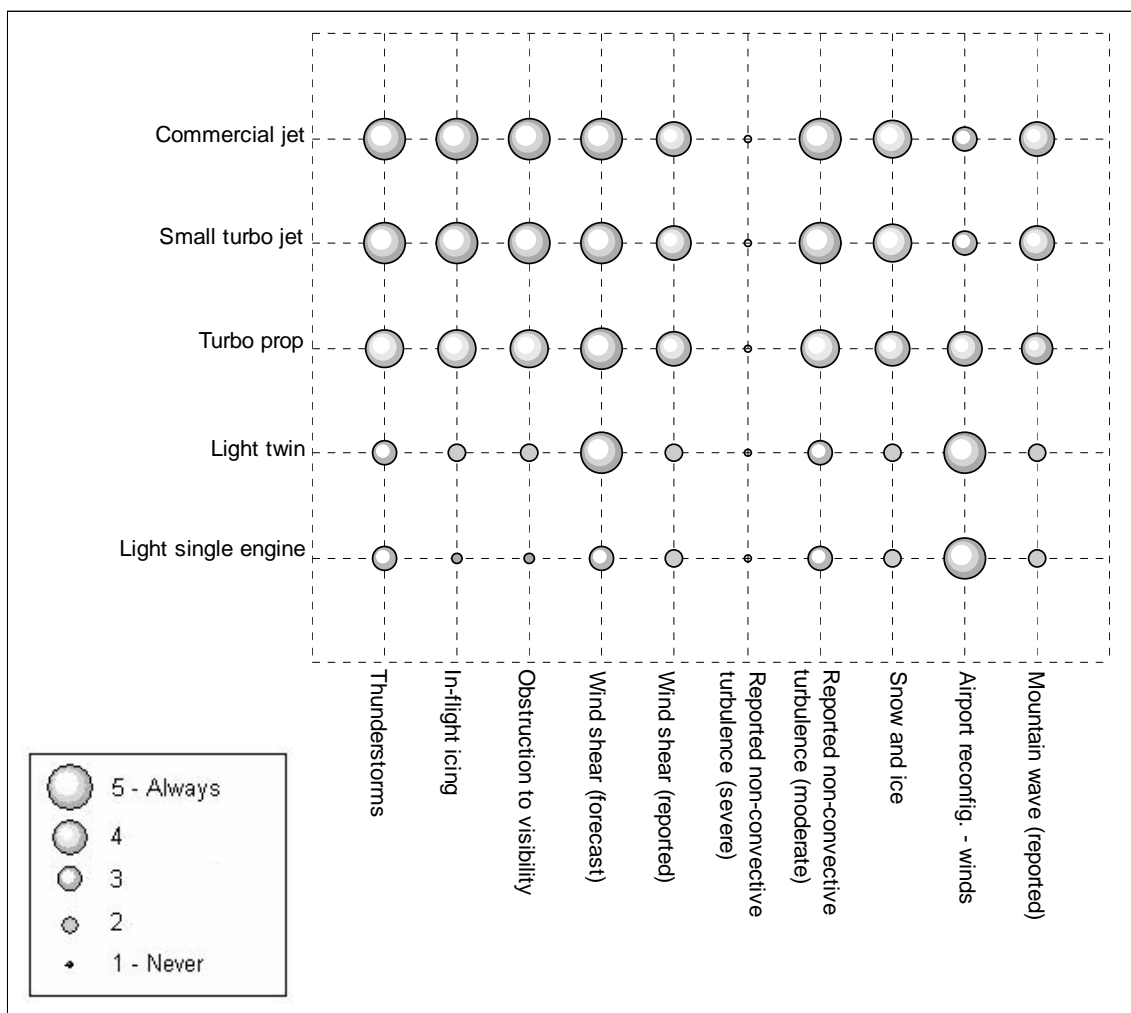


Figure 3. Pilot go/no-go ratings for 10 weather phenomena and 5 types of aircraft operations.

3.2 Controller Operations

3.2.1 The Impact of Adverse Weather Phenomena on Controller Operations

We used the same three aircraft types for the rating of the impact on controller operations by type of pilot operations: GA, air taxi, and air carrier. Figure 4 summarizes the group ratings of the impact of pilot operations and weather phenomena on controller operations. As can be seen in the figure, the highest impact ratings (5) were for thunderstorms, snow and ice, and airport reconfiguration due to changing winds. The lowest ratings (1) were for non-convective turbulence and mountain wave. Quite interestingly, however, the controller impact ratings are identical for all three aircraft operations except for the case of in-flight icing. For this phenomenon, we found a high impact on GA and a low impact on air carriers, reflecting a differential impact due to aircraft characteristics (e.g., performance and equipment).

