The air transportation system infrastructure is comprised of communication, navigation, surveillance, and air traffic management systems, and is known as the National Airspace System. This chapter describes the current very high-frequency and high-frequency modes of communication, very high-frequency omnidirectional range, distance measuring equipment, and instrument landing systems for navigation/guidance to the aircraft, and primary, as well as secondary radars, for surveillance. The two primary functions of the ground-based air traffic management system, viz. traffic flow management for strategic air traffic planning and air traffic control for safe movement of aircraft, are discussed in detail. This chapter also addresses the limited role of automation in both the aircraft cockpit and the ground-based air traffic management system.

The US civil air transportation system today handles over 700 million passengers and 40 billion revenue ton miles of cargo annually that require about 23 million aircraft operations. Each aircraft operation represents a flight from take off to touch down between its departure and destination airports. This number is forecasted to reach a level of 35 million operations by the year 2025. Although the air transportation system has recorded a very high level of safety over the years, the continued growth in demand for air traffic services has created operational inefficiencies, which result in significant flight delays and lost revenue for the users. Today, a majority of decisions in the aircraft and in the ground control system are manual. The human decision making
is intensive for the pilots and controllers in terms of their workloads, and will become unmanageable as traffic levels grow. In order to deal with the traffic growth, the future air transportation system will require increased automation of air/ground functions to enhance safety, capacity, and flight efficiency while reducing delays and workload.

The performance of the air transportation system is measured by four key metrics relating to safety, capacity, flight efficiency/delays, and workload. Because aircraft safety is of the utmost importance, the US Government has established regulations that require the aircraft to maintain a minimum separation distance from other aircraft. These separation minima vary with the phases of flight. Explanations of the separation minima and their influence, as well as limitations on flight operations, are provided. How the use of automation could in the future overcome these limitations is also discussed.

Efforts are underway to define concepts for the next-generation (NextGen) air transportation system in the USA, and the Single European Sky air traffic management (ATM) research project in Europe. The Joint Planning and Development Office, mandated by the US Congress, is charted to develop NextGen concepts for the years 2025 and beyond. The goals and requirements of the NextGen system are presented. Also discussed is the ongoing research and development of new satellite technologies, including data link and satellite-based navigation and surveillance, as well as the needed automation of ground-based decision support functions. It is expected that enhanced automation in the aircraft and in the ground system will provide safe and efficient services to a significantly higher number of aircraft operations in the future.

The civil air transportation system is an essential component of the global economy. It is required for timely movement of people and cargo. Until now, air travel has been the safest mode of transportation per passenger mile. Because of the cost, air transportation has not been the primary mode of transportation for long-distance travel in most countries, even though it has been widely used in the USA. However, the demand for air travel around the world is now increasing at a fast pace to meet multinational commerce needs. For globally harmonized aircraft operations, the International Civil Aviation Organization (ICAO), in collaboration with National Civil Aviation Authorities (CAA), has established standards and operating procedures to be followed by all aircraft operators and air traffic service providers.

In the US, the National Airspace System (NAS) is a complex system of human-centric systems providing communication, navigation, and surveillance (CNS), and air traffic management (ATM) services to aircraft flying passengers and cargo. During 2006, over 700 million passengers used NAS, and the demand for air travel is expected to increase beyond one billion passengers by the year 2015. The annual cargo revenue ton miles exceeded 40 billion in 2006 [67.1], and is continuing to grow with the significant demand for goods and services.

In order to meet the challenges of greater demand for air travel, it is imperative to have an air transportation system that not only maintains or enhances safety, but also provides efficient flight operations. The current aircraft operations and the air traffic control (ATC) services are primarily manual open loop, where the pilots in the aircraft and controllers on the ground interactively make decisions based on the available information. The safety of the aircraft in the air is provided by adhering to the established distance separation rules or separation minima in both the horizontal and vertical domains. Thus, although safety is assured, these separation requirements between aircraft often adversely impact the efficient use of airport and airspace capacity, thereby resulting in flight delays and creating extensive workload for the humans operating the system. With the ever-growing demand for air traffic services, as these capacity resources become scarce, there is a need to develop closed-loop feedback control NAS capabilities that can provide automated decision support to maximize capacity, enhance flight efficiency, and reduce pilot/controller workload by minimizing reliance on cognitive decision making.

This chapter describes the current NAS CNS/ATM infrastructure, and the extent of the role that automation plays in specific aircraft- and ground-based functions for managing and controlling traffic. The limitation of these functions is discussed with their impact on flight safety, airspace/airport capacity, aircraft operational efficiency, and operator workload. The requirements for the future air transportation system are presented, not only to overcome the shortcomings of the current system, but also to meet the service demands of future users effectively. The ongoing application of automated key functions to meet the future system requirements are presented to address hybrid automation/human decision making in the cockpit and on the ground.

The scope of the contents presented here is limited to an understanding of how the automated functions-
generated information helps manual decisions today, and how automation will generate most decisions (except those that are safety critical) in the future for strategic planning and tactical operations during all phases of flight. Any consideration of the use of automation in design and control of the aircraft (except for safe navigation and efficient energy management), or a discussion of the US Government programs to upgrade and automate ground systems, is beyond the scope of this chapter.

### 67.1 Current NAS CNS/ATM Systems Infrastructure

The current NAS infrastructure is comprised of a CNS system architecture, and the ATM system that is dependent upon an integrated system of airports and ATC facilities. The ground-based ATM system includes data/information acquisition and processing as well as display capabilities supporting people in making decisions to manage and control aircraft operations. The CNS architecture deploys:

1. Very high-frequency (VHF) voice/data communication over the continental USA, and high-frequency (HF) communication in the polar region and over the ocean for air/ground communication
2. VHF omnidirectional range (VOR) and distance measuring equipment (DME): ground-based navaids for navigation over pre-established routes, with precision landing guidance to primary airports provided by the instrument landing system (ILS), and nonprecision landing guidance available from VORs and nondirectional beacons (NDB)
3. Surveillance to locate and track the aircraft provided by the primary and secondary surveillance radars (SSR). The weather radars detect and provide weather and wind information in some aircraft cockpits and to the ground system.

The ATM system has two distinct functions: traffic flow management (TFM) and ATC. The TFM function is involved in strategic planning of flight operations across the entire NAS based on the forecasted weather and traffic conditions throughout the airspace and at all major airports. This is to balance the expected demand with the airspace/airport capacity resources in order to maximize operational efficiency and minimize delays. There are, on average, 55,000 daily operations in the NAS. The ATC function provides tactical control...
of airborne aircraft and is designed to help controllers maintain safe separation between aircraft. At an instant of time, the ATC function controls up to 6500 aircraft operations during peak traffic conditions [67.1]. The NAS-wide TFM function is located in the air traffic control system command center (ATCSCC), whereas the regional and local TFM functionality is provided by the traffic management units (TMU) in the 20 air route traffic control centers (ARTCC) and the terminal radar approach control (TRACON) facilities located at the primary airports. The ATC functions for aircraft movements at the airport surface and during departures/arrivals are handled by 400 air traffic control towers (ATCT) located at the airports. The ATC functions to separate aircraft up to about 30 nmi (nautical miles) from the primary airport are provided by 185 TRACONs, and for flights through the rest of the airspace by the ARTCCs. The TFM functions interface with the flight operators through the airline dispatch offices or the airlines operation centers (AOC) and flight service stations (FSS). The ATC functions require direct interaction between the ATC facilities and the aircraft [67.2,3]. Figure 67.1 shows schematically the NAS CNS/ATM infrastructure.

The US Federal Aviation Administration (FAA) has classified the national airspace into six categories in accordance with the ICAO airspace classifications. Airspace classified as class A, B, C, D or E is designated as controlled airspace, where ATC services are available, including air/ground communications, navigation aids, and aircraft-to-aircraft separation assurance. Class G airspace is uncontrolled airspace where the ATC system is not responsible for managing traffic.

The following provides details on controlled airspace classifications:

- **Class A**: Class A airspace covers from 18 000 ft mean sea level (MSL) to 60 000 ft MSL.
- **Class B**: Class B airspace exists at 29 high-traffic-density airports in the US where the aircraft are subjected to positive ATC, i.e., the aircraft need ground control clearances to operate. Class B airspace includes all airspace around these airports from the surface up to 12 000 MSL and spreads out to about 30 nmi.
- **Class C**: Class C airspace exists around 120 airports in the US that have control towers and radar approach control. This class of airspace has two concentric circular areas with a radius of 5 and 10 nmi around the airport, and extends up to 4000 ft above ground level (AGL).
- **Class D**: Class D airspace is a circular area of radius 5 nmi around the airport and extends up to 2500 ft AGL at airports with an ATCT.
- **Class E**: Class E airspace covers the volume of airspace below the class A airspace from surface to 18 000 ft MSL, and excludes airspace covered by classes B, C, and D.

### 67.1.1 Air/Ground Communications Systems and Functions

Today the ATC communications are primarily two-way voice capabilities over a radio system, which allow the controllers and pilots to coordinate tactical flight maneuvers needed for safety. Fundamental to the communication is the spectrum that supports it. For the ATC communications, this spectrum is coordinated worldwide, and is defined in several distinct bands, each used for specific purposes. Due to its long-range propagation characteristics, HF communications at frequencies between 3 and 30 MHz have been used in oceanic and remote polar operations for many years. VHF spectrum in the 117.95–137 MHz band is set aside for operations in well-traveled airspaces that use a line-of-sight radio infrastructure. Additional frequencies are set aside for satellite communications, defined and protected for aeronautical communications in the 1.5 and 1.6 GHz bands [67.4].

