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1 INTRODUCTION

This report discusses the information requirements in the traffic management units (TMUs) of an air route traffic control center (ARTCC). The decision makers in the TMU are traffic management coordinators (TMCs). There are typically three or more TMCs on duty in the TMU around the clock.

The TMC does not fit the layperson's image of an air traffic controller. That image - a controller monitoring aircraft on radar displays and actively controlling those aircraft by issuing cryptic instructions over two-way radios - is a simplified but not incorrect depiction of the sector controller. The sector controller's responsibility is to keep aircraft separated as they traverse a given volume of airspace. In contrast, the TMC does not communicate with or actively control aircraft. The TMC is responsible for ensuring that the flow of air traffic is such that the sector controllers have a fighting chance of keeping aircraft separated.

This study had four objectives: (1) to ascertain the nature of TMC positions and responsibilities, (2) to develop an explanatory account of TMC decision making and action, (3) to specify the information requirements for TMC decision making, and (4) to identify opportunities for FAA action to support TMC decision making with special emphasis on human factors research and technology development.

There are three findings:

(1) The TMC has one and only one responsibility – to manage sector controllers' workload.

(2) There are four TMC positions : the flow position (also called the en-route spacing position), the metering position, the severe weather position, and the traffic management coordinator in charge (TMCIC). TMCs often rotate through all four positions. Every activity at all four TMC positions supports the overarching goal of ensuring that the workload experienced by sector controllers remains within acceptable limits.

(3) There are four classes of information requirements. TMCs need timely access to reliable information about:

- traffic intent,
- sector load,
- air traffic control system command center (ATCSCC) advisories and restrictions on traffic flow, and

- weather.

At all four positions, the TMC needs timely access to reliable information about all four classes of information. The report details human factors issues - sources, uses, and displays of information - relevant to the four classes of information requirements.

The first finding came as something of a surprise given the variety of TMC decision-making 'jobs' enumerated by Yee et al. (1995). The 'jobs' listed by Yee describe observable activities at the four TMU positions. The activities range from crafting a traffic restriction with the assistance of ATCSCC to issuing departure slots for individual aircraft.

1.1 Decision making in the air route traffic control center (ARTCC)

This section provides an overview of decision making in an ARTCC. The overview and the accompanying diagram, Figure 1 (shown on page 3), form the framework for the detailed analysis of TMC decision making that follows.

ARTCCs are FAA facilities that provide the service of managing en-route air traffic and keeping aircraft separated. Two groups of skilled decision makers work together to accomplish this task: sector controllers and TMCs. The sector controller's task is to respond to traffic within a fixed volume of airspace and, when necessary, to issue instructions designed to keep aircraft separated. In contrast, the TMC's task is to anticipate the flow of traffic in order to manage the sector controller's workload. The anticipatory nature of TMC decision making characterizes a class of decision tasks known as 'feedforward control' (Edwards and Lees, 1974; Smith, 1996; Woods, O'Brien, and Hanes, 1987).

Figure 1 illustrates this division of labor and the two characteristic sequences of action and decision making. The rectangles represent actions and decisions. The solid lines represent the flow of information within the ARTCC. The dashed lines represent the flow of information to those outside the ARTCC who are affected by the TMCs' and controllers' decisions, e.g., aircraft, users (airlines), and other FAA facilities. The cycles of information flow and action shown in Figure 1 provide a framework for systematic investigation and disciplined description of TMC and controller decision making. In addition, the framework minimizes the likelihood of overlooking an information requirement or a critical source or use of information.

To manage controller workload, the TMC continuously cycles through the sequence of actions and decisions shown on the left side of Figure 1:

- monitoring displays and other sources of information,
- anticipating changes in the level of traffic that might provoke a surge in controller workload,
- collaborating with ATCSCC and other ARTCCs to issue and coordinate programs or restrictions on traffic flow designed to smooth the flow of traffic and dampen surges in workload, and

- informing sector controllers (via their area supervisors) about those programs or restrictions.

The TMC monitors displays that show the flow of traffic, and the current and forecast weather. To anticipate changes in traffic flow, the TMC compares those data to acceptable limits for sector capacity. The comparison enables the TMC to anticipate change in the current flow of traffic and the impact the changing flow will have on the

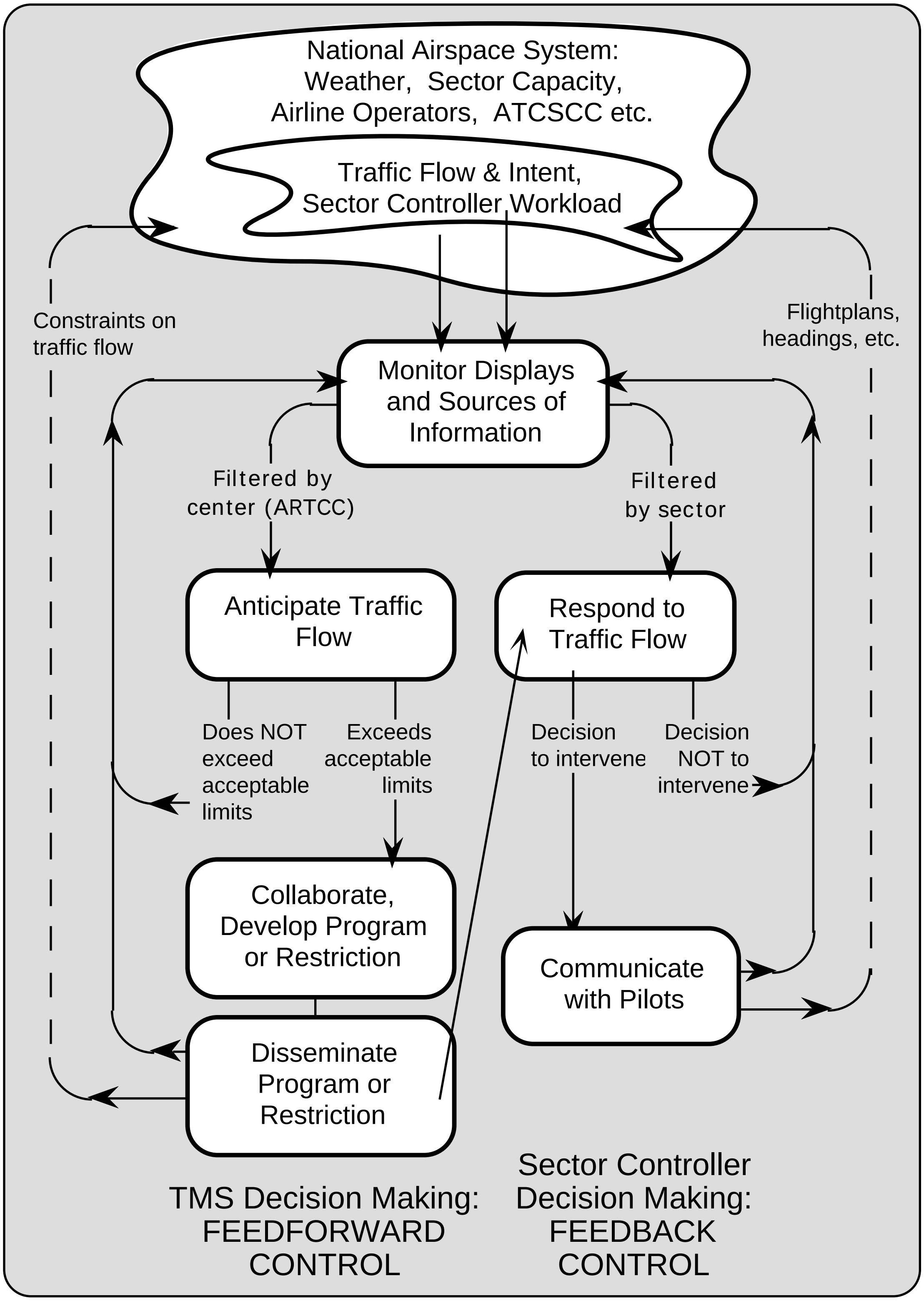

Figure 1. The cycles of decision making and action by traffic management coordinators (TMCs) and sector controllers (modified from Smith, 1996).

demand for sectors and on sector controller workload. If the anticipated change appears unacceptable, the TMC takes action by engaging in collaborative decision making[1].

The collaboration begins when a TMC communicates (shares the expectation of) the impending unacceptable level of sector demand and controller workload with FAA personnel at other FAA facilities. Depending on the situation, these personnel may be stationed at the system command center, adjacent centers, and/or approach control (terminal radar approach control, TRACON)[2]. Together, the TMC and the other FAA personnel are in a position to rectify the situation. The group then plans and agrees upon a 'program' or 'restriction' on traffic flow. Programs and restrictions impose constraints on traffic flow (e.g., all aircraft must be separated by at least 20 nautical miles when crossing the center boundary). These constraints are enabling constraints: they smooth the flow of traffic and/or make it more predictable. Smoother, more predictable traffic reduces sector controller workload. The TMC's enabling constraints provide structure to the sector controller's task and reduce controller workload.

In the final step of a full cycle of feedforward control, the TMC disseminates information about programs and restrictions on traffic flow to 'area supervisors' who, in turn, share the information with sector controllers. An area supervisor is the line supervisor of controllers working a block of geometrically contiguous sectors called an 'area.' Sectors within an area are typically linked by patterns of traffic flow.