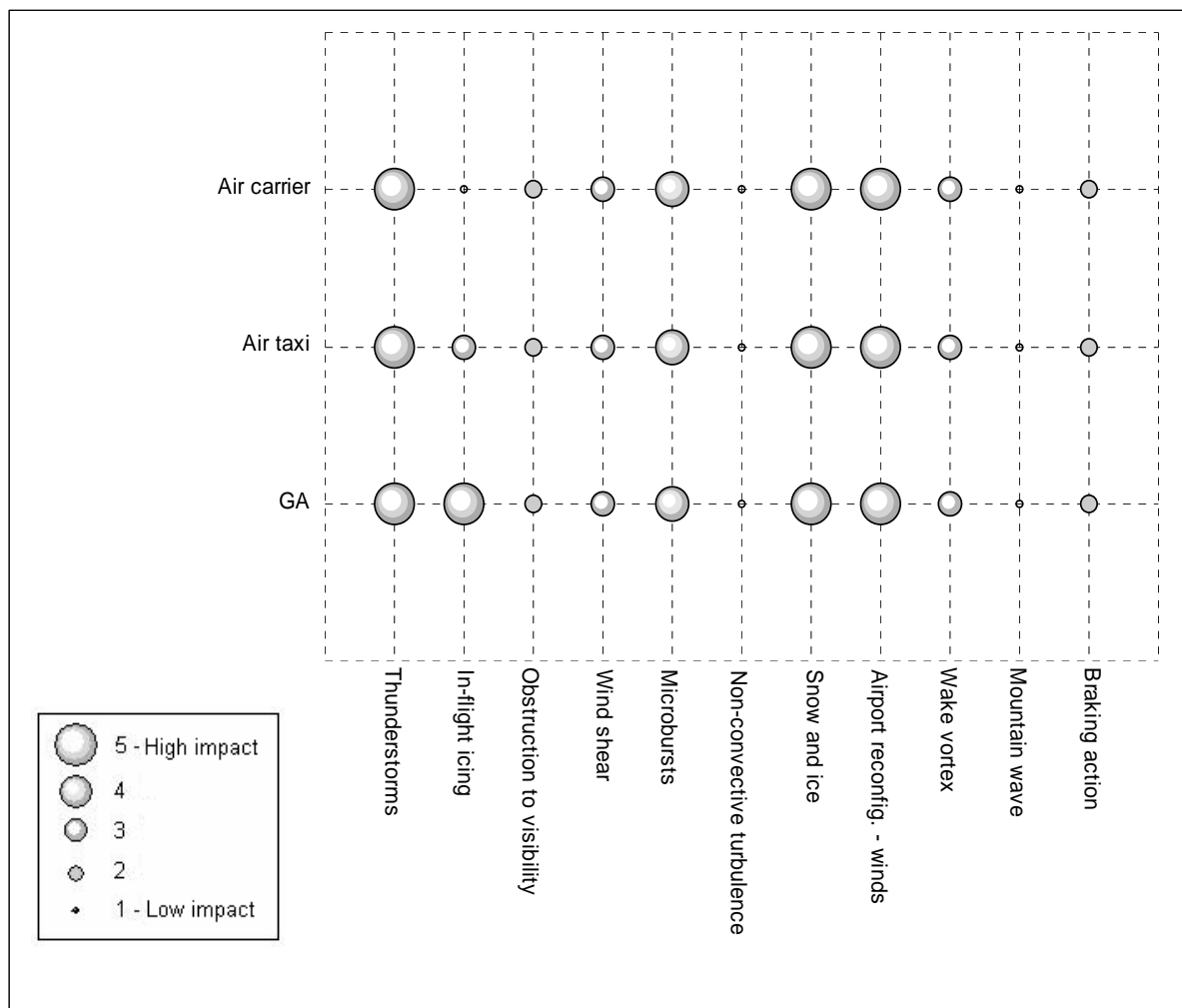


Figure 4. Controller impact ratings for 11 weather phenomena and 3 types of pilot operations.

3.2.2 Control Task Analysis

Through the structured discussions with the controllers of the Weather Working Group, we determined what control tasks (per the CWA) needed to be performed by the controller for safe approaches, departures, and so on, during adverse weather conditions. During this analysis, the Human Factors Group tried to specify general control tasks that are applicable to most adverse weather conditions encountered by terminal controllers. There are always exceptions for these weather situations and control tasks. However, only general cases were useful for this analysis because of our goal to determine controller weather information needs (for a TRACON weather task taxonomy see Rodgers & Drechsler, 1995). Table 1 shows the weather phenomena (A-K) in the left column and the general control tasks in the middle column. In the right column, we show weather information sources that support the controller performing the control tasks. It is important to emphasize, however, that not all of the information sources in the rightmost column are directly available to the controller. We will address the issue of weather information flow in the last section of this document.

The following analyses breaks up thunderstorms into three common situations that terminal controllers encounter. First, we present control tasks for the common situation of deviation requests (A). Second, we address the case of weather avoidance for aircraft that are not equipped with weather radar (B). Third, we address the case of thunderstorms at destination airports (C). The remaining weather phenomena (D-K) are specified similarly to previous analyses of the impact on weather on controller and pilot operations. Finally, we also specify limitations on the available weather information under “Weather Information Sources and Controller Needs”.

Table 1 shows that controllers generally disseminate weather information to pilots, although for thunderstorms (A, B, and C), this information might be incomplete, necessitating the use of other sources of information such as PIREPs. Controllers can also call an FSS and request weather information. However, this option may be impractical, especially during thunderstorms when the controller is under a high workload. For other cases like in-flight icing (D) and non-convective turbulence and winds aloft (H), PIREPs play an even more important role due to a lack of alternative sources of information. (Acronyms in Table 1 are expanded on the Acronym List.)

Table 1. Control Tasks for TRACON Controllers during Adverse Weather Phenomena

Weather phenomena	Control tasks	Weather Information Sources and Controller Needs
<p>A. Thunderstorms (deviation requests).</p> <p>Approach control.</p>	<ol style="list-style-type: none"> 1. Controller gives advance weather advisory to pilot. 2. Pilot contacts ATC. 3. Controller evaluates pilot request. 4. Controller pre-coordinates with other sectors. 5. Controller grants request with changes necessary based on sector traffic. 6. Controller moves other traffic to accommodate deviating traffic. 7. Controller coordinates flow rates and deviations (with supervisor, TMU, en route center, towers, adjacent sectors, etc., regarding deviations around weather). 8. New weather advisories need to be issued to aircraft as required. <p><u>Note:</u> 1, 2, and 3 will happen, then priorities are:</p> <ol style="list-style-type: none"> A. No conflict with traffic. B. Avoid thunderstorms. C. Avoid adjacent airspace. D. 4, 5, and 6 will happen depending on answer to A, B, and C. 	<ol style="list-style-type: none"> 1. Radar/Doppler, ASR 9 (six levels). 2. ASR 7 or 8 (raw radar). 3. PIREPs. 4. Pilot weather radar information is more accurate than the ATC information (controllers make use of pilot weather information). 5. ATC might call FSS for information on weather because they have better resources. 6. Wind information. <p><u>Weather information needs:</u></p> <ol style="list-style-type: none"> 1. Graphical weather displays with short time (10-20 min) forecast capabilities (similar to the capabilities of ITWS, WSP, and MIAWS). 2. Shared weather information. 3. Acceptable, accurate, and timely wind information. 4. Automatic updated terminal tower TDLS.
<p>B. Weather Avoidance (non-weather radar).</p>	<ol style="list-style-type: none"> 1. Pilot contacts controller. 2. Controller contacts pilot (pilot needs help). 3. Controller evaluates pilot request. 4. Controller gives weather information to the pilot. 5. Other pilots contact the controller (<i>where is the weather problem?</i>). 6. Controller locates new pilots. 7. Controller evaluates new request using all available weather information. 8. Controller gives weather advisories to pilots. 9. Controller monitors and updates the weather information to pilots facing weather issues. 10. Return to step 3 (controller action loop repeats). 11. Controller may ask pilot to call FSS/ATC to let them know that they have landed. 	<ol style="list-style-type: none"> 1. Radar/Doppler, ASR 9 (six levels). 2. ASR 7 or 8 (raw radar). 3. PIREPs (including weather radar from pilots if equipped). 4. ATC might call FSS for information on weather because they have better resources. 5. Full weather sequences from area airport resources. 6. Coordination required information from different resources. <p><u>Weather information needs:</u></p> <p>System wide deployment of graphical weather displays with short time (10-20 min) forecast capabilities (similar to the capabilities of ITWS, WSP, and MIAWS).</p>