In the US, a network of VHF radio sites, shown in Fig. 67.2, provides the terrestrial infrastructure over which the voice communications operate. Specific frequencies in the band are provisioned to avoid interference between the operating airspaces, based on...
(67.1), that governs the radio line-of-sight distance \( D \) from the aircraft to the radio horizon

\[ D = K \sqrt{h}, \quad (67.1) \]

where \( D \) = distance (in nautical miles), \( h \) = height (in feet) of the aircraft station, and \( K = 1.23 \), a constant corresponding to an effective Earth’s radius of \( 4/3 \) of the actual radius.

These voice channels either support a single operational ATC position on a specified control frequency, providing half-duplex party-line communications among the controllers and the pilots in a specific airspace, or provide one-way broadcast information for weather or traffic conditions on designated information frequencies, as shown in Fig. 67.3. Air-to-air and emergency frequencies are also specially provisioned for in the VHF band. A continuously monitored emergency frequency has been established worldwide at 121.50 MHz, and an air-to-air channel has been designated for use at 123.45 MHz.

Beyond today’s voice communications, digital technologies are used for data links in the ATC environment, allowing for data communication from an automated ATC system, that can closely integrate and incorporate directly with the aircraft systems. One of the first aeronautical communication data links to operate was the aircraft communications addressing and reporting system (ACARS) introduced in the late 1970s. The ACARS operates at 2.4 kbps, and provides short messages indicating aircraft on, out, off, in (OOOI) events relating to the aircraft leaving the gate, taking off, landing, and arriving at the gate, to help airlines manage their aircraft. This system also operates in the VHF band, and has been expanded to include more applications, including a predeparture clearance (PDC) function for ATC and a digital broadcast automated terminal information service (ATIS). Succeeding ACARS, a digital link, called VHF digital link (VDL) mode 2, was defined and standardized through the ICAO, to provide more capacity and higher speed (31.5 kbps) for airline and ATC operations. Other data link systems that have also been defined and standardized through the ICAO include:

- VDL mode 3, which integrates a digital ATC voice capability with the data link
- VDL mode 4, which can also provide surveillance functions
- Mode-S data link, which integrates data communications with the surveillance information such as from automatic dependent surveillance-broadcast (ADS-B).

In the 1990s, worldwide satellite communications networks for aviation first became available through the commercial satellite service providers, including Inmarsat and Iridium. Satellite communication is displacing the long-range HF voice communications for ATC in many areas of the world and is also providing reliable long-range data links in low-density air traffic environments, such as oceanic airspace as shown shaded green in Fig. 67.4.

New air/ground communications capabilities will provide faster and greater information sharing among ATC systems and aircraft using the above technologies, thereby improving the safety and efficiency of air traffic operations.
As new digital radio communications systems enable aircraft’s control processors to coordinate information with the ground control systems, radio communications will become an even more critical component of managing air traffic control.

The air/ground communications system is a critical component of the ATM system, because it provides aircraft control information (e.g., instructions and clearances to the aircraft) and in some cases feedback information (e.g., aircraft position to the ground) to allow safe and efficient transit of air traffic through an airspace. Depending on the operational environment and specific equipment being employed, other functions and information can be provided over the communications systems, such as broadcast information to the pilots on local terminal weather conditions and runway operations, meteorological information for weather models or pilot-reported turbulence information. Given the ability of an aircraft to operate anywhere in the NAS, the systems on an aircraft must be able to interface with the ATM system, and the pilots must interact with the ATC system wherever they fly.

### 67.1.2 Navigation and Guidance Systems

Until recently, the VOR/DME or the VOR tactical air navigation (TACAN) (VORTAC) system has been the primary guidance system for navigation. Because of its line-of-sight limitation, the VOR/DME navigation is not available everywhere in the NAS, especially in remote mountain, polar, and oceanic regions. With the availability of broadcast signals from Earth-orbiting satellites as a part of global positioning system (GPS), aircraft equipped with GPS receivers can navigate point-to-point anywhere.

**VOR/DME Navigation Systems**

The VOR/DME [67.5, 6] is a short-range navigation system that has been internationally standardized and is in use throughout the world. To achieve a common civil–military system for en route navigation in the US, the distance measurement element of VOR/DME is provided by the military tactical air navigation (TACAN) system. The collocation of VOR and TACAN constitutes a VORTAC ground facility, providing VOR-bearing information to civil users, the TACAN-bearing information to the military aircraft, and distance information to both. At present, there are 775 VORTAC facilities in the US, 145 VOR/DMEs, and 90 VOR-only ground stations. A few more VOR ground stations have been procured by individual organizations that add to the total number of VORs listed above.

The VOR system has been the standard air navigation system to provide aircraft with bearing information with respect to a ground station. The VOR ground station transmission is in the VHF band from 108 to 117.95 MHz, divided into 50 kHz channels modulated by a 30 Hz signal and by a subcarrier of 9960 Hz, which is frequency-modulated (FM) at 30 Hz. The phase of the two 30 Hz signals is adjusted such that the phase coincidence occurs at magnetic north.

The VOR receiver employs a simple superheterodyne front-end followed by an envelope detector and narrow-band filters to separate the individual signal components. The FM signal is demodulated to recover the 30 Hz signal, and the two 30 Hz signals are applied to a phase comparator. The phase difference between these signals corresponds to the magnetic bearing of the aircraft from the ground station. A course selector (i.e., phase shifter) is added to one of the inputs to the phase comparator to permit the pilots to select any desired bearing between 0 and 360°.

The DME system is an electronic range measuring system which provides slant range information to the aircraft. DME is a two-way ranging method with a ground station operating as a transponder. The airborne interrogator transmits pulse pairs at a given ground station frequency and pulse-pair spacing. The ground station detects the presence of the pulse pair when it exceeds some detection threshold. The time of detection of the half-voltage point on the first pulse is used as a time reference for reply. A fixed 50 μs delay is introduced to account for internal delays. This delay can also be used to provide an electronic offset of the
**Instrument Landing Systems**

The ILS is a radio navigation system that provides an equipped aircraft with the horizontal and vertical guidance required for conducting precision landing approaches to the runways in lower-visibility conditions. As shown in Fig. 67.5, the ILS consists of two directional transmitters with a localizer and a glide slope aligned with the runway centerline. The horizontal guidance is provided by a VHF band localizer and the vertical guidance is provided by an ultrahigh-frequency (UHF) band glide slope transmitter. The distance information is provided by the DME, or by low-frequency (LF) marker beacons located at a certain distance from the runway end (threshold), as shown as middle and outer markers in Fig. 67.5. In the NAS, there are approximately 715 airports capable of providing precision instrument approaches. There are three categories of ILS equipment used under different levels of visibility conditions, depending upon when the pilots can see the runway (lights) from a certain height above the ground, called the decision height:

- **Category I:** Visibility minima as low as 1/2 statute mile within 200 ft (60 m) height above touchdown
- **Category II:** Visibility minima as low as 1/4 statute mile within 100–199 ft (30–60 m) height above touchdown
- **Category III:** Visibility minima potentially as low as zero feet within 0–99 ft (0–30 m) height above touchdown.

Although the ILS has proven to be a safe and effective landing aid worldwide, the technology has a number of limitations. First, it is relatively expensive to purchase and install the equipment. The antennae require large clear areas free of metal or metallic reflections, i.e., aircraft taxiing on the airport must be restricted in their position in order to avoid interference with the ILS signal. The ILS equipment must be routinely checked in flight to ensure that it meets the required specifications.

**Satellite Navigation Systems**

There are currently two satellite navigation constellations: the US GPS and the Russian global navigation satellite system (GLONASS), although only GPS is widely used outside of Russia. The implementation of the third and fourth constellations, GALILEO and COMPASS are currently being planned by the European Union and China respectively. Only GPS is discussed in this section, since it is the only operational system widely used by civil aviation.

Each satellite from these constellations continuously broadcasts a signal that carries ephemeris information allowing an accurate calculation of the satellite position and a code allowing for the accurate measurement of the signal propagation time from the satellite to the aircraft. A suitably designed receiver can acquire and track this signal and use the broadcast information, as well as so-called pseudorange measurements derived from the signal propagation time, to compute an accurate position solution every second. Such position solutions, however, do not meet all aviation requirements because their integrity is not assured. Integrity is a measure of trust in relying on the accuracy of the navigation system information, where the system alerts the user when the system is unable to contain the position error within an acceptable limit for safe operation. Several forms of augmentation have been developed in order to obtain the integrity required for aviation. Forms of augmentation that are currently used include a receiver-based technique called receiver autonomous integrity monitoring (RAIM) or aircraft-based augmentation system (ABAS), which uses redundant information from the number of satellites in view to ensure the integrity of the position solutions. Two other augmentation systems are the satellite-based augmentation system (SBAS) and the ground-based augmentation system (GBAS). Each system uses a ground infrastructure to derive corrections and integrity bounds for the satellite signals. The SBAS and GBAS differ in the type of correction and integrity information, as well as the means used to communicate that information to the user receivers. The SBAS is intended to provide service over wide areas and broadcasts the information from the geosynchronous satellites. The GBAS is intended to provide service over terminal areas by broadcasting the information from VHF ground transmitters. A hybrid augmentation system called ground regional augmentation system (GRAS), currently being developed in Australia, provides navigation service over wide areas using a network of VHF ground transmitters.