To keep aircraft separated, the sector controller continuously cycles through the sequence of actions and decisions shown on the right side of Figure 1:

- monitoring a display showing the locations and vectors of traffic,
- responding to those data with decisions designed to keep aircraft separated, and
- communicating those decisions to pilots.

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[1] This report broadly construes the phrase 'collaborative decision making' (CDM) to include any and all types of supportive interaction of decision makers pursuing a mutual goal. This definition subsumes the more focused definition of CDM that has been adopted by many decision makers in the FAA and aviation industry. That focus has been upon flight scheduling and routing and on the joint development of a new decision-aiding tool called the flight schedule monitor (FSM). To repeat, references to CDM in this report should be understood to mean cooperation by decision makers with a common purpose.

[2] TRACON is the FAA facility where controllers manage aircraft departing from or arriving at a major airport. The volume of airspace managed by approach controllers is much smaller than that managed by an ARTCC. The aircraft are also closer together and are generally closer to the ground.

The real-time imperative of the controller's response to information characterizes the class of decision tasks known as 'feedback control.' The lay image of the sector controller captures the essential characteristics of feedback control at an ARTCC.

The TMC participates in feedback control by creating and communicating programs and restrictions on traffic flow. The diagonal arrow in Figure 1 represents the indirect and enabling influence of feedforward control on feedback control.

1.2 Overview of TMC information requirements

The TMC monitors four classes of information: weather, traffic intent, sector capacity, and programs and restrictions on traffic flow. Weather is the major source of uncertainty in aviation. Access to reliable weather forecasts dampens this uncertainty. Incomplete or inaccurate information about traffic intent is the second major source of uncertainty for the TMC. Conversely, knowledge of traffic intent makes it possible for the TMC to anticipate how the flow of traffic will evolve and to generate an expectation of where it will be. The TMC melds information about sector capacity with expectations for the flow of traffic to infer when and where sector controller workload will exceed acceptable limits. Information about programs and restrictions on traffic flow provides the framework within which decisions can be made and actions taken.

1.3 Overview of recommendations

The study identified five opportunities for FAA action directed at meeting the four TMU information requirements. The first four are opportunities for human factors research and development. The fifth is an opportunity to continue to do the right thing.

(1) Develop a protocol for dialog and collaboration between centers and the airlines .

(2) Design and develop an automated communications link between the airline operations centers (AOCs) and the FAA's 'host computer' database.

(3) Support research directed at developing a meaningful metric of sector capacity.

(4) Upgrade the monitor alert function (MAF) of the aircraft situation display (ASD[3]) of the enhanced traffic management system (ETMS).

(5) Maintain the status quo at the Center Weather Service Unit (CWSU), that is, continue to collaborate with the National Weather Service (NWS) and the National

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[3] The ASD has been upgraded since the original release of this report. The new tool is the TSD, traffic situation display.

Oceanographic and Atmospheric Administration (NOAA) and continue to support research and development of meteorological tools for CWSU personnel.

The study also developed recommendations for how the FAA might address these opportunities.

1.4 Organization of the report

The next section of the report describes the positions in the TMU and explains the cycles of TMC decision making and action. The third section makes the brief argument that the TMC has one and only one responsibility – managing sector controller workload. The fourth section details the information requirements and the uses, sources, and displays of information that the TMC monitors. The fifth section reviews the process control cycle (Figure 1, Smith, 1996; 1998) and argues that it provides an explanatory, theoretic framework for understanding TMC and sector controller decision making. The final section summarizes the recommendations for FAA action with emphasis on opportunities for human factors research and development. The glossary defines key terms and acronyms.

1.5 Acknowledgments

This report is based upon more than 160 hours of observation at the Minneapolis and Kansas City centers (ZMP, ZKC). The study was made possible by the voluntary cooperation of many TMU and CWSU personnel at ZMP and ZKC and by the staff of the System Operations Center of Northwest Airlines (NWA). They shall all remain anonymous. The study builds upon the job definitions of Yee et al. (1995). The study was commissioned by the Office of the Chief Scientific and Technical Advisor for Human Factors, AAR-100, of the Federal Aviation Administration. Dr. Thomas McCloy was the technical monitor. The authors thanks Dr. McCloy and Mr. Dino Piccione for their valuable comments on drafts of the manuscript. The opinions are the author's and should not be construed as positions taken by the FAA, NWA or by any of their employees.

2 TMC Positions

This section describes the decision-making positions within the TMU. There are four distinct TMC positions - flow, metering, severe weather, and TMCIC. The information technology that supports each position occupies a separate location within the TMU. TMCs generally rotate through all four TMC positions.

The two main TMC positions are called 'flow' and 'metering'. There are often more than one flow and metering position within a TMU. The flow position anticipates and coordinates all intracenter and intercenter flows of traffic. The metering position anticipates and coordinates traffic in the transition between center airspace and approach control airspace[4]. The exercise of feedforward control at the flow and metering positions involves considerable collaborative decision making with approach control, adjacent centers, and ATCSCC.

The severe weather avoidance program (SWAP) position is staffed only when weather near a major airport forces the TMU to revise flightplans for departing aircraft.

The TMCIC oversees all TMU activity and communicates with ATCSCC and TMCICs at other ARTCCs. The four TMU positions are discussed in turn.

2.1 The flow position

The goal of the flow position is to manage the flow of traffic through center airspace. The TMC at the flow position exercises feedforward control by anticipating and coordinating intracenter and intercenter flows of traffic. There is often more than one flow position within a TMU.

2.1.1 Uses of information

As shown on the left side of Figure 1, the decisions and actions associated with feedforward control at the flow position are:

- monitoring information displays that show the locations and vectors of aircraft and weather,
- anticipating when and where the flow of traffic is likely to generate unacceptable levels of controller workload,
- collaborating with FAA personnel at other sites (e.g., system command center and other facilities) to develop plans (programs and restrictions on traffic flow) that will distribute the anticipated workload, and
- disseminating the plan to area supervisors and sector controllers.

All four of these decisions and actions operate on a dynamic representation of traffic flow. The first step, monitoring, samples data that are used to update the representation. The second step, anticipating, projects the representation into the near future to infer the future locations of aircraft and their impact on sector controller workload. The third and fourth steps, collaborating and disseminating, share the representation with others. The focus of collaborative decision making at the flow position is suggesting and adopting a plan of action (typically a program or

[4] Approach control airspace is managed by controllers at a TRACON. Each TRACON is responsible for traffic landing at and departing from a major airport.

restriction) designed to revise how the flow of traffic (and its representation) evolves.

The TMC at the flow position maintains and continuously updates a representation of dynamic traffic by monitoring radar displays and other sources of information. The displays are set to show aircraft selectively within or approaching center airspace. The short cycle of monitoring and anticipating is the *modus operandi* in the flow position. It is shown in Figure 1 as a return cycle from ‘anticipate traffic flow does NOT exceed acceptable limits’ to ‘monitor displays and sources of information.’

To anticipate differential levels of traffic flow, the TMC projects the representation into the future and compares the expected flow to a set of standardized metrics for sector capacity. (Much will be said about the metrics in the discussions of information requirements and recommendations). Whenever the anticipated flow of traffic appears likely to exceed the value of the metric assigned to a sector, the behavior of the TMC at the flow position takes a dramatic turn. The TMC shifts from monitoring traffic displays and anticipating traffic flow to communicating and collaborating with others to develop plans for redistributing that flow. This collaboration takes full advantage of the ASD . For example, at both ZMP and ZKC, the TMC often creates a map-view display of the current locations of aircraft that are scheduled to land at Chicago’s O’Hare airport (ORD). Aircraft depicted in this representation are linked by destination and shared flightplans. The representation includes the callsigns of aircraft in the group, their common destination, and any relevant restriction information.

There are four types of plans for distributing traffic flow and the associated workload across sector controllers. The plans seen most often at ZMP and ZKC are (a) restrictions or (b) programs for streams of traffic crossing center boundaries. A typical restriction places a lower bound (e.g., 20 nautical miles) on the separation between aircraft following a common flightplan. A typical program delays arrivals into an airport, prevents departures to that airport, or closes the airport entirely. When weather is particularly troublesome, the plan may (c) reroute (revise the flightplans) streams of aircraft or (d) shift entire tiers of aircraft across parallel jetways.

Programs and restrictions on traffic flow redistribute traffic across sectors (and centers) for a specific period of time. Traffic in those sectors during that time must conform to specified constraints, e.g., all must be separated by at least 20 nautical miles when they cross the sector boundary. The constraints are designed to make the flow of traffic more predictable and/or less dense. In addition, the constraints impose structure on the sector controller’s task of keeping aircraft separated. By increasing predictability, reducing density, and providing structure, programs and restrictions reduce sector controller workload. Programs and restrictions are ‘enabling constraints’ – they make it easier for sector controllers to do their job. The TMC at the flow position completes the full cycle of feedforward control by disseminating the enabling constraints to the area supervisors who, in turn, share them with sector controllers.

The TMC at the flow position influences feedback control by developing and disseminating programs and restrictions on traffic flow that the sector controllers must implement. The diagonal arrow in Figure 1 represents the indirect and enabling influence of the TMC's feedforward control on the sector controllers' feedback control. As shown on the right side of Figure 1, the sector controller exercises feedback control. Each controller actively monitors, responds to, and engages aircraft in a sector of airspace.