Weather phenomena	Control tasks	Weather Information Sources and Controller Needs
<p>C. Thunderstorm at the destination airport.</p>	<ol style="list-style-type: none"> 1. Controller reports thunderstorm on or near the airport (within five miles). 2. Controller evaluates traffic needs and weather in immediate area. <ol style="list-style-type: none"> a. Move plane to other runway? b. Bring planes in a tight pattern? c. Start hold? d. Should pilot divert? e. Stop departures/adjust the arrival/departure paths? f. Request a coordinator? g. Coordinate among controller positions (if available)? 3. Controller takes appropriate action (based on step 2). 	<ol style="list-style-type: none"> 1. ASOS. 2. AWSS. 3. ITWS. 4. WSP. 5. MIAWS. 6. Weather observer. 7. Local weather news. 8. PIREPs. 9. Pilots. 10. FSS. 11. NWS. 12. TDWR. 13. LLWAS. 14. ASR9 weather data. <p><u>Weather information needs:</u></p> <p>System wide deployment of graphical weather displays with short time (10-20 min) forecast capabilities (similar to the capabilities of ITWS, WSP, and MIAWS).</p>
<p>D. In-flight icing.</p>	<ol style="list-style-type: none"> 1. Pilot reports icing problem, requests assistance. 2. Controller locates the pilot. <ol style="list-style-type: none"> a. Where is the Pilot? (Direction, altitude, and location.) b. What is under the pilot (for example, MVA)? 3. Controller acts on pilots' request. 4. Controller may request PIREPs from pilots in the area. 5. Pilot may request further action based on information provided. 6. Controller will pass PIREP to internal and external facilities. 7. Action loop will continue until the weather issue is resolved. 	<ol style="list-style-type: none"> 1. PIREPs (time sensitive). 2. Forecasts. 3. FSS (available but impractical). 4. Controllers trade information. <p><u>Weather information needs:</u></p> <p>Accurate and timely icing information.</p>

Weather phenomena	Control tasks	Weather Information Sources and Controller Needs
<p>E. Low ceiling and poor visibility (VFR conditions to IFR).</p>	<ol style="list-style-type: none"> 1. Controller disseminates weather information. 2. Controller asks each VFR pilots about his/her intentions. 3. Controller evaluates and acts on pilot requests. <ol style="list-style-type: none"> a. SVFR. b. Divert to VFR airport. c. Transition airspace. d. Request IFR clearance. e. Declare emergency. 	<ol style="list-style-type: none"> 1. Airport weather sequence reports. 2. PIREPs (flight visibility, bases, and tops). <p><u>Weather information needs:</u></p> <ol style="list-style-type: none"> 1. Weather information from adjacent airports. 2. Trends. 3. Forecasts. 4. Briefing on area weather.
<p>F. Low ceiling and poor visibility (below minimums).</p>	<ol style="list-style-type: none"> 1. Controller disseminates weather information. 2. If pilots indicate that they are below their minimums, respond to their request. 3. Coordinated re-clearance (divert, hold, or continue). 4. Action loop (1-3) may continue until problem is solved. 	<ol style="list-style-type: none"> 1. Airport weather sequence reports. 2. PIREPs (flight visibility, bases, and tops). <p><u>Weather information needs:</u></p> <ol style="list-style-type: none"> 1. Weather information from adjacent airports. 2. Trends. 3. Forecast. 4. Briefing on area weather. 5. Automated RVR (runway visual range). 6. Simple alert ASDE-X/AMASS.
<p>G. Wind shear.</p>	<ol style="list-style-type: none"> 1. Pilot reports wind shear (or the report comes from a sensor or tower). 2. If pilot does not have to take immediate action, the controller executes step 3. If pilot needs to take action, the controller responds (e.g., missed approach instructions, delay vectors, or re-identify aircraft). 3. Controller disseminates information locally. 4. Controller advises FD/FSS as required. 5. Controller reacts to pilot request. 6. Action loop may continue (the order of 3, 4, and 5 might change depending on the circumstances). 	<ol style="list-style-type: none"> 1. ITWS. 2. TDWR. 3. WSP. 4. LLWAS. 5. PIREPs. <p><u>Weather information needs:</u></p> <ol style="list-style-type: none"> 1. Improved accuracy of available tools. 2. Installation of runway-specific sensors. 3. System-wide availability of information to all airports.
<p>H. Non-convective turbulence, winds aloft.</p>	<ol style="list-style-type: none"> 1. Pilot reports turbulence/adverse wind conditions (may include a request where turbulence is given a higher priority). 2. Controller evaluates situation and accommodates request if possible. 3. Controller disseminates PIREP/information. 4. Controller solicits additional information from pilot (is it better at the new altitude?) 5. Action loop may continue. 	<ol style="list-style-type: none"> 1. PIREPs <p><u>Weather information needs:</u></p> <ol style="list-style-type: none"> 1. Turbulence warning algorithm. 2. More accurate winds aloft detection system (NEXRAD). 3. ITFA (integrated turbulence forecast algorithm). A version should be developed for lower altitudes.