There are three main types of aircraft receivers for GPS and augmentations. These receivers provide position solutions to other parts of avionics, such as the flight management system (FMS) and the navigators.
which include displays and controls that provide navigation guidance information to the pilots. Certified aircraft GPS receivers with RAIM can be used for en route navigation, terminal area navigation, and nonprecision approaches for landing operations. In addition, the SBAS aircraft receivers can be used for vertically guided approach and landing operations, called the procedures with vertical guidance (APV) approaches. The primary APV in the USA is the localizer performance with vertical guidance (LPV) approach. GBAS aircraft...
receivers can be used for category I precision approach operations in addition to the terminal area navigation.

The SBAS uses a network of ground stations to receive GPS signals. The signals are forwarded to a master station, where atmospheric and other errors are identified, and a grid of corrections is created. This grid is transmitted to the user through a geosynchronous satellite. The user receiver can then interpolate between the corrections and improve the accuracy and integrity (i.e., the assurance, within specifications, that the navigation position is free from error) of the GPS signal. US operations use a wide-area augmentation system (WAAS), which can provide corrected horizontal and vertical guidance throughout the USA and parts of Canada and Mexico. WAAS was commissioned in 2003. A schematic of WAAS is shown in Fig. 67.6. The Japanese have developed the multifunction transport satellite (MTSAT) satellite-based augmentation system (MSAS), which is an SBAS that provides coverage in the Asia–Pacific region. Similarly, the European Union has developed the European geostationary navigation overlay service (EGNOS) that provides SBAS coverage over Europe and Africa. MSAS was commissioned in 2007 and EGNOS is expected to reach initial operational capability in 2009. The Indian government is developing the GPS and GEO augmented navigation overlay service (GAGAN) system, which will provide SBAS coverage over India. MSAS was commissioned in 2007 and EGNOS is expected to reach initial operational capability in 2009. The Indian government is developing the GPS and GEO augmented navigation overlay service (GAGAN) system, which will provide SBAS coverage over India. MSAS was commissioned in 2007 and EGNOS is expected to reach initial operational capability in 2009.

The GBAS uses a ground station located on or near the airport to receive the GPS signals and to correct for errors. The correction information is forwarded directly to the aircraft via a VHF data link. The US GBAS system is called the local-area augmentation system (LAAS) and is shown in Fig. 67.7. Since the GBAS or LAAS station is located on the airport and near the approach path, there is no interpolation required. The LAAS may have the potential to provide category III service for the approach and landing, while the WAAS will be restricted for landing guidance to category I service. Air Services Australia is also developing a GBAS for certification in 2009.

### 67.1.3 Modes of Navigation

**VOR/DME Mode of Radial Navigation**

There are three types of VOR/DME facilities in the US. The difference among the facilities is related to the volume of airspace around each facility that is protected from interference from another facility. This airspace is known as the standard service volume (SSV). The three types are listed below:

- **Terminal (T):** 25 nmi radius from 1000 to 12,000 ft
- **Low (L):** 40 nmi radius from 1000 to 18,000 ft
- **High (H):** 40 nmi radius from 1000 to 14,500 ft, 100 nmi radius from 14,500 to 18,000 ft, 130 nmi radius from 18,000 to 45,000 ft, 100 nmi radius from 45,000 to 60,000 ft

Coverage below 10,000 ft is defined for reduced radii that are altitude dependent. Only H and L facilities are used for en route navigation. All facilities may be used for terminal area maneuvering and nonprecision approaches. Within the SSV, the pilots are assured of a signal with adequate power protected against interference from other facilities transmitting on the same or adjacent frequencies.

The present NAS en route navigation procedures for a majority of aircraft involve flying along VOR radials in or out of the ground station. The low-altitude vector airways and the high-altitude jet routes are defined by these radials like the highways in the sky.

Flights at or above 24,000 ft MSL are not authorized without a DME whenever the instrument flight rules (IFR) require VOR equipment (US regulations permit substitution of an approved GPS receiver for a DME receiver in most cases). The DME equipment is installed in most commercial aircraft and in a large percentage of corporate and some general aviation aircraft. Smaller aircraft flying at lower altitudes may not need a DME. Also, many aircraft owners are replacing DME receivers with GPS receivers.

**Area Navigation (RNAV) and Required Navigation Performance (RNP)**

The RNAV mode of navigation permits aircraft with appropriate equipment to fly any desired path from point to point without the need to overfly ground stations within the coverage of the station limits using either VOR/DME or DME/DME guidance. RNP provides additional assurance of adherence to the desired navigation path. The US is planning to transition to full RNAV operations, with RNP operations where beneficial.

DME/DME RNAV is considered possible in those areas where the radii defining the DME arcs from at least two stations intersect at an angle between 30 and 150°. RNAV using DME/DME is more accurate than RNAV using VOR/DME, particularly at long ranges. The DME/DME-RNAV is feasible over most of the
USA, although some areas will not have appropriate coverage using DME/DME at some altitudes. Aircraft using satellite navigation have service available over the entire USA and can fly RNAV routes and procedures anywhere in the USA.

### Approach and Landing

The instrument approach procedures to a runway involve landing during instrument meteorological conditions (IMC), and allow the approaches to be abandoned when a landing cannot be completed, such as when the weather is too bad to land, another aircraft is on the runway, or some other reason. The instrument approaches are generally divided into two categories: nonprecision approaches, which have only horizontal guidance; and vertically-guided approaches, which have both horizontal and vertical guidance. In a nonprecision approach, the aircraft flies along a published path and descends to remain above the published minimum altitudes during the approach. The aircraft uses its barometric altimeter to determine the minimum altitudes. The last segment of the approach is called the final segment. The final segment starts at the final approach fix (FAF), continues to a missed approach point (MAP), and is usually aligned with the centerline of the landing runway. The pilot is required to see the runway visually prior to landing. For a nonprecision approach, the aircraft departs the final approach segment and flies along the published horizontal path. The pilot descends to the published minimum altitudes. When the runway is in sight, the aircraft continues to land. If the runway is not in sight by the MAP, then the aircraft executes a missed approach. After a missed approach, an aircraft may attempt another landing approach, or may proceed to an alternate airport. Nonprecision approaches can use VOR, NDB, or the global navigation satellite system (GNSS), of which the US GPS is currently the only operational component for civil aviation.

For a vertically-guided approach, the aircraft departs the final approach fix, but has a vertical and horizontal guided path. Vertically-guided approaches typically align the aircraft on a stabilized glide path, and allow the aircraft to continue on the stabilized path until just before landing. The stabilized vertically guided approach is generally considered superior and safer than the nonprecision approach, which often require vertical maneuvering when the aircraft is near the runway, such as after the runway has been acquired visually by the pilot.

Studies have shown that the controlled flight into terrain (CFIT) accident rates are lower for the vertically guided approaches than for the nonprecision approaches. In addition, the visibility minima for vertically-guided approaches are also generally lower. This has led to a general desire to provide vertically-guided approaches (both APV and precision approaches) to all or most runway ends in the US.

Many commercial aircraft have GPS receivers and sophisticated barometric vertical guidance systems. These aircraft can fly lateral/vertical navigation (LNAV/VNAV) and RNP, approaches, using GPS for horizontal guidance and approved barometric vertical navigation approaches for vertical guidance. The LNAV/VNAV approaches do not have sufficient accuracy or integrity to meet Category I minima, but do provide useful vertical guidance. The US has published over 1577 LNAV/VNAV and 234 RNP approaches, primarily to the runways serving commercial aircraft (as of January 2009).

The augmentation systems discussed earlier have the potential to provide vertically guided approaches to more airports and runways at a lower cost. Currently, an ILS must be installed on each runway end where vertical guidance is desired. However, approaches using GPS/barometric vertical navigation, LNAV/VNAV, or WAAS may be permitted without any ground navigation infrastructure. In addition to the LNAV/VNAV, the FAA is currently developing LPV approaches to most instrument runways. The LPV approach is primarily a WAAS vertically guided approach, and has a requirement of visibility minima equivalent to an ILS category I approach. The FAA has published over 1445 LPV approaches (as of January 2009), and plans to publish approximately 300 LPVs per year.

The LAAS system will use the GNSS landing system (GLS) approach. The GLS approach is equivalent to a category I ILS approach, but could also attain category II and category III performance. One LAAS station can serve each runway end at the airport, so there is a potential for reducing the ILS infrastructure and saving costs with LAAS. The LAAS system has not yet been commissioned, so no GLS approaches have been developed at this time.

#### 67.1.4 ATC Surveillance Systems and Aircraft Tracking

**ATC surveillance** refers to the process of determining where aircraft currently are in a given volume of airspace. **Aircraft tracking** refers to the process of correlating successive measurements of various aircraft positions with the identified flights, thereby forming a hist-
tory or track of positions, where each flight has recently been. Time-averaging the successive changes in a given aircraft’s track position yields an estimate of that aircraft’s current position and velocity. Given the aircraft’s current position and velocity, its next position can be predicted for the purpose of surveillance data correlation.

ATC Surveillance Radar Systems

ATC surveillance systems locate weather and aircraft, which enable the ground controllers to separate aircraft safely by providing pilots with surrounding aircraft and weather advisory information. They involve both the ground and aircraft components. Two types of systems are currently used for aircraft surveillance:

- Search or primary radar (radio detection and ranging)
- Beacon or SSR.

The primary radar is so called because it was the first radar system developed and fielded for ATC. The secondary radar was the second radar system developed and fielded, and is used as the major radar for ATC surveillance today. Whenever the secondary radar fails, the primary radar serves as a backup. The primary radar also fills in the coverage for secondary radar dropouts. The primary radars detect two-dimensional (2-D) horizontal position of aircraft by sensing radar energy reflected from the surface of the aircraft. Although the primary radars provide aircraft position in terms of range and azimuth, other relevant data about an aircraft’s identification and its altitude are not available. The primary surveillance is noncooperative, i.e., it detects aircraft position without the aid of an aircraft-based transmitter/receiver unit, termed a transponder. The primary surveillance systems are used to detect all airborne objects, including aircraft with such failures as loss of electronic power or failure of the transponder.