To summarize, the TMC at the flow position exercises feedforward control by anticipating changes in the flow of traffic and by developing programs and restrictions. Programs and restrictions on traffic flow are designed to distribute the anticipated traffic and workload across sectors (and centers) and to make it easier for sector controllers to keep traffic separated.

2.1.2 Sources of information

To exercise feedforward control, the TMC at the flow position monitors at least one ASD window and a plan view display (PVD[5]) of 'live' radar returns, uses the telephone, and consults the CWSU.

ETMS, ASD

In the flow position, the TMC actively monitors one or more ASD windows. The ASD is part of the enhanced traffic management system (ETMS). The ETMS is the FAA's computer system for tracking and predicting the flow of air traffic. The ETMS taps both the database in the FAA's 'host computer' and a composite radar image of the locations of aircraft aloft. The composite radar image posts the last-reported locations of aircraft by synthesizing data derived from multiple radar sources. The 'host' database integrates aircraft transponder data with the most recent flightplan data. Prior to departure, the flightplan data are the scheduled departure (and arrival) times posted in the Official Airline Guide (OAG). Once an aircraft is aloft, the flightplan data in the host computer reflect the actual departure time and any changes to the flightplan made by sector controllers or airline dispatchers.

The ETMS is supported by UNIX-based software capable of generating multiple, independent 'windows' on a computer monitor. Each ASD window presents a map-view image of the last-reported locations of selected aircraft. At the flow position, the field of view in each window generally extends beyond the center boundaries several hundred miles into adjacent centers' airspace. The selection of aircraft can be programmed or 'filtered' by the TMC to highlight groups of aircraft with a common set of characteristics.

The map-view display of ORD landers provides insight into the principles that structure the representations developed at the flow position. These

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[5] The PVD has been upgraded since the original release of this report. The new screen is part of the DSR, display system replacement.

representations cluster aircraft by destination, flightplan, or restriction. Clustering aircraft reduces the complexity of feedforward control by (1) helping the TMC anticipate the evolution of changing levels of traffic and workload across sectors and time and (2) guiding the development of plans that redistribute traffic and workload.

The number and composition of ASD windows is largely a function of TMC preference and the demands of the day. Typically, one window at the flow position highlights all overflights through center airspace with superimposed weather data[6]. A second window is usually the monitor alert (MA) function. (The MA is discussed in detail in section 4.2). If more than two windows are shown, a third may highlight aircraft with flightplans filed as part the National Route Program (NRP)[7]. Yet another window may highlight aircraft flying at or above 37,000 feet. The possibilities for information shown in ASD windows are constrained only by an individual's command of the ETMS UNIX-based scripting language and its line editor.

The flexibility of the ASD allows the TMC at the flow position to generate maps that show several different groups of aircraft simultaneously. These maps are explicit representations that greatly facilitate (a) the communication of critical information during shift changes and times of high workload and (b) the collaboration required to formulate programs and restrictions on traffic flow. The ASD maps reduce the workload associated with feedforward control by transforming what would otherwise have to be an implicit (mental) representation into an explicit (visual) representation.

PVD

The TMC at the flow position also monitors a PVD. A PVD is a large circular, monochrome, composite-radar display that was introduced in the 1970's and has enjoyed a series of software upgrades. The software that drives the PVD integrates live composite radar and transponder data with flightplan information from the FAA's host computer. The radar data are updated every 6 to 10 seconds. This relatively rapid update rate makes the PVD the most reliable source of information about the likely locations of aircraft. The field of view on the PVD at the flow position generally extends a short distance beyond the center boundaries into adjacent centers' airspace.

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[6] During the convective weather season (spring and early summer), the weather data are usually Nexrad echo-top imagery. Nexrad is the National Weather Services' ground-based weather radar system. An echo-top image is a mosaic of color-coded squares 2 or 4 km on a side. The color coding indicates the highest altitude of coherent radar returns (echoes) in each square of the mosaic. Echo-top imagery shows where the clouds are and how high they are. The higher the cloud, the more severe the weather.

[7] NRP allows airlines to file non-traditional flightplans for selected flights. Traditionally, flightplans are lists of waypoints (intersections, places to check in) along a controller-<u>pref</u>erred route. Under NRP, a flightplan can deviate from the 'pref.' route.

The TMC at the flow position occasionally uses the PVD to echo a sector controller's PVD. In this mode, the TMC has no control over PVD settings. The echo mode is used primarily to ascertain the cause of a conflict alert or to assess the demand on a sector and the controller's workload.

Telephone

The TMC at the flow position uses the telephone to communicate with colleagues at the system command center and adjacent centers. The telephone is the medium for their collaborative decision making. The FAA's procedures make the command center the intermediary in all intercenter conversations. On rare occasions, the TMC working the flow position may call the TMU at an adjacent center directly, without routing the call through the command center. These calls typically address individual aircraft rather than streams of aircraft.

CWSU

The CWSU is a source of information for the entire center. The CWSU generates a portfolio of ASD displays specifically designed to meet the center's need for reliable and timely information about weather. For example, some of the displays span the United States to show the location of the jet stream and the altitudes and regions where icing is likely to occur. Other displays focus on the center's airspace showing the likelihoods of precipitation and the direction of storms. Still other displays make point predictions for weather at airports. The CWSU updates these displays at least three times a day and holds regular briefings attended by the TMC at the flow position, the TMU supervisor, and area supervisors.

In sum, the flow position monitors the ASD and the PVD, and uses the telephone to meet requirements for information about weather, traffic flow, restrictions on traffic flow, and sector controller workload.

2.2 The metering position

As aircraft descend in preparation for landing at a major airport, their velocities decrease and their paths converge. The points where arrivals converge are called 'corner posts.' There are usually four corner posts arranged in a square pattern centered on the airport. There is always one and there are often two 'arrival fixes' at each corner post. Every flightplan specifies an arrival fix. An arrival fix assigns an aircraft an altitude over given surface location. Corner posts and arrival fixes impose structure on the flow of arrivals and define the boundary between airspace controlled by sector controllers at the center and airspace controlled by controllers at approach control (TRACON).

The goal of the metering position is to coordinate the transition between center airspace and approach control airspace for streams of arrivals into major airports (e.g., MSP in ZMP, and STL in ZKC). The TMC at the metering position exercises feedforward control by anticipating the need for and coordinating plans for streams of arrivals. There is often more than one metering position within a TMU.

2.2.1 Uses of information

The sequence of decisions and actions at the metering position are the same as they are at the flow position. They too are shown on the left side of Figure 1. The TMC at the metering position monitors a map-view display on the PVD showing aircraft in the area containing the airspace managed by TRACON controllers. The purpose of monitoring this area is to maintain and update a dynamic representation of the flow of arrivals. At the monitoring position, the representation is made explicit at all times; that is, the representation is the PVD display.

The TMC uses the representation to anticipate and prepare for periods of high demand for an arrival fix. When the flow of arrivals does not exceed acceptable limits, the TMC cycles between monitoring and anticipating, taking the shorter loop for feedforward control. In contrast, when the demand is expected to exceed the capacity of the fix or the airport, the behavior of the TMC shifts to the longer feedforward cycle of monitoring, anticipating, collaborating, and disseminating.

The goal of collaborative decision making at the metering position is to develop plans to redistribute the arrival streams and the demand for arrival fixes. The decision to be made is whether the demand can be diminished internally (within the center) or whether external (system-wide) actions will be required. Internal options include ‘metering’ and ‘fix balancing.’ Metering, from which the position takes its name, assigns a time at a fix to every aircraft in the stream of arrivals. Metering specifies a series of precise constraints on the flow of arrivals and on the hand-off to the controllers at the TRACON. Fix balancing consists of rerouting specific aircraft from a busy arrival fix to a less busy fix. Rerouting shifts a portion of the burden of managing arrivals from one sector controller to another.

Collaboration to determine internal options takes full advantage of available information technology. The TMC’s partner in the collaborative process is a customized decision tool called the ‘delay manager program.’ The delay manager program is software that assigns a time at a fix to every aircraft and calculates the delays the aircraft will incur. The TMC interacts with the software by setting the parameters that govern the time-at-a-fix algorithm used by the delay manager program. The parameters include the interval between consecutive times-at-a-fix and the duration of the metering program. The TMC can override assignments of time-at-a-fix via fix balancing. The TMC then disseminates to low-altitude sector controllers the delays calculated by the delay manager program and any reroutes for fix balancing. The sector controllers, in turn, have the task of exercising feedback control by issuing commands that vector aircraft so that they reach their assigned fixes at their assigned times.

When the flow of arrivals cannot be accommodated internally due to weather or some other limitation on arrival capacity, the TMC contacts the system command center and adjacent centers. The TMC’s discussion with these human partners focuses on four elements:

- the representation of the streams of arrivals,

- the expected demand for arrival fixes,
- the capacity of the fixes and airport to accommodate that demand, and
- sources of constraint on that capacity.