Weather phenomena	Control tasks	Weather Information Sources and Controller Needs
I. Snow and ice.	<ol style="list-style-type: none"> 1. Controller is informed of snow/ice accumulation (by tower, airport, snow team, etc.) to the point where operations are impacted. 2. Controller reacts to situation (hold operation, airborne holding, create gap for ground equipment, grant diversion requests, switch operation, increase spacing, change runway, etc.). 3. Action loop may continue. 	<ol style="list-style-type: none"> 1. Field condition reports from airport authority (phone, fax, etc.). 2. Braking action advisories. 3. PIREPs. 4. Tower coordination. <p><u>Weather information needs:</u></p> <ol style="list-style-type: none"> 1. Automated updates and dissemination of field condition reports. 2. Additional weather information like accumulation and satellite airport conditions. 3. Ability to identify snow (calibration of NEXRAD type product for winter conditions).
J. Airport reconfiguration in response to wind changes.	<ol style="list-style-type: none"> 1. Tower advises controller of need to change operation (airport size significantly affects complexity). 2. Controller evaluates traffic (PIREP of significant tail/cross winds, noise abatements, disabled a/c, NAVAID outage, etc.) and coordinates the arrival cut-off point for current runway. 3. Controller performs coordination as appropriate (often done by supervisor) to center, tower, satellite airports, and adjacent sectors. 4. Action loop may continue. 	<ol style="list-style-type: none"> 1. Wind indicator. 2. Terminal area forecasts. 3. PIREPs <p><u>Weather information needs:</u></p> <ol style="list-style-type: none"> 1. Improved runway wind system (runway specific anemometer). 2. Gust front prediction (ITWS, MIAWS, WSP, and TDWR have this information).
K. Wake vortex.	<ol style="list-style-type: none"> 1. Controller determines wake turbulence action required (per 7110.65). 2. Controller applies appropriate separation. 3. Controller issues wake turbulence advisory (as required). 	<ol style="list-style-type: none"> 1. 7110.65 2. Specialized training. <p><u>Weather information needs:</u></p> <ol style="list-style-type: none"> 1. Improved training in when and how to apply wake turbulence procedures. 2. Simplified wake turbulence procedures. 3. Automated vortex sensors.

This analysis also revealed several information needs for the controller. Specifically, there is a lack of a graphical display of weather areas with short-time forecast (10-20 min) capabilities for the controller. This information is especially important for the controller during thunderstorms. There is also a lack of weather information from adjacent airports. During conditions of low ceiling and poor visibility, controllers must often divert VFR flights to satellite airports. Without accessible information regarding the conditions at these airports, controllers are experiencing increased workload due to an increase in communications and poor weather situation awareness. For non-convective turbulence and adverse winds, there is a shortfall in the accuracy of available tools. Deployment of runway-specific sensors, winds aloft detection systems, and turbulence warning algorithms would mitigate these deficiencies.

3.2.3 Strategies Analysis

The previous analysis determined what a controller has to do when controlling aircraft during adverse weather phenomena. In this analysis, we assess how the controller can perform the control tasks by means of strategies.

Strategies are an important part of any work domain analysis and especially for complex domains like ATC. For example, Sperandio (1978) investigated how controllers regulate their working strategies as a function of increased workload. As traffic increases, controllers adopt different strategies to avoid a situation where they are at risk of losing situation awareness.

We used the eight weather phenomena for the present strategies analysis. Table 2 shows the weather phenomena (A-H) in the left column and the strategies in the right column. In general, several general strategies are available for the controller for severe weather avoidance. For example, controllers can use 10 different strategies in the case of thunderstorms (A). For airport reconfiguration in response to wind changes (G), controllers can use six general strategies to perform the control task.

The strategies for weather phenomena A-C and F-H have one important thing in common. The controller has some degree of weather situation awareness and can often disseminate weather information to pilots in advance. For wind shear (D) and non-convective turbulence and winds aloft (E), however, the controller can only adopt the available strategies *after the fact* (a pilot will report about turbulence/adverse wind conditions to the controller - the controller will act on this information *after* the report). This reflects the lack of accuracy in available detections systems and a lack of system-wide dissemination of information. FAA (2002) has also recognized these deficiencies and has proposed several mitigation strategies.

Table 2. TRACON Controller Strategies for Eight Adverse Weather Phenomena

Weather Phenomena	Strategies
A. Thunderstorms.	<ol style="list-style-type: none"> 1. Vector around. 2. Climb above. 3. Descend below. 4. Hold. 5. Divert to alternate airport. 6. Give clearance to deviate as necessary then proceed on course. 7. Adjust flow rate. 8. Stop departures. 9. Point out. 10. Refuse hand offs.
B. In-flight icing.	<ol style="list-style-type: none"> 1. Climb. 2. Descend. 3. Vector.

Weather Phenomena	Strategies
C. Low ceiling and poor visibility.	<ol style="list-style-type: none"> 1. Vector around. 2. Climb above. 3. Descend below. 4. Hold. 5. Divert to alternate airport. 6. Give clearance to deviate as necessary then proceed on course. 7. Adjust flow rate. 8. Stop departures. 9. Point out. 10. Refuse hand offs.
D. Wind shear.	1. Solicit and disseminate PIREPs (<i>after the fact</i>).
E. Non-convective turbulence, winds aloft.	<ol style="list-style-type: none"> 1. Climb (<i>after the fact</i>). 2. Descend (<i>after the fact</i>). 3. Solicit and disseminate PIREPs.
F. Snow and ice.	<ol style="list-style-type: none"> 1. Delay vectors. 2. Adjust flow rate. 3. Divert to alternate airport. 4. Hold. 5. Stop departures. 6. Provide current braking action reports.
G. Airport reconfiguration in response to wind changes.	<ol style="list-style-type: none"> 1. Delay vectors. 2. Adjust flow rate. 3. Hold. 4. Stop departures. 5. Speed adjustments. 6. Divert (as necessary).
H. Wake vortex.	<ol style="list-style-type: none"> 1. Speed adjustments. 2. Climb. 3. Descend. 4. Adjust in-trail spacing. 5. Suggest pilot apply visual separation.

3.2.4 Current Weather Information Flow in the TRACON Domain

An important domain constraint in the current TRACON environment is the flow of weather information. Figure 5 presents most of the weather information displays available in the TRACON environment. It must be emphasized, however, that these displays are not available in every facility. Large differences exist between facilities with some TRACONs having few weather displays and others have most or all of the weather displays. Appendix A presents a more detailed description of these weather displays.