The secondary surveillance came about in an attempt to overcome some of the limitations and deficiencies of primary surveillance. The secondary surveillance is cooperative, because it requires the aircraft transponders in order to detect aircraft, to positively identify aircraft, and also to receive altitude reports of aircraft, depending on the transponder mode. The SSR requires the aircraft to be equipped with a transponder. The SSR ground station transmits radio frequency at 1030 MHz pulses from a rotating antenna. Upon receiving the ground signal, the transponder transmits a reply on a different frequency 1090 MHz. The aircraft range ($\rho$) and bearing ($\theta$) are determined from the time delay and radar antenna direction [67.7]. Most airports and TRACONs in the USA use short-range radar or an airport surveillance radar (ASR). These radars provide surveillance coverage up to 60 nmi and 30,000 ft. The ARTCCs use air route surveillance radars (ARSR), which have a range of about 200 nmi and coverage up to 60,000 ft. A mode C transponder transmits altitude information.

The digital terminal radars using monopulse technology are ASR-11 and mode select sensor (mode S), and the en route ARSR are ATC beacon interrogators (ATCBI-6). The terminal radars provide position information updates every 4–5 s, and the en route radars update every 10–13 s. Generally the primary radar and the SSR antennae are collocated to detect 2-D aircraft positions consistently. The primary airport surveillance is provided by an airport surface detection equipment (ASDE-3), and the secondary surveillance by ASDE-X using multilateration techniques.

Ground Automation Systems and Functions

The en route and terminal automation systems convert target position ($\rho$, $\theta$) into Cartesian coordinates, and correlate targets with the aircraft tracks. A track maintains state data for an aircraft across the radar scan updates. The tracker derives additional data such as the aircraft ground speed and heading for display. The velocity (speed and heading) information is also used in the aircraft track prediction, and by higher-level automation functions such as conflict alert (CA) and minimum safe warning altitude (MSAW), discussed later. The tracks can be automatically or manually initiated by the controller. All IFR aircraft are required to file a flight plan. When there is flight plan data available in the system, a track is automatically associated with the flight plan so that the flight data, such as the aircraft identification, is included with the speed, heading, and altitude in the displayed alphanumeric tag (in the form of a data block on the controller’s display). If a target correlates with a track, the target position is used to update the position of the display symbol, which the controllers use for aircraft separation. If no target information is received in a scan, then the predicted track position is used to update the aircraft position on the display.

The terminal automation system initially included only single-radar displays, where all target data were received from only a single controller-selected radar site. The latest automation system upgrades provide a mosaic display selection to the controllers. The mosaic partitions the surveillance area into a grid with different cells assignable to different radar sites. The en route automation system includes an ARTCC facility-wide
mosaic display. The automation system processes digitized radar weather messages and handles display formatting. The map messages are converted into display messages with \(x\), \(y\) coordinates, and transmitted to the display channel along with the radar flight target data for display.

### 67.1.5 Aircraft Tracking

The ground ATC automation system provides aircraft position, velocity, and altitude information to the controllers to help them ensure safe separation between aircraft based on established separation minima. These minima are based on the accuracy and frequency or update rate of aircraft position data and altitude displayed to the controller. Moreover, each aircraft must be positively identified and accurately displayed. The NAS tracking system and the automated radar terminal system (ARTS), as a part of en route and terminal automation systems, respectively, process radar position inputs to track aircraft and display information to the controllers.

The aircraft tracking function computes the position and velocity of all tracked aircraft within the ARTCC’s radar coverage, and provides the means for maintaining identity information (in alphanumeric form) with the appropriate search and beacon targets on the radar controller’s display. Because of the cooperative nature of ATC, flight plan information concerning the planned route of flight, aircraft speed, altitude, and assigned beacon identity code are used in the processing by this function. The current tracker used in both the en route and terminal automation systems is a linear \(\alpha, \beta\) tracker. With the position update rates mentioned earlier, the tracker lags in detecting positions accurately during aircraft maneuvers. The future automation system enhancements will include a seven-state interactive multiple model (IMM) Kalman filter tracker including \(\alpha, \beta\). With the position update rates mentioned earlier, the tracker lags in detecting positions accurately during aircraft maneuvers. The future automation system enhancements will include a seven-state interactive multiple model (IMM) Kalman filter tracker including \(\alpha, \beta\), \(x, \dot{x}\), \(y, \dot{y}\), \(z, \dot{z}\), and turn rate to improve accuracy of position and velocity determination not only during straight and level flight, but also during maneuvers.

The accuracy of position and velocity determination by the tracking function is crucial in maintaining the desired separations between aircraft. Thus, in the future, as the aircraft surveillance and tracking accuracy improve, they could support reduction of minimum separation requirements, thereby not only helping to maintain safety but also to increase airspace/airport capacity. The ongoing deployment of standard terminal automation replacement system (STARS) uses a multisensor (instead of a single sensor in ARTS) IMM Kalman filter tracker to significantly improve the accuracy of position and velocity estimation.

#### Automatic Dependent Surveillance-Broadcast (ADS-B)

The radar systems discussed above provide independent surveillance for detecting aircraft. In order to enhance not only the accuracy of position/velocity determination, but also to increase coverage NAS-wide (current limitation of radars in remote/mountain areas in the USA), the ADS-B system provides cooperative surveillance by broadcasting the GPS-derived position information once every second using onboard navigation equipment. The ADS-B broadcasts include aircraft identification, position, velocity, and intent (future aircraft positions) within 100 nmi. Other aircraft equipped with an ADS-B receiver can process and display the aircraft in their vicinity on a display called the cockpit display of traffic information (CDTI). The ADS-B receivers on the ground can also receive the aircraft broadcast information. The large commercial aircraft use a 1090 MHz mode S extended squitter, and the smaller high-end general aviation aircraft use a universal access transceiver (UAT) 978 MHz for transmitting ADS-B information. The aircraft and the ground stations receive information from all line-of-sight aircraft.

ADS-B is currently being used in the State of Alaska, where there is limited radar coverage. Efforts are underway to provide ADS-B information along the US east coast from New Jersey to Florida. In spite of higher accuracy and update rate, the use of ADS-B as a single surveillance system has limitations. Any loss of, or errors in, the GPS signals could adversely impact the aircraft detection. Therefore it is also necessary to continue using primary and secondary surveillance radars complemented by ADS-B. The future automation and tracking system will derive a unique single track for each aircraft using ADS-B and radar measurements by using data fusion techniques.

### 67.1.6 Air Traffic Management Functions

#### Traffic Flow Management

The TFM function is responsible for managing the NAS airspace/airport capacity resources by efficiently balancing the demand for air traffic services with available system capacity. The TFM monitors expected demand to produce safe, orderly, and expeditious flow of traffic to minimize delays due to congestion and adverse weather. The ATCSCC has the authority to direct strategic planning of TFM initiatives on a national basis, and
is the final approving authority for all regional interfa-
cility TFM initiatives. It has four key responsibilities:

- Monitor air traffic demand, status of airports and
  airspace, and forecasted weather across the USA
- Coordinate with regional and local facilities to
  plan and implement traffic flow constraints (aircraft
  ground delays, ground hold/stops, altitude restric-
tions, rerouting etc.)
- Assess NAS performance for long-term improve-
ments
- Provide a central point of contact for the NAS users.

The TFM initiatives include:

- For more than 6 days in advance, plan strategies
  to identify long-term system demands and airspace
  choke points, as well as recommend operational and
  procedural changes
- From 6 days to 1 day in advance, predict near-term
  traffic loads and use weather forecasts to develop
  strategies for balancing traffic demand and capacity
- On the day of operations, analyze the impact of
  planned constraints based on flight schedules and
  predicted weather, as well as collaborate with the
  users for dealing with the constraints and dem-
  and/capacity imbalance
- After the day of operations, analyze the archived
  operations data to assess effectiveness of the traffic
  flow initiatives.

The regional (ARTCC) and local (TRACON) TFM
functions deal with daily and hourly operations by bal-
ancing the demand with the predefined sector (segments
of airspace within the jurisdiction of each facility) capacity.

As part of TFM automation, the enhanced traffic
management system (ETMS) provides NAS-wide in-
f ormation on traffic loads at capacity-limited resources
such as the airports, routes, route merge points (fixes),
and airspace sectors. The two components of the TFM
automation system are the traffic situation display,
which provides a map-oriented display for showing
aircraft positions, routes, and weather data, and the
monitor/alert function, which alerts when the traffic
demand in sectors or at fixes is predicted to exceed pre-
determined threshold values. A flight schedule monitor
provides capabilities to predict airport congestion, and
supports planning and monitoring of ground delays as
a part of ground delay program (GDP).