The most common constraints on fix and airport capacity are current and forecast weather at the airport and in the vicinity of the approach paths. Less common are congestion at the gates and airport maintenance (e.g. runway repair, snow removal). The goal of the discussion is to develop system-wide plans that will redistribute arrivals and the demand for fixes. Options include airborne ‘holding,’ ‘ground-delay programs,’ and ‘ground-stop programs.’ Holding requires aircraft to join a holding pattern, that is, to follow a race-track pattern at an assigned altitude over a specified radio navigation aid. Holding reduces the aircraft’s net forward velocity to zero, relieving some of the demand for a fix and shifting a portion of the burden for managing arrivals from TRACON and low-altitude sector controllers to high-altitude sector controllers. Laterally extensive holding patterns can shift a portion of the burden to adjacent centers.

Ground-delay programs reduce the arrival rate into the airport by increasing the interval between departure times. This spreading of departures is implemented by issuing all aircraft an ‘estimated departure clearance time’ (EDCT) and a ‘controlled time of arrival’ (CTA). These constraints reduce arrival rates at the airport for a fixed period of time to alleviate anticipated congestion.

Ground-stop programs are more severe than ground-delay programs. They hold all flights on the ground until further notice. No EDCTs or CTAs are issued. Ground stops reduce arrival rates to zero for an indefinite period of time. Both ground-delay and ground-stops programs can significantly disrupt airline schedules and operations.

The TMC at the metering position does not issue the commands to join a holding pattern or to remain on the ground. The TMC communicates the need for holding patterns or programs to personnel at the system command center who, in turn, disseminate the information to the relevant FAA facilities and the airlines.

To summarize, the TMC working the metering position exercises feedforward control by anticipating periods of high demand for arrival fixes and by developing programs and restrictions designed to distribute the anticipated workload across sectors and centers.

2.2.2 Sources of information

Sources of information at the metering position are the PVD, the delay manager program, the ASD, the CWSU, and the telephone.

PVD

In the metering position, the TMC actively monitors a PVD showing a map view of the area containing the airspace managed by TRACON controllers in order to maintain and update a dynamic representation of the flow of arrivals. The display shows the locations of aircraft, arrival fixes, runways, and the boundary between center airspace and approach control airspace. The PVD display is the TMC's representation of arrivals. The TMC uses the PVD representation to anticipate and prepare for periods of high demand for arrival fixes. When demand is likely to be high, the TMC generally superimposes the list generated by the delay manager program on the map-view display of arrivals.

Delay manager program

The delay manager program is software that assigns aircraft to time-slots at arrival fixes and calculates the delays the aircraft will incur. To anticipate periods of high demand, the TMC pays attention to the list of calculated delay times. These delays are passed to low-altitude sector controllers who have the task of vectoring aircraft to reach their assigned fixes at their assigned times.

ASD, CWSU

Weather is generally the major constraint on the capacity of an arrival fix and an entire airport. The primary sources of weather data are the Nexrad images on the ASD and the customized ASD displays and airport forecasts made by the CWSU. The TMC at the metering position monitors the ASD and CWSU forecasts to anticipate the need to collaborate with the command center and other FAA facilities and to initiate a program.

The metering position does not use the ASD to monitor traffic because the update rate to the ETMS from the FAA's host computer is too slow (once every 2 to 6 minutes) to provide a sufficiently precise image of the locations of aircraft in the arrival stream. The metering position relies on the PVD.

Telephone

The telephone is the medium for collaborative decision making at the metering position. Decision makers involved in these conversations ('Telcons') include FAA personnel at the command center, at approach control, and at the airport tower, and the chief dispatchers of airlines that use the airport as a hub (e.g., NWA at MSP and TWA at STL). Topics range from particular aircraft and flightplans (e.g., pilots who refuse a particular runway) to options for ground-delay programs.

2.3 The SWAP position

A TMC works the severe weather avoidance program (SWAP) position only when weather threatens a major airport within center airspace (e.g., MSP in ZMP and STL in ZKC). The task at the SWAP position is to assign flightplans to aircraft departing from an airport threatened by weather and to distribute flightplans across sectors. Fightplans are constraints on when and where an aircraft is expected to be. Once a flightplan is assigned, the FAA's host computer disseminates the plan to the airlines and to the centers and sector controllers who will manage the flight.

The computer-aided distribution of information completes the link between feedforward and feedback control shown by the dashed line in Figure 1.

The source of information at the SWAP position is a PVD showing a map view of the area containing the airspace managed by TRACON controllers. The TMC uses the map to maintain and update a dynamic representation of the flow of departures. The representation takes into account the geometry of departure fixes, the locations of storm cells, the demand for departure sectors, and destinations. To assign a flightplan, the TMU uses a system of codes. Each code is a short alphanumeric string that represents an entire controller-preferred route from the departure runway to the arrival fix. The shorthand enables the TMC to focus on the changing weather and the changing demand for sectors rather than on typing the entire flightplan.

2.4 The TMCIC, traffic management coordinator in charge

The TMCIC wears many hats. It is the TMCIC who typically communicates the need for and develops programs or restrictions with ATCSCC and other ARTCCs. The TMCIC frequently assists the flow and metering positions . During busy times, the TMCIC may take a walkie-talkie to the control room floor to act as a liaison between the TMU and the area supervisors.

A TMCIC takes a walkie-talkie to the control room floor to expedite the dissemination of constraints from the TMU to the area supervisors and sector controllers. The constraints range from newly issued programs and restrictions on traffic flow to impending changes in traffic flow to the anticipated duration of heavy traffic. This information allows the area supervisors to assign staff to sectors and lets the sector controllers know what to expect. The supervisor with a walkie-talkie forms the link between feedforward and feedback control shown by the diagonal line in Figure 1.

In addition, a TMCIC on the floor relays information from area supervisors back to the TMU about the distribution of workload across sectors and areas and the feasibility of meeting restriction criteria. In sum, the role of the TMCIC on the floor is to help the area supervisors and sector controllers anticipate traffic flows.

3 WORKLOAD MANAGEMENT - THE ONE RESPONSIBILITY

This section makes the brief argument that the TMC has one and only one responsibility: the management of sector controller workload. Given Yee's extensive enumeration of TMC jobs, this claim may appear to oversimplify what the TMC does. However, Yee does not address <u>why</u> the jobs appear in the list. The argument first summarizes the TMC positions that subsume Yee's list of jobs. It then identifies the common purpose for the actions the TMC takes.

The flow position anticipates and develops programs and restrictions for the flow of intracenter and intercenter traffic. The metering position anticipates and develops programs and restrictions for streams of landing traffic. The SWAP position develops flightplans for streams of departures. The TMCIC disseminates these plans.

The plans developed by the TMC impose constraints on the flow of traffic that redistribute traffic across sectors (and centers) for specific (or indefinite) periods of time. Traffic in those sectors during that time must conform to specified criteria. As a result, traffic flow becomes more predictable and/or less dense.

Increased predictability and decreased density reduce workload. Sector controllers find heavy traffic difficult to manage. They uniformly detest surprises in the flow of traffic. When traffic adheres to their expectations, they find it much easier to ensure that traffic remains separated. By increasing predictability and/or decreasing traffic density, the TMC who develops and disseminates programs and restrictions reduces sector controller workload. Stated more generally, the products of feedforward control are enabling constraints that facilitate feedback control.

All TMC actions are directed at the goal of managing sector controller workload. Achieving that goal is the TMC's sole responsibility.

4 INFORMATION REQUIREMENTS: USES, SOURCES, DISPLAYS, & RECOMMENDATIONS

The preceding review of TMC positions indicates the TMC needs immediate access to accurate data about four classes of information:

- traffic intent,
- sector capacity,
- programs and restrictions on traffic flow, and
- weather.

Table 1 lists the information requirements and the current sources and displays of relevant data, and summarizes opportunities for FAA action directed at meeting those requirements. In the discussion that follows, a happy face ☺ indicates consensus among the collaborators in this study that current technology largely meets the information requirement. A scowl 😐 indicates consensus that current technology could and should be upgraded. A sad face ☹ indicates current technology does not begin to address the information requirement.

4.1 Traffic Intent ☹

4.1.1 Information requirement and uses

Traffic intent data indicate when and where an aircraft plans to be. The flightplan is a promissory note of traffic intent. Traffic information displays reveal actual, exercised traffic intent. Displays of revealed traffic intent present the basic data used by the TMC to exercise feedforward control. The TMC monitors traffic information displays to anticipate trends in the density of traffic, to plan the flow of traffic, and to infer changes in the demand for a sector or arrival fix.

Similarly, the sector controller uses traffic intent data to exercise feedback control. The host computer summarizes a flightplan on a paper strip that presents traffic intent data in a standardized format. These strips are the sector controller's source of expectations about the flow of traffic. Controllers compare traffic intent data to 'live' radar returns and to the constraints on traffic flow to ascertain when and how to intervene to keep traffic separated.

4.1.2 Information sources and displays

There are four sources of traffic intent information at the TMU: (1) the FAA's host computer's database of flightplans, (2) 'live' radar returns that reveal the current locations of aircraft, (3) ASD windows that integrate the expected locations, altitudes, and vectors of aircraft, and (4) direct TMU-AOC communication. The four sources and displays are discussed in turn.

ETMS - FAA host-computer database

Feedforward control is only as good as the data that inform it. Anticipating traffic flow requires data that are upgraded as soon as flightplans are filed and whenever they are changed. The resounding perception at the TMUs visited during this study is that current ETMS technology does not meet this information requirement.