Not all of the weather information is directly available to the controller. Although information about terminal winds, barometric pressure, temperature, and visibility values are available, most of the weather displays with information about precipitation and storms (i.e., WSP, Corridor Integrated Weather System [CIWS], ITWS, and Terminal Doppler Weather Radar [TDWR]) are not at the TCW. When the operational circumstances dictate a need, the controller receives this information from the supervisor or the TMU. Alternatively, in situations where conditions permit, controllers may walk across the room to acquire this information directly from the ITWS display.

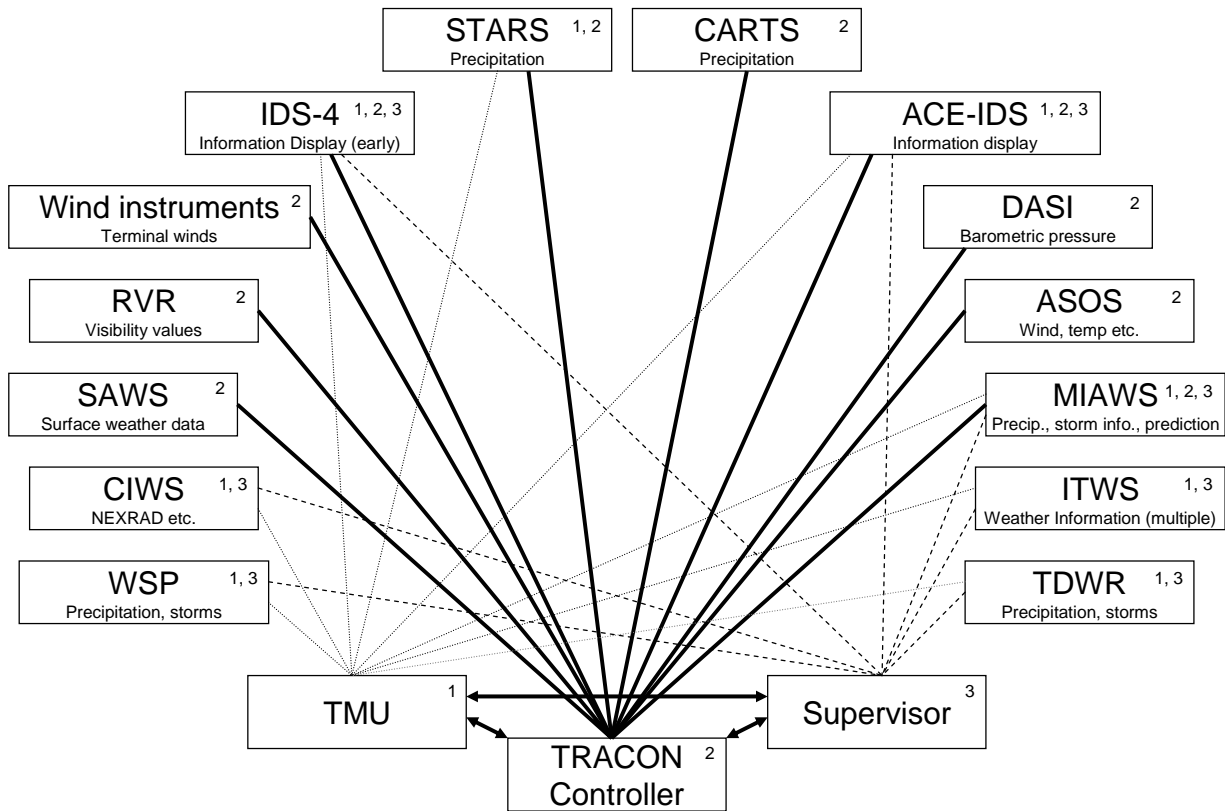


Figure 5. The current terminal weather information flow.

At the bottom of the figure, there is a representation of the TMU (1), the TRACON controller (2), and the Supervisor (3). Above this triad, there is a representation of the current weather displays in the terminal environment (14 displays, starting with WSP on the left, and ending with TDWR on the right). Each weather display has a connection to the triad showing the recipient of this information. There is also a numeric representation depicted in the upper right-hand corner for each weather display. For example, the recipients of the WSP display are the TMU and the Supervisor, shown by the line connections and the 1 and 3 label in the WSP box. The arrows between the TMU, TRACON controller, and the Supervisor depict the flow of weather information among the triad entities. The main flow of weather information goes from the TMU to the Supervisor and from the Supervisor to the TRACON controller. However, there is also a flow of weather information directly from the TMU to the TRACON controller, and from the TRACON controller to the TMU and the Supervisor. The acronym list contains an expansion of the various systems in Figure 5.

Considering the impact of thunderstorms on controller and pilot operations, it is somewhat surprising that TRACON controllers do not have immediate access to a graphical weather display with short-time forecast like the ITWS, WSP, or the Medium-Intensity Airport Weather System (MIAWS). To circumvent this information limitation, controllers make use of weather radar information from pilots in equipped aircraft. PIREPs are an important source of weather information for the controller.

However, because of the weather display limitation for controllers, there is an increased workload during thunderstorms for the controller to seek timely and accurate information. This is especially true for controllers facing weather avoidance for non-equipped aircraft.

3.2.5 Weather Information Requirements

This analysis also reveals several weather information needs not currently met in the TRACON domain. First, there is a need for a graphical weather display with short-time forecast capabilities at the TCW. Controllers need an accurate (veridical) mental model of weather locations and movements in order realize available control strategies. There is also a lack of efficient dissemination of weather information from adjacent airports. Controllers frequently divert aircraft to satellite airports during conditions of low ceiling and poor visibility. A lack of good weather information and poor weather situation awareness will increase communications and controller workload. There is also a lack of accurate tools for the detection and dissemination of information about non-convective turbulence and adverse winds. Controllers are unable to disseminate advance information to pilots; they apply their control strategies *after the fact*.

4. DISCUSSION

Environmental constraints set boundaries for goal-directed behavior. They remove degrees of freedom for operators and constrain the available control options. TRACON domain constraints include, but are not limited to, local aspects such as runway configurations, mountains and high buildings, aircraft performance characteristics, control procedures, and hazardous weather. The present analysis, focused on the constraints imposed by the impact from adverse weather on pilot and controller operations and the current limitations in TRACON weather information flow.