### Air Traffic Control Services

The primary task of the ATC function is to safely guide
and separate aircraft flying under IFR, i.e., monitor
and maneuver aircraft to keep them separated by the
established separation minima and provide navigation
guidance in the airspace where there is no navigation
coverage. The following are specific clearances issued
by the controllers to service flights from gate to gate:

- Taxi/runway assignment: when the aircraft is ready
to depart, the ATC function issues a clearance for
the aircraft to start taxiing on an assigned taxiway
and wait before the entry to the assigned runway
with a clearance to take off. Similarly the aircraft
are given landing clearances to specific runways.
- Departure/arrival guidance: unless the aircraft are
capable of flying RNAV procedures from/to the air-
ports, the controller provides navigation guidance in
the airspace around the airport where there is no
navigation guidance available in the form of vec-
tors. These are compass headings that the pilots are
required to fly under ground system monitoring. In
addition, the controllers issue altitude changes and
speed adjustments to prevent conflicts by maintain-
ing the required distance spacings between aircraft
for safety. For departures, the navigation guidance is
provided from radar contact (when an aircraft has
been positively identified on the radar display) until
the aircraft is able to navigate on its own. For ar-
rivals, the guidance is provided from the entry into
the terminal airspace, or from the termination fix of
a standard terminal arrival route (STAR), to the final
approach course for landing.
- Separation from other aircraft: once the aircraft are
en route, the controllers ensure that each aircraft
is safely separated from all other aircraft in accor-
dance with the prescribed rules. When the desired
minimum separation is expected to be violated, the
controllers issue altitude/heading/speed clearances
increase separation.
- Safety alerts: controllers provide the aircraft with
low-altitude or obstruction warnings based on in-
formation provided by MSAW; wake turbulence
cautionary advisories, in case lighter aircraft are
following a heavy aircraft; and information on haz-
ardous weather, such as wind shear, using Doppler
weather radars and low-level wind-shear alert sys-
tem (LLWAS).
67.2 Functional Role of Automation in Aircraft for Flight Safety and Efficiency

As digital computers have become smaller, faster, more powerful, and more robust over the past decades, aircraft have benefited from their use in the cockpit to automate key functions. In the late 1970s and early 1980s, for example, automation was aimed primarily at reducing the pilot workload of managing complex aircraft systems such as electrical, hydraulic, fuel, and pressurization. This led to the elimination of the flight engineer position in the aircraft. Automation in modern aircraft has been effectively applied to enhance flight safety and efficiency. Although the enhanced ground proximity warning system and the predictive windshear detection system alert the pilots to stay away from dangerous terrain and dangerous weather conditions, the traffic alert and collision avoidance system (TCAS) is the most significant capability in the cockpit for warning pilots about the presence of other aircraft in the vicinity.

The TCAS has its hardware and software integrated with the other systems in the aircraft cockpit. Its purpose is to avoid midair collisions, acting as a last-minute safety net when normal aircraft separation measures have failed. The TCAS issues radio interrogations that query ATC transponders carried onboard most aircraft. Measuring the time of the replies enables the calculation of each aircraft’s slant range. The tracking of an aircraft’s slant range every second yields the aircraft’s closure rate. The reply also provides the aircraft barometric altitude, which can be compared to that of its own.

There are two different versions of TCAS for use on different classes of aircraft. The first, TCAS I, indicates the bearing and relative altitude of all aircraft within a selected range (generally 10–20 miles). With color-coded symbols and aural alerts, the display indicates which aircraft pose potential threats. This constitutes the traffic advisory (TA) portion of the system. TCAS I does not offer solutions to resolve the conflicts, but does supply pilots with important data so that they can determine the best course of action. The determination of a potential collision threat is time based, rather than based on a fixed distance, as is used by the ground automation functions. The calculation of the time to potential conflict \( \tau \) is given by

\[
\tau = -(r - k^2 / \dot{r}) / \dot{r},
\]

where \( r \) is the tracked range, \( \dot{r} \) is the estimated relative divergent range rate, and \( k \) is a constant for a given altitude. Another time calculation is used for the vertical plane.

TCAS uses a modified \( \tau \), which predicts the time to a specified minimum distance. This distance allows for some lateral acceleration, without which TCAS could provide inadequate warning time.

In addition to a traffic display, the more comprehensive TCAS II also provides pilots with vertical resolution advisories (RA) when needed. The system determines the vertical profile of each aircraft during climbing, descending, or level phase of flight. The TCAS II then issues an RA advising the pilot to execute an evasive maneuver necessary to avoid the other aircraft in the form of climb or descend, or limiting vertical rates. If both aircraft are equipped with TCAS II, then their systems coordinate to ensure compatible RAs.

As the cost of fuel has risen, automation is also used to enhance the efficiency of flight operations by employing thrust and energy state management techniques. The FMS on a modern transport-category aircraft takes inputs from a wide range of sensors, and couples these with data from a comprehensive navigation and flight performance database. The FMS generates an optimum flight profile in order to achieve the operator’s objectives of minimizing direct operating costs, which are made up of flight time and fuel-related costs.

The FMS includes a flight management computer system (FMCS) coupled with a flight guidance system, a thrust management system, and an electronic flight instrument system (EFIS) to provide total flight management capabilities. The FMCS consists of two flight management computers (FMC) and multiple control display units (MCDU) to provide pilot interface for data entry/review. The FMC provides flight planning and performance management, navigation database storage and retrieval, precise navigation and guidance, and interface with other aircraft systems. Using the current computed vertical profile data from the performance function, the guidance function compares actual and desired altitude and altitude rate, and generates pitch and thrust commands as input to the flight guidance and control (autopilot) and thrust management systems, respectively. These systems include autopilots, flight directors, and an autothrottle. Each autopilot uses a flight control computer (FCC), which signals movement of aircraft ailerons and elevators. The autopilot captures and holds the selected altitude when in vertical speed, altitude change, or vertical navigation mode. The au-
to the throttle adjusts the throttles to achieve the desired speed. The EFIS function of the FMC provides dynamic and background data to the EFIS symbol generator as well as selection of nav aids.

The FMCS functions include:

- Flight plan management: provides on board flight planning from a global database including pre-defined routes.
- Guidance: by integrating precise position and on-board flight planning information, provides three-dimensional (3-D) navigation plus speed or four-dimensional (4-D) navigation including 3-D and time. Lateral guidance provides precise path control and smooth maneuvers at turning points. Vertical guidance provides precise vertical path control.
- Performance management: provides optimum speed, altitude, and thrust settings to minimize operational costs. A choice of economy or alternative flight modes is also available.

The aircraft operator, for example, can select at the outset what is most important to the airline’s bottom line for that particular flight (operating at minimum fuel cost, operating with minimum flight time, or a blend between the two). The FMCS then determines the optimum vertical profile and speed schedule for the flight, taking into account all known factors such as en route winds, temperatures, and aircraft weight. The FMCS constantly refines its output to account for any change in actual winds or temperature. The wind field data that provides the FMCS with information on future waypoints is easily uplinked to the aircraft using an air–ground data link. If the flight is not constrained by the ATC restrictions, the flight profile dictated by the FMCS will be the optimum. In the case when the ATC constraints are imposed, the FMCS will still provide an optimum profile within those constraints.

In many implementations of the modern FMS, the management of the speed and altitude profiles effectively replace the shortcomings of the non-FMS relic of look-up performance tables and rules of thumb. The FMCS outputs can be fed directly to the aircraft autopilot/flight director system (APFDS), thereby reducing workload for the pilot and making him/her better aware of the progress of the flight flown by the automation system.

67.3 Functional Role of Automation in the Ground System for Flight Safety and Efficiency

In the ground automation system, two functions, MSAW and CA, provide safety alerts to the controllers in all ARTCCs and most TRACONS. The MSAW checks aircraft tracks for current and predicted conflicts with a terrain, and the CA checks for aircraft-to-aircraft conflicts. Both functions alert the controllers through display indications and audible outputs. The user request evaluation tool (URET) is an automation system deployed in the ARTCCs to detect potential conflicts 20 min in advance in order to help controllers take early decisions to resolve aircraft-to-aircraft and aircraft-to-airspace conflicts.

67.3.1 Minimum Safe Altitude Warning

The MSAW function is used to detect the proximity of aircraft to a terrain or surface obstructions. It uses two subfunctions for detecting hazards. One subfunction detects the proximity of an aircraft on the final approach for landing to the required minimum descent altitude or the decision height for the approach. The second subfunction is used to detect whether the aircraft is in hazardous proximity to a terrain outside the approach areas. The location of the aircraft is compared against an internally defined digital map containing the heights of the highest obstructions within the defined areas. When a hazard is detected, the automation system produces a visual alert by displaying a flashing symbol near the affected aircraft. The automation system also sets off an alarm when a hazard is detected.

67.3.2 Conflict Alert

The CA function detects an imminent loss of separation between two controlled aircraft that could lead to a potential mid-air collision. It can detect conflicts both for those aircraft that are traveling in a straight line and for those that are executing turns in a maneuver. When an alert is detected, the automation system displays a flashing symbol next to the positions of the aircraft that are in jeopardy. The CA function also sets off an aural alarm to warn the controller that a conflict has been detected.
Potential conflicts, defined by a horizontal separation parameter and an altitude separation parameter, are detected by projecting a volume of airspace constructed about each track along its velocity vector from its present position to a position some time in the future. En route CA function typically uses a horizontal parameter of 4.8 nmi, an altitude of 1000 ft, and a projection time parameter of 120 s. The corresponding terminal CA function uses the horizontal parameter of 1.2 nmi, 375 ft vertically, and a projection time of 40 s. The CA function considers only the aircraft tracked by the ground automation systems with valid altitude information. If another aircraft is found within the volume of the projected airspace for a given subject aircraft, a potential conflict is declared and an indication is given on the displays for the sector(s) controlling the aircraft.

67.3.3 User Request Evaluation Tool

The URET [67.8] replaces flight progress strips with electronic flight information, thereby reducing the need to maintain and mark strips. In addition, URET notifies the controllers of aircraft-to-aircraft separation problems and aircraft-to-special activity airspace problems.