Table 1 - Information requirements at the TMU, current sources and displays of information, and recommendations for research and action.

Requirement	Data source	Display	Recommendations for human factors research and development
Traffic Intent			
Database of flightplans	ETMS		Sponsor a joint industry/FAA initiative for the automated transfer of flightplan and program data: upgrade the host database.
Current aircraft locations	ETMS; radar returns	ASD, PVD	Increase the bandwidth and connectivity of ETMS transmission; upgrade the host database prior to departure.
Protocol for TMU/AOC/ATCSCC collaboration	Telephone		Develop a protocol for TMU-AOC-ATCSCC dialog and collaborative decision making.
Sector Capacity			
Meaningful metric of sector capacity	Arbitrary count	Monitor alert function (MAF) of the ETMS	Support research to identify the factors that determine sector controller workload and to develop a meaningful metric of sector capacity.
Forecast of density	ETMS	ASD	Retool the monitor alert system to access the improved database and the metric of sector capacity and to forecast traffic demand and capacity overload in real time.
Restrictions on traffic flow			
System-wide distribution and documentation	Telephone		Sponsor a joint industry/FAA initiative for the automated transfer of flightplan and program data: upgrade the host database.
			Recommended action
Weather			
Current	ETMS/ASD	Several, typically Nexrad composite radar	Maintain National Weather Service (NWS) personnel in the CWSU and the collaborative relationship with the NWS.
Forecast	CWSU	CWSU-generated computer graphics	

The ETMS is tied into the FAA's 'host' computer. The host has the latest flightplan data once a flight is airborne. The data reflect updates made by the airlines and by sector controllers. The perceived shortcoming of the ETMS focuses upon the lack of updates prior to departure. Before a flight becomes airborne, the host relies upon data in the Official Airline Guide (OAG). The OAG is a schedule of departure and arrival times that is published months in advance. It is a marketing tool, not an operational tool. The data in the OAG are invariably inaccurate whenever traffic is delayed. Accordingly, prior to departure, the data in the host computer are often inaccurate. Many TMCs view this inaccuracy as a flaw in the ETMS rather than an issue for database management.

PVD

The requirement for access to data about the current locations of aircraft is well met by the technology and software behind the PVD. Improvements could be made but the PVD is not the weak link in the system.

ASD

The locations of traffic shown on the ASD are rarely precise. The lack of precision is due to a delay in data delivery by the national feed from the FAA's data distribution hub (at the Volpe National Transportation Systems Center). The data themselves are transponder data and composite radar returns that are highly accurate at the time of that return. Unfortunately, the delay in data delivery can be as long as 6 minutes. As a result, the ASD shows where aircraft were, not where they are. At the flow position, the delay is rarely problematic due to the relatively long time horizons in the planning of intracenter and intercenter traffic flow. However, the delay precludes using the ASD at the metering position.

TMU-AOC communication

The TMC, whether at the flow, metering or SWAP position, needs to know about changes in airline (AOC) planning as soon as plans change. The FAA's host computer keeps track of changes flight-by-flight but does not convey the full spectrum of changes or their ramifications in a glance or a word. What the TMC needs is an open, flexible mechanism for the timely, impromptu exchange of information with the AOC. The TMUs and the AOCs would both benefit from a protocol for direct dialog.

4.1.3 Recommendations

To review, the quality of traffic intent data is uneven in spite of their importance to both the TMC and the sector controller. Specifically, the FAA's host-computer database may not be current prior to departure. Exacerbating this problem is the lack of a formalized TMU-AOC communication link that could be consulted to ascertain the accuracy of the host data. Another shortcoming is the slow update rate of host-computer data to the ETMS and the ASD. Three steps should be taken to remedy this situation: (1) upgrade the link between the airlines and the host-computer database to provide earlier and up-to-date information on flightplans prior to departure, (2) develop a protocol for impromptu TMU-AOC dialog, and (3) increase the rate at which the ETMS distributes traffic intent data.

Upgrade pre-departure data in the FAA’s host-computer database

Every position in the TMU needs access to a dynamic database of as-filed flightplans that is updated as soon as they are filed and whenever filings change. Such a database would accurately reflect plans for all aircraft, including those on NRP routes, both prior to and after departure. Currently, the host computer relies on a marketing tool, the OAG, for flight data prior to departure. Reliance on the OAG is viewed by many TMCs as a flaw in the ETMS.

Ascertaining the locus of the perceived flaw was beyond the scope of this study. There are at least two likely loci. Both may be implicated. The first is the airlines operations centers. The AOCs may not be delivering up-to-date flightplan information to the FAA. The second is the FAA’s host computer and information distribution network. The requisite data may not be getting into the host computer or sent out to the TMUs and the sector controllers in a timely manner.

Regardless of the locus of the hiatus in information flow, what is needed are automated uplinks between the FAA and all AOCs. The linkages would require sophisticated, but off-the-shelf, telecommunications technology. Current policy would probably route the linkages through the system command center. Whatever the route, such a system could be used to speed communication in both directions. TMUs (and the entire air traffic control system) would learn of changing flightplans in a much more timely fashion. Dispatchers at AOCs could be alerted to evolving constraints on airports, sectors, and centers. A joint industry/FAA initiative should support research and development efforts that address this information requirement.

Develop a protocol for TMU-AOC communication and collaboration

Every position at the TMU would be more able to anticipate and plan for patterns and changes in traffic flow if it were to have access to an established protocol for dialog with the airlines whenever the communication was needed. For example, during the season of convective weather, collaborative discussions would often focus on the prognosis for the weather two to six hours ahead. Other common points of interest include the airlines’ plans for routes around weather and the implications of those routes for traffic density and sector capacity.

The regularly-scheduled, centrally-coordinated ‘Telcons’ (party line telephone conferences conducted by the system command center) do not meet this requirement. Most of the information passed during a telecomm itemizes airport landing rates, runway configurations, and ground delay programs at airports where delays are relatively routine due to prevailing weather conditions (e.g., SFO, STL). These data are typically better suited to electronic distribution than to voice communication. However, the telecoms demonstrate that the technology for open and impromptu exchanges of information between the AOCs and TMUs is in place.

Both the FAA and users stand to benefit from both (1) automating AOC uplinks to the FAA's host computer and (2) instituting a communications system for collaborative decision making. A joint industry/FAA initiative should support research and development efforts that address both information requirements.

Speed the update rate from the host computer to the ETMS

The impediments to more rapid updating of data shown by the ETMS and its ASD are purely technological. The issues are 'bandwidth' and 'connectivity.' Bandwidth addresses the rate of data transmission. Connectivity addresses the mode of transmission and access to the data. The FAA should support engineering efforts to increase the bandwidth of the ETMS feed to the TMUs. The FAA should push the commercial vendors of the ETMS feed to differentiate their products by offering improved connectivity.

4.2 Sector Capacity ☹

4.2.1 Information uses and requirements

To anticipate levels of traffic flow, the TMC at the flow position first generates an expectation for the future flow of traffic through sectors within center airspace. The TMC then compares the expected level of flow to a metric of sector capacity. The metric sets the threshold for the acceptable level of traffic within a sector. There is one metric per sector. Each metric is tailored to its sector.

The process of comparing data to a threshold has two information requirements. The first is a meaningful sector-specific threshold. The TMC needs to know that thresholds for sector capacity reflect the full suite of human factors considerations that constrain the performance of sector controllers. The second information requirement is a continuous feed of accurate forecasts of traffic demand for a sector. The TMC needs to trust the data that are compared to the threshold.

4.2.2 Current metric

The current metric for sector capacity is a fixed count of aircraft per unit time (e.g., 12 aircraft within the sector in any 15 minute period). While elegantly simple, the arbitrary counts[8] neglect a wealth of human factors that are likely to affect a sector controller's performance at the task of managing the flow of traffic through the sector. These factors include, but are not limited to, the spatial distribution of aircraft, the geometry of their flightplans, the variance in their airspeeds, the demand for changes in altitude, the geometry of the sector, and the prevailing patterns of traffic in adjacent sectors.

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[8] The arbiters of the count metric were a group of TMU supervisors and area supervisors who met to set the metrics more than a decade ago.

4.2.3 Current source and display of information

The current source of information about the demand for traffic is the ETMS. The technology used to forecast and display traffic demand is the monitor alert (MA) function of the ETMS. The MA is software that accesses the ETMS and generates a forecast for the level of traffic demand for sectors. The MA's forecasts are displayed in an ASD window. The display draws the TMC's attention to sectors where traffic density currently exceeds or is expected to exceed the arbitrary count.

As Yee diplomatically notes, the monitor alert function of the ETMS "is not as useful as it could be." At the TMUs visited during this study, the MA is cited for its inaccuracy far more often than it is credited with being a useful tool. The sources of inaccuracy are its naïve metric for sector capacity and its ignorance of traffic intent.

4.2.4 Dynamic density, the foundation for an alternative definition of sector capacity

In 1995, the RTCA[9] Task Force for Free Flight wrote a position paper that proposed a vision of the future of aviation in the United States (RTCA Inc., 1995). In that report, the RTCA coined the term 'dynamic density' without offering a concise definition. Subsequently, planners from the FAA and the aviation industry adopted the concept of dynamic density when framing their Action Plan for Free Flight Implementation. The passage below is taken directly from the joint government/ industry action plan that can be seen on an FAA website (http://seta2.nasi.hq.faa.gov/rtca/recom.idc).