Pilots and controllers reported thunderstorms are the most common phenomena, with certain geographical areas having full storms every evening. When severe thunderstorms happen on the East coast, the entire area from Atlanta to Boston can be affected. Severe thunderstorms can bring airports to a stand still. Wind shear is also dependent of geographical region with certain regions more affected than others. The frequency of microbursts is also dependent on the geographic location. According to pilots, it is very common in the area around Las Vegas but much less frequent on the east coast. Snow and ice is also geographically dependent, a seasonal problem for most of the US except for Alaska. Mountain waves affect areas near mountains, especially in the Rockies. During these adverse weather conditions, GA is the aircraft type affected the most. Adverse weather phenomena also affect pilots' go/no-go flight decisions. In general, thunderstorms, microbursts, and snow and ice provide the highest impact ratings regardless of aircraft type. However, pilots are less likely to make a go decision when flying a light single engine or light twin aircraft. In the case of reported non-convective turbulence, pilots always make a no-go decision regardless of aircraft type. For controller operations, we found the highest impact from thunderstorms, snow and ice, and airport reconfiguration due to changing winds.

In our control task analysis, we found that controllers generally disseminate weather information to pilots. However, the controllers' information is often incomplete, necessitating the use of PIREPs. These real-time reports from pilots are currently an important source of information for the controller because the controller does not have timely and precise information available on adverse weather (especially thunderstorms). This causes an increase in the communication among the controller, pilot, supervisor, TMU, tower, adjacent sectors, and Air Route Traffic Control Centers adding to the controller workload and the workload of the groups included in the

communication. Controllers want to make decisions in advance and give weather advisories well ahead in time to avoid last minute decisions. During adverse weather conditions, controllers are trying to avoid conflicts between aircraft, prevent aircraft from entering or re-entering the thunderstorm, and avoid aircraft entering adjacent airspace without coordination.

Our strategies analysis shows that controllers can use several control options to achieve their goals during adverse weather conditions. An exception is the case of wind shear and non-convective turbulence. For these situations, the results show that controllers only can adopt their control strategies *after the fact*. Although controllers can use multiple control strategies to achieve their goals, there are instances where their degrees of freedom are constrained. An example is the case of weather avoidance for aircraft that are not equipped with weather radar. Under these conditions, some control strategies are not applicable unless the controller has timely and accurate weather information regarding the location and movement of the storm. Controllers need to know the current weather location and movements in the near future in order to realize the use of available control strategies.

The importance of timely and accurate weather information is highlighted by reports from the en route domain. Evidently, en route controllers have improved their weather situation awareness after the introduction of NEXRAD on their workstation (Amis, 2002). Besides being an aid for en route controllers during thunderstorms, Amis also reports that the weather display increased their confidence level while controlling traffic under these adverse conditions.

An important constraint in the TRACON domain is the flow of weather information. In most cases, controllers have immediate access to information about terminal winds, visibility values, barometric pressure, and temperature. However, most TRACON controllers lack detailed information about storms and their movements (e.g., information from ITWS and TDWR). Controllers must get this information from the supervisor or the TMU. In cases of severe weather, this adds to the workload and necessitates an increased communication between the controller, supervisor, TMU, and the pilots. During thunderstorms, pilots frequently ask controllers if other airplanes already have made it through, or which way traffic is deviating. In general, equipped aircraft has a much better depiction of weather (from radar) than controllers have and can see much further out. However, in certain situations pilots will contact their dispatcher for additional weather information. It is important to keep in mind, however, that there is much disparity in weather resources between different TRACON facilities. They are all differently equipped, vary in staffing, and whereas some facilities may not have enough weather information equipment, other facilities have every weather information system available in the terminal domain.

Weather situation awareness in the future will likely advance, as planned improvements in the flow of information among controllers, pilots, and flight dispatchers are in place (Ahlstrom & Della Rocco, 2003). In the current TRACON environment, the lack of equipment standardization, disrupted weather information flow, and a lack of good tactical weather displays all work against high weather situation awareness. As stated by Vicente (1997) in his *ecological compatibility principle*, the content and structure of the interface must ensure that operators can acquire an accurate mental model of the actual system behavior. Put in controller terms for weather situation awareness, this means a mental model that combines the perception of time, airspace volume, sector traffic flow, current weather location, weather movements in the near

future, and the available control options. Accurate, timely, and readily accessible weather information is a prerequisite for all of these model components. The knowledge that controllers have about the location and movement of thunderstorms, for example, makes up the controllers' internal mental model of the weather situation (St-Cyr & Burns, 2001a). During thunderstorms, controllers will use this knowledge for effective and safe decision making while controlling traffic. It is therefore important that these mental models match the true state of affairs of the environment (TRACON domain). This is especially true for correspondence-driven domains where we have an external reality that imposes dynamic constraints on the operator's actions (Vicente, 1999). The present study does not cover weather display options and computer-human-interface (CHI) solutions (Ahlstrom & Della Rocco, 2003). However, it is important to consider these issues in reference to weather situation awareness.

Pilots consider several factors when making judgments about flights and go/no-go flight decisions. For example, Driskill et al. (1997), investigated GA pilots' comfort levels for flights affected by variables like terrain, ceiling, visibility, and precipitation. Driskill et al. found that pilot's use of weather information is consistent with expert opinions regarding the risk of Visual Flight Rules (VFR) flights under the conditions investigated. However, they also found that pilots vary in their ratings of comfort levels for flights under various weather conditions. Beringer and Schvaneveldt (2002) found that novice and experienced GA pilots rank weather factors similarly, but the ratings vary depending on the phase of flight and more experienced pilots assigned a higher importance to weather factors compared to novice pilots. Wiegmann, Goh, and O'Hare (2003) investigated GA pilots' decisions to continue or divert VFR flights into adverse weather. They found that VFR flights into instrumental meteorological conditions (IMC) could partly be an effect of poor weather situation awareness and experience from the pilots. Results showed that pilots who flew into deteriorating weather early flew longer in the weather before deviating. These pilots were much more optimistic in their projection of the weather than the pilots who experienced the worsening weather conditions later in their flight. Wiegmann et al. suggest that pilot training in the assessment of critical weather cues could increase their weather evaluation skills and help reduce this major safety hazard. In the present study, pilot ratings showed that the degree of impact from adverse weather phenomena was contingent upon aircraft type. Light single engine and light twin aircraft had the highest impact rating, followed by turbo prop, small turbo jet, and, finally, commercial jet showing the least impact of all aircraft types. We found the highest impact ratings for pilot operations for thunderstorms, wind shear, microbursts, snow and ice, and mountain wave. These two constraints (aircraft type and pilot operations) affected pilot decisions regarding flying in areas of adverse weather. We found a trend where the go/no-go decision ratings for light single engine and light twin aircraft had fewer clear-cut go decisions compared to turbo prop, small turbo jet, and commercial jet.