The URET is a decision support function that combines real-time flight plan and en route automation track data with site adaptation, aircraft performance characteristics, and winds and temperatures aloft to construct four-dimensional (4-D) flight profiles, or trajectories for both predeparture and active flights. For the latter, it also adapts itself to the observed behavior of the aircraft, dynamically adjusting predicted speeds, climb, and descent rates based on the performance of the flight as it is tracked through the en route airspace. The URET’s predicted trajectories are used to continuously detect potential aircraft conflicts up to 20 min into the future, and to provide strategic notification to the appropriate controllers. These trajectories also provide the basis for the NAS trial flight planning capability. The trial flight planning process allows the controllers to check if a desired change in an aircraft flight plan would result in potential conflicts with other aircraft later, before such a change in the flight plan is approved.

67.3.4 Traffic Management Advisor

The traffic management advisor (TMA) is a decision function supported by the en route automation in the ARTCCs to assist traffic management personnel and controllers in optimizing arrival traffic flows to capacity-constrained airports. The TMA uses aircraft trajectory models, real-time radar track data, flight plan data, and wind data updated every 12 s to compute optimal schedule arrival times at the TRACON entry (meter) fixes. The TMA algorithms consider IFR separation minima for the airspace and final approaches to the runways, desired airport acceptance rates, and other ATC constraints. They determine the delays for the aircraft while they are still in the en route airspace controlled by the ARTCC so that the desired airport acceptance rates are not exceeded.

The TMA is intended to enhance the efficiency of flight operations and increase throughput relating to airport capacity during periods of peak traffic demand [67.9]. The aircraft-specific time delays are displayed to the controllers. It is at the controller’s discretion to maneuver the aircraft to achieve the required delays. The TMA is intended to help controllers land more aircraft per unit time, and redistribute the unavoidable delays for aircraft from the lower (near the airport) to higher altitudes in the ARTCCs for fuel efficiency and reduced direct operating costs. Additionally, the TMA is expected to reduce flight time for aircraft by reducing holding and vectoring outside of the TRACON airspace. This is achieved by coordinating and optimally sequencing flights to the runways arriving from different directions.

The MSAW and the CA functions have been implemented in both the en route and terminal automation systems for a number of years. The URET and TMA functions are being deployed, and all ARTCCs will have them in use in the near future.

67.4 CNS/ATM Functional Limitations with Impact on Operational Performance Measures

As stated earlier, the current CNS/ATM functions provide information to the pilots and controllers, and most of the decisions in the aircraft and on the ground are made open loop manually. The primary requirement is to conduct safe flight operations by following a set of separation rules either by maintaining a safe distance between the aircraft or safe altitude separation. The controllers manually trying to achieve these separations between aircraft by relying on tracked aircraft position and velocity information often permit larger separations.
than the required minimums by adding a safety buffer. The use of distance separations larger than the desired minimum reduces capacity, especially at airports. With fewer aircraft permitted to depart and land than the separation minima would otherwise allow, delays due to the reduced capacity add operating costs for the users. In order to delay aircraft in the air while trying to meet the safe separation objectives, the controllers deviate aircraft from their desired optimum paths by issuing additional clearances to maneuver the aircraft by changing their paths, altitudes or speeds. Any deviations from the desired minimum flight profiles increase workload for both the controllers and the pilots, who have to manually fly the aircraft during these maneuvers, while the controllers continue to monitor aircraft compliance to the changes.

Figure 67.8 illustrates the impact of separation minima on the operational performance measures relating to flight safety, airport capacity, aircraft operational efficiency, and controller workload, which are discussed below.

### 67.4.1 Current Separation Minima for Controlled IFR Aircraft

For all controlled aircraft using IFR, the radar-tracked position, velocity, and altitude information are used by the controllers to keep the aircraft separated using the separation minima rules presented in Table 67.1. The separation requirements apply in all controlled airspace, except during the departure and landing phases of flight. These are based upon the radar resolution accuracy and update rate in the horizontal domain, and on the accuracy of the altimeter in the vertical domain. In addition to the radar tracking capabilities, the longitudinal or in-trail separation minima on the final approaches also depend upon the aircraft wake turbulence. All aircraft generate a wake, which is a disturbance caused by a pair of counter-rotating vortices trailing from the wing tips. The strength of these vortices depends upon the size/weight of the leading aircraft and affects the trailing aircraft by imposing rolling moments exceeding the roll-control capability of the aircraft behind. Because of this wake turbulence effect, the controllers are required to use larger separations for trailing aircraft behind larger or heavier aircraft, including a Boeing B-757. These rules directly impact the capacity of the NAS [67.10, 11].

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**Minimum Lateral Separation between Adjacent Routes**

Two aircraft navigating on different airways must have their route centerlines separated laterally by 8 nmi as long as the aircraft are less than 51 nmi from
### Table 67.1 Separation minima

<table>
<thead>
<tr>
<th>Flight phase</th>
<th>Separation minima</th>
<th>Requirements</th>
<th>Controlling factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>En route airspace</td>
<td>5 nmi horizontal</td>
<td>Below 60,000 ft, if multiple radar sensors (mosaic mode) used or either aircraft is more than 40 nmi from antenna, and 60 nmi if mode S surveillance is used</td>
<td>Radar resolution accuracy and update rate</td>
</tr>
<tr>
<td>En route path width</td>
<td>8 nmi</td>
<td>Adjacent route separation minima</td>
<td>Navigation mode and system accuracy</td>
</tr>
<tr>
<td>Terminal airspace</td>
<td>3 nmi horizontal</td>
<td>Below 18,000 ft, if radar in single-sensor mode and both aircraft within 40 nmi of antenna</td>
<td>Radar resolution accuracy and update rate</td>
</tr>
<tr>
<td>All airspace</td>
<td>2000 ft vertical</td>
<td>Above 29,000 ft</td>
<td>Altimeter accuracy</td>
</tr>
<tr>
<td></td>
<td>1000 ft</td>
<td>Above 29,000 ft (RVSM*) or all aircraft at or below 29,000 ft</td>
<td>RVSM certified altimeter above 29,000 ft</td>
</tr>
<tr>
<td>Successive arrivals – Same runway or parallel runways spaced &lt; 2500 ft apart</td>
<td>Longitudinal: 3.0 nmi</td>
<td>Radar in single sensor mode and both aircraft within 40 nmi of the antenna</td>
<td>Radar resolution accuracy and update rate</td>
</tr>
<tr>
<td></td>
<td>2.5 nmi</td>
<td>On final approach, if runway occupancy time is 50 s or less and no wake turbulence effect</td>
<td>Runway occupancy time</td>
</tr>
<tr>
<td></td>
<td>4/5/6 nmi</td>
<td>Behind a heavy aircraft or B757 (depends on trailing aircraft type)</td>
<td>Wake turbulence</td>
</tr>
<tr>
<td>Parallel approaches – Independent ILS approaches to dual runways</td>
<td>Simultaneous operations once established on final approach</td>
<td>Runways ≥ 4300 ft apart</td>
<td>Blunder recovery</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Require ASR</td>
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<td></td>
<td></td>
<td>Runways 3400–4300 ft apart</td>
<td>Radar resolution accuracy and update rate</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Require final monitor aid or PRM</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td>Runways 3000–3400 ft apart</td>
<td>Localizer resolution **</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Require PRM and 2.5° localizer offset</td>
<td></td>
</tr>
<tr>
<td>Parallel approaches – Dependent ILS approaches to dual runways</td>
<td>2.0 nmi diagonal between aircraft on adjacent runways</td>
<td>Runways ≥ 4300 ft apart</td>
<td>Blunder recovery</td>
</tr>
<tr>
<td></td>
<td>1.5 nmi diagonal between aircraft on adjacent runways</td>
<td>Runways 2500–4300 ft apart</td>
<td>Wake turbulence is an issue below 2500 ft runway spacing</td>
</tr>
<tr>
<td>Successive departures – Same runway or parallel runways spaced &lt; 2500 ft apart</td>
<td>1.0 nmi</td>
<td>Courses diverge by 15° or more (not behind heavy/B757)</td>
<td>Radar separation</td>
</tr>
<tr>
<td></td>
<td>2.0 nmi increasing to 3.0 nmi</td>
<td>Courses do not diverge</td>
<td>Wake turbulence</td>
</tr>
<tr>
<td></td>
<td>Wake vortex separation: – Distance (see above) – Time (2 min)</td>
<td>Radar separation</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Behind a heavy/B757 aircraft</td>
<td>Wake turbulence</td>
</tr>
<tr>
<td>Simultaneous departures – Parallel or nonintersecting runways</td>
<td>Simultaneous operations</td>
<td>Parallel runways separated by 2500 ft or more and courses diverge by 15° or more</td>
<td>Radar separation</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Non intersecting runways with courses diverge by 15° or more</td>
<td>Wake turbulence</td>
</tr>
<tr>
<td>Departure and arrival – Same runway</td>
<td>2.0 nmi increasing to 3.0 nmi</td>
<td>Within 40 nmi of the radar antenna</td>
<td>Radar separation</td>
</tr>
<tr>
<td></td>
<td>2.0 nmi increasing to 5.0 nmi</td>
<td>Not within 40 nmi of the radar antenna</td>
<td>Radar resolution accuracy and update rate</td>
</tr>
</tbody>
</table>
Table 67.1 (cont.)