> Recommendation 24. Develop methodology and tools to measure and predict dynamic density.
>
> a. Use modeling tools to identify the parameters of dynamic density and to characterize issues.
>
> b. Develop concept for how metrics would be used operationally for both TFM[10] and ATC.
>
> c. Plan and conduct human-in-the-loop experiments to develop dynamic density metrics and to understand the predictability of airspace density. Determine the level of intent information required.
>
> d. Investigate impact of dynamic density on free scheduling, routing, and maneuvering.

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[9] RTCA Inc. (formally the Radio and Technical Committee on Aeronautics) is a nonprofit corporation that functions as a federal advisory committee on aviation issues.

[10] TFM: traffic flow management, the goal of the TMC at the flow position.

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e.   Perform field tests at selected sites to validate the
operations concept and the ability of metrics to predict
airspace manageability.

f.   Incorporate successful metrics into Monitor Alert (or its
replacement) and into ATC decision support systems, as
appropriate.
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Note that the authors of the action plan, like the RTCA Task Force, do not offer a definition of dynamic density. However, they do make clear that they envision dynamic density, whatever it might be, as the foundation for retooling the monitor alert function of the ETMS. They foresee funding research to define dynamic density and to develop metrics of sector capacity.

4.2.5 Recommendations

Support research to define the factors that determine sector capacity

The first information requirement is a meaningful metric of sector capacity. The FAA should pursue Recommendation 24 and support a concerted research effort to develop an algorithm for computing metrics. Smith, Scallen, Knecht, and Hancock (1998) recently published a theoretical study of dynamic density which takes the first step in the direction this research should take. They defined dynamic density as a proxy for the likelihood (risk) of collision.

Research to develop metrics of sector capacity should refine this (or another) definition to take into account the factors that determine the complexity of managing the flow of traffic through a sector. The accounting of relevant factors should use both process and performance measures of controller workload and the likelihood of collision. The collaboration of sector controllers and other center personnel will be critical to the success of the project. The research effort should couple observations and laboratory simulation studies of sector controllers working sectors that frequently experience unacceptably heavy levels of traffic and/or complex traffic patterns. The project should include the development of a computational model of the human factors and traffic patterns that threaten to overwhelm the controller's ability to keep traffic separated.

Upgrade pre-departure data in the FAA's host-computer database

The second information requirement is accurate forecasting of the flow of traffic through a sector. The monitor alert function relies on data in the ETMS to generate its forecasts. The forecasts are only as reliable as the data in the system. As discussed above, the host computer and ETMS use OAG data rather than filed flightplans prior to a flight's departure. The ETMS does not disseminate reliable data about a flight until it is airborne. As a result, forecasts of traffic demand for a sector that look more than an hour ahead are often contaminated by inappropriate data. The remedy to this source of inadequacy is the joint industry/FAA initiative discussed above. The initiative must support research and development efforts directed at creating and providing access to a dynamic database of as-filed flightplans that are updated as soon as they are filed and whenever filings change.