5. CONCLUSIONS

In the present study, we provide a great deal of data on terminal controllers' current practices of controlling traffic during adverse weather conditions. We use the framework of CWA to organize the data into a coherent and systematic structure. Taken together, our analysis suggests possible improvements in the weather information flow and improved requirements for terminal controllers' weather information displays. However, our analysis does not provide an exhaustive and definite account on the necessary developments. The CWA is a means to extract

information about a complex work domain. However, it is not possible to provide a definite and exhaustive account of weather information needs by analytical methods alone. This empirical question requires the use of suitable empirical methods. The time has now come to go beyond the analytical work (Ahlstrom & Della Rocco, 2003) and set the stage for an empirical evaluation. This requires real time human-in-the-loop simulations where weather scenarios, weather information, and display characteristics are systematically manipulated. This is the only way to provide true insights into terminal controllers' weather information needs for the safe, efficient, and collaborative efforts required to handle adverse weather conditions in the NAS.

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Acronyms

ACE-IDS	Automated Surface Observing System Controller Equipment-Information Display System
AFAST	Active Final Approach Spacing Tool
AMASS	Airport Movement Area Safety System
ARTS	Automated Radar Terminal Systems
ASDE-X	Airport Surface Detection Equipment Model X Program
ASOS	Automated Surface Observing System
ASR	Airport Surveillance Radar
ASR-WSP	Airport Surveillance Radar-Weather System Processor
ASWON	Aviation Surface Weather Observation Network
ATC	Air Traffic Control
AVOSS	Aviation Vortex Spacing System
AWSS	Automated Weather Sensors System
CARTS	Common ARTS Display
CHI	Computer-Human-Interface
CIP	Current Icing Potential
CIWS	Corridor Integrated Weather System
CTAS	Center-TRACON Automation System
CWA	Cognitive Work Analysis
DASI	Digital Altimeter Setting Indicator
DOD	Department of Defense
EDI	External Data Interface
FAA	Federal Aviation Administration
FD	Flight Data
FIP	Forecast Icing Potential
FSS	Flight Service Station
GA	General Aviation
IDS	Information Display System
IFR	Instrument Flight Rules
IMC	Instrumental Meteorological Conditions
ITFA	Integrated Turbulence Forecast Algorithm
ITWS	Integrated Terminal Weather System
LLWAS	Low Level Wind Shear Alert System
MDCRS	Meteorological Data Collection and Reporting System
MIAWS	Medium-Intensity Airport Weather System
MNS	Mission Needs Statement for Aviation Weather
MVA	Minimum Vectoring Altitude
NAS	National Airspace System
NASA	National Aeronautics and Space Administration
NAVAID	Navigational Aid
NCAR	National Center for Atmospheric Research
NEXRAD	Next Generation Weather Data
NPN	Wind Profiler Network
NWS	National Weather Service
PIREP	Pilot Report

RVR	Runway Visual Range
SAWS	Stand Alone Weather Sensors
SIU	System Interface Units
SLD	Super Cool Liquid Droplets
STARS	Standard Terminal Automation Replacement System
SVFR	Special Visual Flight Rules
SVR	Slant Visual Range
TCW	Terminal Controller Workstation
TDLS	Tower Data Link Services
TDWR	Terminal Doppler Weather Radar
TMU	Traffic Management Unit
TRACON	Terminal Radar Approach Control
VFR	Visual Flight Rules
WSP	Weather Systems Processor

Appendix A

TRACON Weather Display Description

Weather display	Product name	Product description
ACE-IDS	Automated Surface Observing System (ASOS) Controller Equipment - Information Display System	<ul style="list-style-type: none"> - Designed for use in air traffic control towers, radar approach control facilities, en route centers, automated flight service stations, weather stations, maintenance facilities, training facilities, airline and airport operations, and military air fields. - ACE-IDS allows data from multiple internal and external sources to be consolidated on the screen in many combinations and formats for easy access within a graphical user interface. - ACE-IDS can show reference data such as charts, maps, approach plates, procedures, etc., can be integrated with real-time data collected by interfaces to other systems. - ACE-IDS alerts automatically to changes in critical information. <p>http://www.sysatl.com/pages/aceids/aceidsfacts.htm</p>
ASOS	Automated Surface Observing System	<ul style="list-style-type: none"> - ASOS is an automated observing system being sponsored by the Federal Aviation Administration, National Weather Service (NWS) and the Department of Defense (DOD). - ASOS provides weather observations that include temperature, dew point, wind, altimeter setting, visibility, sky condition, and precipitation. - 569 FAA-sponsored and 313 NWS-sponsored ASOSs are installed at airports throughout the country. <p>http://www2.faa.gov/asos/asosinfo.htm</p>

CARTS	Common ARTS Display	<ul style="list-style-type: none"> - ARTS programs have a common air traffic control mission with similar functional requirements. - CARTS has been implemented at approximately 130 small-to-medium-sized TRACONs with ARTS IIE systems and at 8 large TRACONs with ARTS IIIE systems. <p>http://www2.faa.gov/ats/atb/Sectors/Automation/CommonArts/description.htm</p>
CIWS	The Corridor Integrated Weather System	<ul style="list-style-type: none"> - CIWS provides en route traffic flow managers with accurate, automated high update information on storm locations and 0-2 hour forecasts of storms. - CIWS help traffic flow managers achieve more efficient tactical use of the airspace. <p>http://ams.confex.com/ams/13ac10av/10ARAM/abstracts/38892.htm</p>
DASI	Digital Altimeter Setting Indicator	<ul style="list-style-type: none"> - DASI displays the altimeter-setting indicator for air traffic operations. - DASI measures atmospheric pressure and converts the value into actual sea level pressure based on the U.S. Standard Atmospheric Table. <p>http://www1.faa.gov/AUA/ipt_prod/tower/TOW-FACT.HTM</p>