<table>
<thead>
<tr>
<th>Flight phase</th>
<th>Separation minima</th>
<th>Requirements</th>
<th>Controlling factor</th>
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</thead>
<tbody>
<tr>
<td>Departure and arrival – Same runway</td>
<td></td>
<td>Within 40 nmi of the radar antenna</td>
<td>Radar separation</td>
</tr>
<tr>
<td></td>
<td>2.0 nmi increasing to</td>
<td>Radar resolution accuracy and update rate</td>
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<tr>
<td></td>
<td>3.0 nmi</td>
<td></td>
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</tr>
<tr>
<td>Departure and arrival – Parallel or nonintersecting runways</td>
<td>2.0 nmi increasing to 5.0 nmi</td>
<td>Not within 40 nmi of the radar antenna</td>
<td>Radar separation</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Thresholds are even ***</td>
<td>Wake turbulence</td>
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<tr>
<td></td>
<td></td>
<td>Runway thresholds are at least 2500 ft apart</td>
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<td></td>
<td></td>
<td>Missed approach and departure courses diverge by</td>
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<td></td>
<td></td>
<td>at least 30°</td>
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<td>Missed approach by a heavy jet cannot overtake</td>
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<td>departing aircraft</td>
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</table>

* Aircraft equipped with required vertical separation minimum (RVSM) certified altimeter;  
** RNAV/RNP arrivals may reduce lateral deviations and enable arrivals to runway with separation less than 3400 ft without the need to offset one of the approaches;  
*** Staggered thresholds increase or decrease the runway separation required.

### 67.4.2 Flight Safety Assessment Metrics

In spite of millions of operations over the years, there have been an insignificant number (1198 from 1959 to 2006) of passenger aircraft accidents [67.12] as a result of controllers enforcing the above separation minima. US and Canadian operators were involved in only one-third of these accidents. However, due to system inaccuracies and human judgment, aircraft sometimes come closer to each other than the established separation minima. In order to minimize the number of separation violations, the controllers add an extra buffer to the desired separation, especially during the landing phase of flight where wake turbulence could be critical to aircraft safety. Even with the increased separation between aircraft due to the added buffer, there are still flights that occasionally end up with less than the desired minimum separations. In order to assess and analyze the causes of reduced separations, the following two performance measures are determined from the recorded operational data or controller/pilot reports [67.13]:

- **Operational errors**: an occurrence attributable to an element of the ATC system in which less than the applicable separation minima results between two or more aircraft, or between an aircraft and the terrain or obstacles (e.g., operations below the minimum vectoring altitude, equipment/personnel on runways, or aircraft lands or departs on a runway closed to operations after receiving air traffic authorization).

- **Operational deviations**: an occurrence attributable to an element of the ATC system in which the applicable separation minima, as referenced above, in the operational error were maintained, but the aircraft penetrated the airspace that was delegated to another airspace sector or facility without prior coordination and approval; or an aircraft, vehicle, equipment, or personnel encroached upon a landing area that was delegated to another position of operation without prior coordination or approval.

The ATC system continues to work on mitigating the causes of the above errors and deviations.

### 67.4.3 Determination of Airport Capacity

Even though the traveling public is the ultimate user of the NAS resources, from an operational perspective, what matters most is the actual number of flight operations that the CNS/ATM system is able to handle without delays. The separation rules no doubt are intended to ensure safety, but they also directly relate to airport capacity. These separation requirements limit the number of operations when the traffic demand is heavy. Often airspace congestion is caused by traffic demand exceeding the airport capacity. Consequently, maximum utilization of airport capacity is paramount to keeping the flight delays to a minimum. The allowable operations at an airport depend upon a number of separate elements including the surrounding airspace, the runways...
and taxiways, the gates and parking apron, and the terminal building (including ticket counters, security gates, and baggage claim areas). Any one of these elements could limit the number of passengers that can be accommodated per unit time (hourly, daily) at an airport.

The airport capacity is defined as the maximum sustainable runway throughput of aircraft arrivals and departures on a long-term basis, given continuous sustained traffic demand. Although the actual throughput may be different in a given hour, due to short-run variations in aircraft mix, control procedures, etc., the measure of theoretical capacity is relevant for comparison of operational performance at airports, or developmental alternatives to enhance capacity at a given airport. The following factors are part of the airport capacity estimation process [67.14]:

- Aircraft characteristics:
  - Final approach speed
  - Runway occupancy time (ROT) – mean and standard deviation (the ROT for arrivals is the average time interval from the time an aircraft crosses the runway threshold to the time when it exits the runway)
- Aircraft fleet mix (percentage of different aircraft types and/or weight classes)
- Separation minima (as discussed in Table 67.1):
  - Minimum arrival separations (arrival–arrival)
  - Minimum arrival/departure separation for the shared runway
  - Minimum departure separations (departure–departure)
  - Minimum interarrival separation (minimum required separation distance plus a performance buffer for safety)
- Relative percentage mix of arrivals and departures, or an arrival/departure ratio, for a given time period
- Performance spacing buffer.

As mentioned earlier, a buffer is added for safety to the required minimum separation distance between successive arrivals. This buffer reflects the variations in aircraft performance, as well as the manual control process for turning aircraft for the final approach. The buffer was estimated based on data collected in the USA in the 1970s, but is still used in estimating capacity for the airports. This buffer was determined to be a normally distributed interarrival error of 18 s (1σ) to reflect the spacing error at the threshold [67.14]. The mean interarrival separation is assumed to be 1.65σ above the minimum desired separations. This 5% approximation is a modeling construct only to account for a number of factors primarily relating to speed variability. It does not imply that 5% of the actual aircraft pairs in-

<table>
<thead>
<tr>
<th>Aircraft weight classes</th>
<th>Leading aircraft type</th>
<th>Heavy</th>
<th>B757</th>
<th>Large</th>
<th>Small</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trailing aircraft</td>
<td></td>
<td>Heavy</td>
<td>4</td>
<td>4.5</td>
<td>2.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>B757</td>
<td>5</td>
<td>4</td>
<td>2.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Small</td>
<td>6</td>
<td>5</td>
<td>4</td>
</tr>
</tbody>
</table>

Table 67.2 Wake vortex interarrival separation (nmi)

Fig. 67.9 Interarrival time determination
trail lack minimum desired separation. Although it is possible that the actual interarrival spacing could be represented by other distributions, the FAA airport capacity model has always used a normal distribution. The model is intended to provide an estimate of airport capacity for relative comparison purposes. It is not intended to estimate an actual controller’s ability to achieve a certain level of arrival throughput. Table 67.2 shows the required separation minima between successive arrivals based on the wake vortex considerations for different weight classes of aircraft. Figure 67.9 shows the delineation of interarrival time (IAT) given by

\[
IAT = \frac{\text{Desired minimum separation} + 1.65\sigma}{\text{Final approach speed of trailing aircraft}}
\]  

(67.3)

Airport Capacity for Arrival Operations on a Single Runway

The arrival capacity [67.15] is computed by determining the average time between successive arrivals, and inverting this time to find the maximum number of arrivals per hour.

\[
\text{Capacity} = \frac{3600 \times \text{Average time separation between departures}}{3600 \times \text{TAA}}.
\]  

(67.4)

The required time separation for each aircraft class pair \((TAA(i, j))\) is determined by comparing the arrival runway occupancy time of the lead aircraft \(i\) and the IAT over the runway threshold for the aircraft pair \(ij\), and selecting the larger of these two values. The frequency with which each aircraft class pair would occur is assumed to be the product of their individual frequencies, e.g., the frequency of occurrence of the class pair \(i, j = \%i \times \%j / 10000\). Therefore, the average time separation between arrival pairs is computed as the sum over all class pairs of the product of \(TAA(i, j)\) and the frequency with which the pair is expected to occur.

\[
\text{TAA} = \sum_{i,j} TAA(i, j) \times \%i \times \%j / 10000.
\]  

(67.5)

In determining the arrival runway occupancy time and the landing time between arrivals, the airport capacity estimation process used is an airport capacity model (ACM) that considers the variability of aircraft, pilots, and controllers, as expressed by the standard deviations of arrival runway occupancy time and arrival–arrival time separation. In addition, to determine the time between arrivals over the runway threshold, the ACM considers the final approach velocities of the aircraft pair and the length of the common final approach path. If the velocity of the trailing aircraft is less than the velocity of the lead aircraft, the specified minimum arrival–arrival separation is considered at the merge point of the two approach paths.

Airport Capacity for Departure Operations on a Single Runway

The capacity of a departure-only runway is given by

\[
\text{Capacity} = \frac{3600 \times \text{Average time separation between departures}}{3600 \times \text{TDD}}.
\]  

(67.6)

The required time separation for each aircraft class pair \((TDD(k, l))\) is determined by comparing the departure runway occupancy time of the lead aircraft \(k\) and the time separation between departures (from the runway threshold) for the aircraft pair \(kl\). The larger of these two values is assumed to be the required time separation at the runway threshold for this pair of departure aircraft classes. The average time separation between departures is computed as the sum over all class pairs of the product of \(TDD(k, l)\) for each aircraft class pair and the frequency with which the aircraft class pair is expected to occur:

\[
TDD = \sum_{i,j} TDD(i, j) \times \%k \times \%l / 10000.
\]  

(67.7)

Airport Capacity for Mixed Arrival/Departure Operations on a Single Runway

To insert departures between arrival pairs, the airport capacity model imposes the following requirements:

- The departures cannot roll if an arrival is already on the runway.
- The departures cannot roll if:
  - An arrival is within some specified distance of the runway threshold, or
  - The departure cannot clear the runway before the arrival comes over the threshold.
- The departure–departure separation minima must also be met to insert multiple departures between an arrival pair.

By employing these conditions, the model computes the probability of inserting one, two, or three departures between each arrival pair. The interleaved departure capacity is then determined from these probabilities and the aircraft mix.
Airport Capacity for Dependent Arrivals and Departures on Two Runways

The model can also compute the capacity for a pair of runways when departures on one runway are dependent on the arrivals to the other runway. The departures cannot be released if an arrival is within a specified distance from the runway threshold, but can be released as soon as the arrival touches down. It is not necessary to wait until the arrival has exited the runway.