4.3 Receipt and documentation of Programs and Restrictions on traffic flow ☺

Programs and restrictions on traffic flow are the TMCs' method for distributing workload across sectors and centers and, ultimately, across sector controllers. For example, the TMC at the flow position at Chicago center (ZAU, located in Aurora, Illinois) routinely requests that system command center issue restrictions on traffic landing at O'Hare that is entering Chicago airspace from Minneapolis and Kansas City airspace. The command center issues the restrictions to make it easier for sector controllers at ZAU to manage the workload involved in handling the heavy density of traffic landing at O'Hare. The shorthand for a typical restriction reads:

```
ZAU/ZMP 14:00-16:30 ORD LTFC 2/20
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This shorthand means that Chicago center (ZAU) has informed Minneapolis center (ZMP) that between 14:00 and 16:30 Minneapolis center must see to it that O'Hare (ORD) landing traffic (LTFC) crosses into Chicago airspace along no more than two jetways and be separated by no fewer than 20 nautical miles.

When weather at an airport is too severe to support safe landings, the best option for the TMC at the metering position is often a ground-delay or ground-stop program. A ground-delay program reduces the arrival rate into the airport. A ground-stop program reduces the arrival rate to zero and holds all departing flights on the ground until further notice. Both types of programs are designed to keep an uncertain situation from getting more complex.

The TMC at the SWAP position issues a third type of program. SWAP routes change the first several segments of a flightplan in order to expedite departures from an airport threatened by severe weather.

The effect of issuing a program or restriction is to offload part of the workload across sector controllers. In the example, Chicago center shifts part of the burden from its controllers to controllers at Minneapolis center.

4.3.1 Information requirement

The system of collaborative decision making that requests and issues a program or restriction is in place and appears to operate smoothly and efficiently. In contrast, the system for receiving a program or restriction is *ad hoc* and is potentially inefficient. All positions in the TMU need to be able to access precise information about programs and restrictions that influence the flow of traffic in the center's airspace. This information should appear in a standardized format and be posted on a dedicated display that is visible to all.

4.3.2 Current source of information

The TMC at the flow position typically receives information about a new program or restriction from the system command center over the telephone. The TMC then has the responsibility of passing the information to the entire TMU and through the chain of command to the sector controllers. In the example above, the TMC would have to contact the area supervisors of the sector controllers working aircraft that plan to land at O'Hare. Those controllers would then have the responsibility of creating two strings of traffic while keeping traffic in each string separated by at least 20 miles.

4.3.3 Displays

The two TMUs visited during this study, ZMP and ZKC, have independently developed essentially identical external memory devices for programs and restrictions[11]. The device at both TMUs is a large white board that anyone can write on and everyone can read. The whiteboard helps a TMC remember and communicate the restrictions on traffic flow that arrive during the day.

The white boards are spontaneous adaptations to the demands of the task. Their similarity across TMUs is a testament to the power of the task to shape the devices and methods used to perform it.

4.3.4 Recommendations

> Publish programs and restrictions on traffic flow over a centralized communications system that uses off-the-shelf hardware

While the white boards are laudable, there should be no need for them in the information age. The shorthand written on the white boards has limited content and a small number of formats that are fixed by convention. These data should be 'published' - disseminated and displayed - to all involved centers and the command center simultaneously via a centralized communications system that uses off-the-shelf hardware. A monitor in a centralized location in every TMU should be dedicated to the display of program and restriction data.

There is no good reason to prevent the AOCs from being able to read this information as well. For example, if the major airlines knew that ZAU had restricted arrivals from ZMP and ZKC, they might be willing and able to file NRP flightplans designed to merge into the restricted streams of arrivals. After all, an aircraft that gets into the sequence without delay is likely to burn less fuel than an aircraft that is put into a holding pattern as it attempts to enter the sequence in an overloaded sector. Further, better planning early in the day might obviate the need for a program or restrictions on traffic flow later in the day.

A ready candidate for dissemination of program and restriction data to the airlines is a page on a web site with limited access. More exorbitant hardware systems can be imagined. Regardless of publication mode, the system-wide and systematic dissemination of programs and restrictions on traffic flow should receive immediate

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[11] A shopping list is a familiar example of an external memory device. It enables physical (visual) representation and communication of information that must be remembered.

attention. Once again, both the FAA and the airlines stand to benefit from such a system. A joint industry/FAA initiative should support research and development efforts that address this information requirement.

Refine the SWAP procedure

The SWAP position expedites the flow of traffic departing an airport when weather is threatening. The TMC's task is to keep aircraft away from the weather and to avoid overloading departure (and other) sectors.

The current SWAP system is outdated. It was designed at the time when all aircraft followed controller-preferred routes ('pref. routes'), that is, before the advent of the NRP. The current SWAP system forces the TMC to revoke an aircraft's entire flightplan and to reassign it a 'pref.' route. What is needed is partial reassignment of the flightplan, not wholesale reassignment. The TMC at the SWAP position is concerned only with that portion of the flightplan near the affected airport. Often, only the initial segments of the (NRP) flightplan are affected by the severe weather. The TMC should be able to allow aircraft to converge with their filed (NRP) flightplans at some distance away from the threatening weather.

What is needed, once again, is a direct communications link between TMUs and AOCs that will allow the TMC to inform dispatchers of partial SWAP routes and enable dispatchers to update flightplans with those routes. The envisioned system would shift a portion of the burden of flightplan reassignment from the TMU to the airlines. A joint industry/FAA initiative should support research and development efforts that address this opportunity for mutual benefit.

4.4 Weather ☺

4.4.1 Information requirement

The TMC relies on an accurate depiction of current weather within the center and nationwide and on reliable forecasts of near-term (two to six to nine hours in the future) weather conditions within the center, at center airports, and nationwide.

4.4.2 Uses of information

The flow position relies on regional weather information to anticipate changes in the flow of traffic. Aircraft are likely to avoid sectors plagued by bad weather and, conversely, are likely to converge on sectors that offer windows between storm cells. Weather-induced changes in traffic flow can dramatically alter the demand for sectors and sector controller workload. The metering and flow positions use local weather data to anticipate and develop programs and restrictions for arrivals and 'pref. routes' for departures.

4.4.3 Current sources of information

All weather data are provided by personnel of the center weather service unit (CWSU) who are employees of the National Weather Service (NWS). These professional meteorologists rely on numerous and diverse meteorological tools and sources of information, including commercial vendors. Assessing the information requirements of the CWSU would require a separate study.

4.4.4 Displays

The CWSU generates a suite of ASD windows specifically designed to meet the center's need for reliable and timely meteorological information. In addition, the TMC often superimposes weather and traffic data on ASD windows. The most commonly displayed meteorological datum is a color-coded map of the elevation of cloud tops[12]. Another frequently displayed datum is the location of lightning strikes in the last hour. As one TMC said, "lightning shows me places pilots are going to avoid."

4.4.5 Implication - Maintain FAA-NWS collaboration

Weather is a major source of uncertainty when trying to anticipate the flow of traffic. CWSU personnel work to reduce this uncertainty. However, as CWSU personnel are the first to point out, their forecasts are only as good as the information they receive. It is likely that it will always be possible to improve the observation and analytic tools used by meteorologists. The FAA should continue to collaborate with the NWS and other allied agencies and institutions and to support research and development of meteorological tools for CWSU personnel. While this conclusion does not have a human factors research-and-development component, it does have a prescriptive social component. CWSU personnel are partners in the ARTCC's mission. They need and deserve the FAA's continued support.

5 EXPLANATORY ACCOUNT

This section summarizes the cycles of decision making and action that specify the information requirements for the TMC and sector controller. It characterizes the TMC and sector controller as process control agents (operators) and their decision making as a process control task. The first section defines process control. The second section refers to Figure 1 (shown on page 3) to illustrate the concept of process control cycles. The final section explains the organization and distribution of jobs in an ARTCC as a natural division of labor in a process control task.

[12] A useful, task-sensitive color-coding scheme appears to have been set by convention. Jet aircraft can generally fly above cloud tops shown in light green (tops to 30,000 ft). They may be able to fly over or between tops shown in dark green (40,000 ft). Tops shown in yellow are a barrier to commercial traffic (50,000 ft). Tops shown in red represent truly menacing thunderstorm cells (tops above 50,000 ft).

5.1 Process control

Process control is a class of tasks. Air traffic control is the exemplar of the class. The goal of process control is to keep a dynamic system within specified limits. Process control tasks share four defining characteristics:

- Monitoring: An operator monitors a dynamic system (e.g., the flow of air traffic) that interacts with an environment that is largely beyond the operator's control (weather, users, system command center).

- Feedforward control: The operator works to anticipate change in the system and in its interaction with its environment and to compensate for those changes by adjusting the limits placed on the system (programs and restrictions on traffic flow).

- Feedback control: The operator responds to the current state of system by adjusting system parameters (headings, airspeeds, and altitudes) designed to keep the system within its limits.

- Feedback: The operator has access to information about the impact of adjustments to system limits and parameters on the system's interaction with its environment.

All sector controllers and TMCs are process control agents or operators. They work to keep a dynamic system, the flow of air traffic, within acceptable limits (e.g., aircraft separated by more than 1,000 feet vertically or five nautical miles horizontally). The system is part of a larger environment that includes natural elements (weather, terrain) and products of human creation (the National Airspace System). The elements that define the environment are largely beyond the TMC's or the controller's control.

The sector controller's responsibility is feedback control. Controllers respond to the current flow of traffic and take action to keep aircraft separated by distances greater than the acceptable limits for separation. The TMC's responsibility is feedforward control. The TMC modulates the flow of traffic by issuing programs and restrictions on traffic flow designed to keep the workload in a sector within a controller's capacity. Both the TMC and the controller have access to information that provides feedback on their actions.

5.2 The cycles of process control

Figure 1 (page 3) presents the process control cycles for decision making at an ARTCC. The cloud shown at the top of Figure 1 represents the aviation environment that surrounds the system controlled at an ARTCC. The system to be controlled is the flow of air traffic and sector controller workload. The cycles on the left represent feedforward control. The cycles on the right represent feedback control. The boxes represent the series of information processing activities that support decision making and action. The arrows define the flow of information between these activities. The diagonal arrow illustrates the flow of information and interaction between the feedforward and feedback cycles.

5.2.1 Monitoring

Monitoring is the operator's *modus operandi*. The goal of monitoring is to obtain information about the system and its sources of constraint. The sector controller systematically scans the PVD for information about the constraints on current traffic flow. The TMC systematically scans ASD windows and the PVD for information about the constraints on future traffic flow and on sector controller workload.

Sources of constraint

The dynamic environment of commercial aviation imposes four sources of constraint on TMC and sector controller decision making: traffic intent, sector capacity, programs and restrictions on traffic flow, and weather. The four sources of constraint fully specify the information the TMC and the sector controller must monitor. Stated more generally, task constraints fully define information requirements.

Weather and traffic intent are exogenous sources of constraint - they are environmental, organizational, and economic forces beyond ARTCC control. Sector capacity is an endogenous source of constraint – its limitations are inherent in the geometry of the system and the limited human capacity for workload. Programs and restrictions on traffic flow are constraints imposed by TMCs to solve portions of their process control problem. Programs and restrictions are enabling constraints; they enable a TMC to distribute traffic and workload and define the limits on traffic flow for sector controllers.

5.2.2 Feedforward control

The left-hand cycles through Figure 1 represents the cycles of information processing that exercise feedforward control. At the ARTCC, feedforward control is the domain of the TMC.

The first step is to monitor ASD windows, the PVD, the telephone, and the whiteboard to develop and update a representation of traffic flow. (The TMC at the flow position monitors the flow of intracenter and intercenter traffic. The TMC at the metering position monitors the flow of arrivals. The TMC at the SWAP position monitors the flow of departures. The TMC at the military position monitors the flow of military aircraft.) The second step is to anticipate the flow of traffic and its impact on the sector controllers. To anticipate differential levels of traffic flow, the TMC projects the representation into the future and compares the expected flow to metrics of sector (or arrival fix) capacity. When the comparison finds that the expected flow does not exceed acceptable limits, the TMC returns to monitoring. The short cycle of monitoring and anticipating is by far the most common mode of feedforward control.