IDS-4	Information Display System 4	<ul style="list-style-type: none"> - IDS-4 is a hardware/software product especially designed to meet the information needs of air traffic control personnel. This integrated data collection, distribution, and display system supplies static, as well as automatic updates of rapidly changing, critical information to air traffic controllers, their supervisors, and related personnel. - There are 148 IDS4 systems in the field, encompassing approximately 280 airports and 400 FAA facilities. These systems consist of approximately 2500 IDS4 workstations, 33 External Data Interface (EDI) systems, 9 System Interface Units (SIU), and over 250 interface connections to other FAA and National Weather Service (NWS) systems. In terms of units fielded, this constitutes one of the largest of the FAA's systems. <p>http://www.sysatl.com/pages/ids4/ids4facts.htm</p>
ITWS	Integrated Terminal Weather System	<ul style="list-style-type: none"> - ITWS provides automated weather information for use by air traffic controllers and supervisors in airport terminal airspace (60 miles around the airport.) - ITWS provides products that require no meteorological interpretation to air traffic controllers, air traffic management systems, pilots, and airlines. - ITWS provides a comprehensive current weather situation and highly accurate forecasts of expected weather conditions for 30 minutes in the future. The ITWS achieves this through integration of data and information from FAA and National Weather Service (NWS) sensors such as the Terminal Doppler Weather Radar (TDWR), the Next Generation Weather Radar (NEXRAD), airport surveillance radar, Low Level Wind Shear Alert System (LLWAS), automated weather and surface observing systems, lightning detection systems, NWS weather models and aircraft via the meteorological data collection and reporting system (MDCRS). - Automated weather products produced by the ITWS for ATC include wind shear and microburst detection and predictions, storm cell intensity and direction, lightning information and detailed data of the winds in the terminal area. <p>http://www.raytheon.com/products/itws/ref_docs/itws.pdf</p>

MIAWS	Medium Intensity Airport Weather System	<p>- MIAWS provides a weather processing and display system for medium-level operations airports that lack dedicated weather sensors. MIAWS provides near-term, low-cost weather information to these airports.</p> <p>http://www.tsc.com/SETS/_3MIAWS.htm</p>
RVR	Runway Visual Range	<p>- The runway visual range is the maximum distance at which the runway, or the specified lights or markers delineating it, can be seen from a position above a specified point on its centerline. This value is normally determined by visibility sensors located alongside and higher than the centerline of the runway.</p> <p>- RVR is calculated from visibility, ambient light level, and runway light intensity. It is common practice to use a transmissometer or forward scatter meter as the RVR visibility sensor. A transmissometer measures the transmittance of the atmosphere over a baseline distance while a forward scatter meter measures the extinction coefficient of the atmosphere. RVR is then derived from equations that also account for ambient light (background luminance) and runway light intensity based on the expected detection sensitivity of the pilot's eye.</p> <p>http://www.met.tamu.edu/class/METAR/metar-pg8-RVR.html</p>
SAWS	Stand Alone Weather Sensors	<p>- SAWS is a part of the Aviation Surface Weather Observation Network (ASWON) and will serve as a backup to the Automated Surface Observing System (ASOS) at Service Level-C Air Traffic Control Towers, collocated Terminal Radar Approach Control facilities, and selected Automated Flight Service Stations.</p> <p>- The SAWS sensor suite automatically collects, processes, and broadcasts surface weather data to air traffic controllers. It provides information for wind speed (plus direction and gusts), altimeter setting, temperature, and dew point.</p> <p>SAWS: http://www1.faa.gov/aua/ipt_prod/weather/saws.htm</p> <p>ASWON: http://www1.faa.gov/aua/ipt_prod/weather/txt430a.htm</p> <p>ASOS: http://www2.faa.gov/asos/asosinfo.htm</p>

<p>STARS</p>	<p>Standard Terminal Automation Replacement System</p>	<ul style="list-style-type: none"> - STARS is a joint Federal Aviation Administration (FAA) and Department of Defense (DOD) program to replace Automated Radar Terminal Systems (ARTS) and other capacity-constrained, older technology systems at 172 FAA and up to 199 DOD terminal radar approach control facilities and associated towers. - STARS will be used by controllers to provide air traffic control (ATC) services to aircraft in terminal areas. Typical terminal area ATC services include: the separation and sequencing of air traffic, the provision of traffic alerts and weather advisories, and radar vectoring for departing and arriving traffic. - STARS will accommodate air traffic growth and the introduction of new automation functions which improve the safety and efficiency of the National Airspace System (NAS). <p>http://www2.faa.gov/aua/ipt_prod/terminal/ex-stars.htm</p>
<p>TDWR</p>	<p>Terminal Doppler Weather Radar</p>	<ul style="list-style-type: none"> - TDWR provides timely and accurate detection of hazardous wind shear in and near airport terminal approach and departure corridors. - TDWR operates at C-Band frequencies that are high enough to pick out fine moisture particles in the air. The TDWR sends out a pencil-beam signal that the moisture reflects. The system detects the reflection and measures the Doppler shift (the frequency change that occurs when a signal bounces off a moving particle). The system then calculates the wind speeds and alerts air traffic controllers to sudden, potentially hazardous air currents. - TDWR scans at five-minute intervals in two modes providing a full 360 degree monitoring sweep or a concentrated sector sweep in a hazardous weather region. It provides a one-minute update for initial wind shear information. - TDWR predicts wind shear with more than 90 percent accuracy. <p>http://www.raytheon.com/products/tdwr/</p>

Wind instruments	Terminal wind products	<p>Terminal wind information generated from different sources:</p> <ul style="list-style-type: none"> a) Integrated Terminal Weather System (ITWS) b) Automated Surface Observing System (ASOS) c) Stand Alone Weather Sensors (SAWS) <p>ITWS: http://www.raytheon.com/products/itws/ref_docs/itws.pdf</p> <p>ASOS: http://www2.faa.gov/asos/index.htm</p> <p>SAWS: SAWS: http://www1.faa.gov/aua/ipt_prod/weather/saws.htm</p>
WSP	Weather Systems Processor	<p>- WSP provides low-cost, high quality, wind shear detection equipment at medium air traffic density airports not equipped with Terminal Doppler Weather Radar (TDWR).</p> <p>http://www.tc.faa.gov/its/cmd/visitors/data/ACT-300/wsp.pdf</p>