The TMC takes the third step in feedforward control only when the expectation appears to violate one of the limits on system performance. These limits include the metric for sector capacity and the capacity of airports. The TMC shifts from monitoring displays and anticipating flow to communicating a representation of expected traffic flow and collaborating with others to develop plans for redistributing that flow. The products of collaborative decision making at the TMU are programs and restrictions, constraints designed to enable sector controllers to manage the flow of traffic. The final step in the long cycle of feedforward control is dissemination of programs and restrictions. The bold dashed arrow represents the dissemination of enabling constraints to the sector controllers. The fine solid line on the left side of Figure 1 illustrates the TMC's return to monitoring. The fine dashed line on the far left illustrates the indirect impact of the TMC's actions on the aviation environment.

5.2.3 Feedback control and intervention

The right-hand cycles through Figure 1 represent the cycles of information processing that exercise feedback control. Feedback control focuses on what to do to keep the system within its limits. At an ARTCC, feedback control is the exclusive domain of the sector controller.

The first step is to scan the PVD systematically for information that indicates the current status of traffic and its rate of change. When the rate of change is likely to drive the process to exceed its limits, the sector controller responds. Responding to traffic involves making a series of non-independent decisions in real time. The decisions are (1) whether the flow of traffic is operating within limits, and (2) if not, what to do to ensure the system remains within or returns to those limits. The controller's task is to loop through these decisions and to initiate adjustments when needed. More often than not, the controller decides the system is within limits and no adjustment is needed. The decision not to intervene triggers the short cycle of feedback control.

The decision to intervene triggers the long cycle of feedback control. Interventions instruct pilots to adjust system parameters (e.g., make a turn, climb, or descend) in order to alter the interaction of the system with its environment. The fine dashed line on the right side of Figure 1 illustrates the coupling between feedback control and the process to be controlled. The fine solid line illustrates the sector controller's return to monitoring.

5.3 The distribution of process control cycles in an ARTCC

The two types of jobs at an ARTCC distribute the responsibilities of process control across the cycles through the process control task. The TMC exercises feedforward control by anticipating the status of traffic, changes in traffic demand, and changes in sector controller workload, and by issuing (or accepting) programs and restrictions. The sector controller exercises feedback control by keeping aircraft within a sector separated. The cycles of process control shown in Figure 1 explain the information requirements and all actions taken by a TMC and sector controller.

6 SUMMARY OF RECOMMENDATIONS

Section 4 contains eight specific recommendations that can be consolidated into five courses of action. This section summarizes those courses of action. The first four are opportunities for human factors research and development. The fifth is an opportunity to continue to do the right thing.

6.1 Develop a protocol for TMU-AOC-ATCSCC dialog and collaborative decision making

An established protocol for dialog and collaboration between the TMU, the systems command center, and the airlines would improve the ability of the TMC to anticipate the flow of traffic and the demand for sectors and arrival fixes. Plans could be made further in advance and more efficiently if the TMC were able to hold impromptu dialogs with dispatchers. Both the FAA and the airlines stand to benefit from developing a communications system that could be used whenever collaborative decision making is needed. The current system of regularly-scheduled telecoms does not satisfy this need but does demonstrate that the necessary technology is in place. The FAA should support research that addresses this information requirement.

6.2 Sponsor a joint industry/FAA initiative for the automated transfer of (pre-departure) data to the FAA's host-computer database

A joint industry/FAA initiative should support research directed at designing and developing (or improving) an automated communications link between the AOCs and the FAA's host computer. The host and the ETMS have yet to take full advantage of advances in information technology. The joint initiative should address this shortcoming. The automated uplink should support at least three TMC information requirements. First, the system should update in real time a database of as-filed flightplans, both pre- and post-departure, that can be accessed by the ETMS and its ASD windows. Second, the system should provide a mechanism for publishing - disseminating and displaying - the evolving constraints on the NAS including programs and restrictions on traffic flow. Third, the system should inform AOCs of partial SWAP routes and enable dispatchers to update flightplans with those routes. The envisioned system would supplement the protocol for dialog as a channel for collaborative decision making.

6.3 Support research and development directed at upgrading the monitor alert function (MAF) of the ETMS

The FAA needs to support research efforts that address the reformulation of the monitor alert function of the ETMS. To be useful, the monitor alert must (1) access, before aircraft take off, the flightplans that dispatchers file, (2) respond quickly to changes in flightplans, and (3) use a meaningful metric for sector capacity. The first two needs can be met by supporting the development of technology that will upgrade the ETMS and ASD (or their replacements) with a user-friendly interface and improved bandwidth and connectivity to the FAA host computer.

The need for a meaningful metric for sector capacity identifies an opportunity to support human factors research and development efforts directed at reformulating the metric of sector capacity.

6.4 Support research directed at reformulating the metric of sector capacity

Defining a meaningful metric of sector capacity will require defining the factors that determine sector controller workload. The research should conduct observational and experimental studies with professional air traffic controllers and traffic management coordinators as collaborators. Redefining the metric will require a field examination of the impact of traffic flow, in all its variants, on sector controller workload and laboratory and modeling analyses of alternative algorithms for the metric. The integration of an upgraded host/ETMS database and a meaningful metric of sector capacity would produce an entirely new monitor alert function that would better serve its purpose and improve the efficiency of TMC decision making.

6.5 Maintain FAA-NWS-NOAA collaboration

All personnel at an ARTCC, both those who work sectors and those at the TMU, need to be confident that the weather data and forecasts they receive are as timely and accurate as possible. The professional meteorologists at the CWSU work to reduce the uncertainty posed by weather and to improve the quality of air traffic control. The FAA should continue to collaborate with the NWS and other allied agencies and institutions and to support research and development of meteorological tools for CWSU personnel. This recommendation is to maintain and improve the status quo, that is, to continue to do the right thing.

6.6 Summary

This report has identified five courses of action the FAA could take to address the information requirements of traffic management coordinators at air route traffic control centers. There are four opportunities for human factors research and development and one for continuing a successful collaboration:

- To develop a mechanism and protocol for TMU-AOC-ATCSCC dialog and collaborative decision making. This work will require an extensive program of observational and in-situ empirical studies at various TMUs, AOCs, and at the system command center.

- To support efforts to upgrade the link between the AOCs and the FAA host computer. This work will require a joint FAA/industry initiative to identify the loci of the current hiatus in information flow and to speed the automated transfer of flightplan information between the AOCs and the FAA, and among FAA facilities.

- To support the development of technology that will improve the performance of the ETMS and the ASD (or their replacements). This work will require an engineering effort directed at enhancing the bandwidth, connectivity and user interface of the ETMS and ASD (or their replacements).

- To support research directed at reformulating the metric of sector capacity. This work will require an extensive program of human factors research directed at explicating the factors that determine sector controller workload and sector capacity.

- To continue to support FAA-NWS-NOAA collaboration so that the TMU has immediate access to forecasts made by professional meteorologists.

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GLOSSARY

AOC Airline Operations Center. The facility where employees of an airline plan and coordinate flightplans, aircraft, maintenance, personnel, and related services.

Approach control See TRACON.

Area supervisor An area supervisor is the line supervisor of sector controllers working a block of geometrically contiguous sectors – the 'area.' Sectors within an area are typically linked by patterns of traffic flow.

ARTCC Air Route Traffic Control Center. The FAA facility where sector controllers and traffic management coordinators work to keep aircraft separated. There are 20 ARTCCs in the contiguous United States. The first letter in the three letter acronym for an ARTCC is always Z (e.g., ZKC, Kansas City Center; ZMP, Minneapolis Center).

ASD Aircraft Situation Display. A map-view computer display of aircraft locations that can be programmed ('filtered') by the user. The display is typically set to superimpose a map, the last-reported location of selected aircraft, and information about weather (e.g., a composite image of radar returns.)

ATCSCC Air Traffic Control System Command Center. The FAA facility that oversees the system-wide flow of air traffic and coordinates the actions of ARTCCs.

Callsign An unique identifier for a flightplan/aircraft, e.g., NWA123, that is usually identical to the flight number familiar to travelers.

Center In an effort to minimize the jargon of acronyms, this report often uses the words 'the center' to refer to the ARTCC where the TMC works.

Command center See ATCSCC

CWSU Center Weather Service Unit. The unit of the ARTCC staffed by professional meteorologists employed by the National Weather Service.

ETMS Enhanced Traffic Management System. The FAA's computer system for tracking and predicting the flow of air traffic. Introduced in the 1980's, the ETMS is due for an upgrade. The ETMS traffic data are updated every 2 or 6 minutes, depending on location and bandwidth.

FAA Federal Aviation Administration

Flightplan The four dimensional set of constraints on where a flight is expected to be and when it is expected to be there. Flightplans typically contain a series of waypoints and jetways, an arrival fix, and times to be at the fix and several of the waypoints. The constraints and the expectations they engender are shared by the air carrier, the flightdeck (pilots), and air traffic control.

Jetway A 'highway in the sky,' a designated route between specific geographic locations called 'waypoints' or 'intersections' along which aircraft travel. For decades, all flightplans have had to link a sequence of jetways along a controller-preferred route called a 'pref.' route.

Nexrad The National Weather Services' ground-based weather radar system. An echo-top image is a mosaic of color-coded squares 2 or 4 km on a side. The color coding indicates the highest altitude of coherent radar returns (echoes) in each square of the mosaic. Nexrad echo-top imagery shows where the clouds are and how high they are. The higher the cloud, the more severe the weather.

NAS The National Airspace System is the interaction of commercial aviation, civilian aviation, the FAA, vendors, suppliers, and related parties and agencies.

NOAA National Oceanographic and Atmospheric Administration

NRP National Route Program. The NRP is one of the first steps in the phased reorganization of the National Airspace System. This program allows airlines to file non-traditional flightplans for selected flights. Traditionally, flightplans are lists of waypoints (intersections, places to check in) and jetways along a controller-preferred route. Under NRP, a flightplan can deviate from the 'pref.' route.

NWS National Weather Service

Pref. route A controller-preferred route for aircraft to follow between departure airport A and destination B. There is a pref. route for every regularly-scheduled flightplan.

PVD Plan View Display. The monochrome, large-screen, composite-radar, top-down (map, plan view) display introduced in the 1970's.

RTCA RTCA, Inc. (formally the Radio and Technical Committee on Aeronautics) is a nonprofit corporation that functions as a Federal advisory committee on aviation issues.

Sector The basic unit of airspace. A sector is a precisely-defined three-dimensional volume of airspace. Sectors are organized in a hierarchy of control within an ARTCC. A set of contiguous sectors form an 'area.' Operations within an area are overseen by an area supervisor. There are typically four to six areas in an ARTCC. The TMU oversees operations within the areas.

Sector controller The air traffic controller who is responsible for maintaining separation between aircraft within a sector.

SWAP Severe Weather Avoidance Program. One of the secondary positions taken by a TMC. In this position, the TMC is responsible for issuing reroutes for aircraft departing an airport threatened by severe weather. In the current system, the issued reroute revises a flight's entire flightplan.

System Command To minimize the use of jargon, this report often uses the words 'system command' or 'system command center' to refer ATCSCC, the FAA facility that oversees the system-wide flow of air traffic.

TMC Traffic Management Coordinator. An air traffic controller who works in the TMU. TMCs are responsible for the flow of aircraft through or within the center's airspace, not for maintaining separation between individual aircraft.

TMCIC Traffic Management Coordinator in Charge. The TMC responsible for overseeing TMU activity and for communicating with ATCSCC and TMCICs in other ARTCCs.

TMU Traffic Management Unit. The unit of the ARTCC staffed by air traffic controllers who manage sector controller workload by coordinating the flow of traffic within and across ARTCC boundaries and overseeing area operations.

TRACON Terminal Radar Approach Control. The FAA facility where controllers manage aircraft departing from or arriving at a major airport. The volume of airspace managed by approach controllers is much smaller than that managed by an ARTCC. The aircraft are also closer together and are generally closer to the ground. A departing aircraft communicates with an approach controller before being 'handed-off' to a sector control in the ARTCC. A reciprocal hand-off is made prior to landing.

Waypoint A specific geographic location (latitude/longitude fix) with a unique five character name used to construct and follow flightplans.

ZAU Chicago ARTCC (in Aurora, Illinois)

ZKC Kansas City ARTCC

ZMP Minneapolis ARTCC