The logic for computing the departure capacity of this configuration is similar to that used for a single runway. After the interarrival times are obtained, the probability of performing one, two, or three departures in each interarrival gap is calculated. The departure–departure separation minima are enforced, not just between the departures in the same interarrival gap, but also between the departures in the adjacent gaps. This is rarely necessary for mixed aircraft operations on a single runway, because the time required for an arrival operation is usually greater than the departure–departure separation minima.

67.4.4 Aircraft Delays to Measure Operational Efficiency

Ideally all aircraft operators would like to fly the most wind-favored airway or a direct route if they are RNAV equipped, from the origination airport to the destination airport. This is generally feasible during light traffic periods when the airports are not operating at capacity. During medium to heavy periods of traffic demand, the airport capacity limits the number of departures and arrivals, which result in delays. As shown in Fig. 67.10, the number of annual controlled IFR aircraft operations (including air carrier, commuters, air taxi, and high-end general aviation aircraft) is expected to grow from a current 23 to 35 million by the year 2025. Unless means are explored to increase capacity, especially at the major airports, delays will continue to increase, thereby impacting the aircraft operational efficiency that will significantly increase the users’ direct operating costs.

Fig. 67.11 shows the increase in average delays per aircraft in the NAS at 35 major airports. As shown in the figure, the average delay per flight will increase from the current 10 to 63 min by the year 2025, almost six times, as demand continues to grow, if the NAS continues to operate as it does today. This will have an unacceptable economic impact on the airlines, which may find it almost impossible to run the operations needed to meet the demand. Consequently, it becomes imperative for government service providers to find ways to enhance airport capacity without compromising on safety.

67.4.5 Measuring Controller Workload

The primary role of a controller is to process a significant amount of information and make timely decisions to maintain safe and efficient flow of traffic. This involves acquiring traffic information by continuously monitoring traffic, perceiving potential separation violation problems, and deciding when and how to resolve these problems. In order to perform these functions, the controllers are involved in a number of tasks: monitoring traffic situations on radar displays, entering data through a keyboard, conducting mental assessment...
of potential conflicts, communicating with other controllers/facility people, and communicating clearances (routine and conflict resolution) with the pilots. Thus, a human response to these number of tasks is used to measure workload [67.16], which has both physical and mental components. Perceiving and resolving potential aircraft conflicts, especially during heavy traffic, require more cognitive resources than handling other routine tasks.

The workload (mental) primarily depends upon the time interval between detecting a separation violation and dealing with it. The earlier a decision is made to resolve the conflict, the less the workload for a controller. In congested airspace, especially where the aircraft are continually maneuvers (climbing, descending, turning, and changing speed), the controller workload is not only affected by the number of aircraft under control, but also by the impact of their changing geometrics, which creates complexity [67.17]. The complexity not only depends upon the level of peak traffic, but also upon the specific traffic situations, e.g., the number of aircraft on independent, converging or intersecting paths in horizontal and vertical domains. Rightly perceiving problems resulting from complexity requires timely detection and resolution of these problems, in addition to communicating the resolution clearances to the pilots. This often turns out to be a very stressful process that has a major impact on the workload of the controllers.

In the future, it is envisioned that automation will accurately detect, resolve, and communicate actions directly to the aircraft over a data link (rather than currently by voice) in order to significantly reduce the controller workload, as traffic continues to grow.

### 67.5 Future Air Transportation System Requirements and Functional Automation

In November 2005, the European Consortium of Member States signed to define the vision and goals of the Single European Sky ATM research (SESAR), and to develop, validate, and implement SESAR concepts to meet air traffic demand beyond year 2020. The US 108th Congress and the President mandated the design and deployment of an air transportation system to meet the nation’s needs in 2025 by passing and signing into law Vision 100 – Century of Aviation Reauthorization Act (Public Law 108-176). The transformed air transportation system should be responsive to the social, economic, political, and technological changes, and should meet the future needs for safety, capacity, efficiency, and security. The legislation established a joint planning and development office (JPDO), which is supported by the Department of Transportation (DOT), the FAA, the Department of Defense (DoD), the Department of Commerce (DOC), the National Aeronautics and Space Administration (NASA), the Department of Homeland Security (DHS), and the Office of Science and Technology Policy (OSTP) in the White House. The JPDO published the next-generation (NextGen) air transportation system integrated plan [67.18] defining the objectives for the 2025 air transportation system. The following objectives relate to the specific requirements for safety, capacity, and operational efficiency:

- Maintain the aviation record of safety as the safest mode of transportation
- Improve the level of safety as demand continues to grow
- Enhance airport capacity to satisfy future growth in demand up to three times the current level
- Minimize the impact of weather and other traffic disruptions on NAS operations
- Reduce the transit time from domestic curb-to-curb by 30%.
67.5.1 Automation Approach to Meet Future Air Transportation System Requirements

Increased level of automation in the aircraft and in the ground system will help to meet the above stated requirements for the NextGen air transportation system. In order to improve safety, enhanced aircraft situational awareness in the cockpit and in the ground system will be needed to minimize operational deviations and errors. To maximize capacity and flight efficiency, the future airspace design will have to support each aircraft filing its own desired 4-D flight plans including route, altitudes, and expected times at key waypoints, while the ground automation system will ascertain that these flight plans are conflict free. This would require the ground automation system to accurately estimate aircraft trajectories correlated in space and time, and precisely predict conflicts in order to negotiate any change in their flight plans with the users. Ground-based conflict-free flight planning, with the aircraft adhering to the agreed trajectories, will reduce the need for tactical controller intervention, which would minimize workload. As such, future research should concentrate on developing means to automate the air/ground functions to enhance safety and capacity while reducing flight delays and workload. In order to achieve this, an automation approach is as follows.

Safety
The automation predicts aircraft conflict problems and provides decision support to the controllers in resolving them.

Capacity
No doubt the building of new runways and airports increases airport capacity, but it is a time-consuming process to address the environmental and adjoining community issues required to add new runways to the major airports or build new airports. Although the airports authorities in the US are considering the construction of a few new runways, and a couple of new airports outside Chicago and Las Vegas, the majority of future capacity improvements will have to come from using new technologies and automation by:

- Reducing separation minima, including route widths
- Reducing performance spacing buffers
- Developing automated RNP approaches.

Flight Efficiency and Delays
- Automation supports departure/arrival planning
- For strategic end-to-end flight planning, automation deals with system uncertainties.

Workload
- Automation handles routine ground/air clearances
- Transfer some ground-based decisions to the aircraft with automation assisting aircraft in self-sequencing, merging, and spacing.

67.5.2 Development of Automated Functional Capabilities

Relying on automation decision support and new technologies, the following functional capabilities are going through exploratory research and potential development to meet the above requirements for the future air transportation system.

Automated Problem Resolution to Enhance Safety
As discussed earlier, the URET function in the ground system provides the en route controllers with an automated conflict detection capability, which uses predicted aircraft trajectories to continuously detect potential aircraft separation problems up to 20 min into the future, and accordingly alert the appropriate controllers. This function is being enhanced so that the ground automation provides the controller with solutions or resolutions of aircraft conflicts with other aircraft, segments of airspace, and hazardous weather cells. The MITRE Corp. center for advanced aviation system development (CAASD) is developing such a capability, called problem analysis resolution and ranking (PARR). When the URET detects a conflict, the PARR examines strategic vertical, lateral, and speed change options to resolve these conflicts.

The PARR may be initiated for a specific aircraft with one or more problems, or for a specific problem. In these cases, the PARR examines a variety of resolution dimensions and directions. If initiated for an aircraft, the PARR generates resolutions which maneuver only that aircraft. If initiated for an aircraft-to-aircraft problem, the resolutions for each of the two involved aircraft are generated.

For a given aircraft to be maneuvered, the PARR searches for problem-free trajectories to resolve all problems with that aircraft (within URET’s 20 min
lookahead horizon) in an operationally acceptable manner, without introducing any new problems. The search process examines, in turn, maneuvers in each of the following five dimensions/directions, thus yielding up to five resolutions for that aircraft:

1. Select an altitude above the altitude of the problem aircraft
2. Select an altitude below the altitude of the problem aircraft
3. Turn aircraft left of the route
4. Turn aircraft right of the route
5. Increase or decrease speed.

Each completed \textit{PARR} resolutions are ranked, color-coded, and displayed on the URET plans display; for example, conflicts predicted with violation of separation minima are coded red. This provides the controllers with information to set priorities in dealing with the problems. After the aircraft follow the resolution maneuvers, and there is no more problem, the aircraft return and continue on their original flight trajectory. The \textit{PARR} could also generate resolutions around hazardous weather areas.

It is expected that the \textit{PARR} function will significantly enhance safety. The safety enhancements are important, since the relaxation of ATC restrictions in the future could lead to more complex traffic patterns. The \textit{PARR} would assist in maintaining or enhancing safety in two ways. First, the \textit{PARR} provides an automation capability with which the controllers can obtain an improved, strategic situational understanding, e.g., by quickly assessing which altitude, speed, or direct-to-fix alternatives are problem free. Second, the resolutions provided by \textit{PARR} allow the controller to easily implement strategic, problem-free resolutions, which would allow more time for decision-making and coordination for handling other pilot requests.

\section*{Reducing Separation Minima to Enhance Capacity}

The airport capacity for a single runway depends upon the weight-class-based wake vortex separations between successive aircraft in-trail on a final approach, the length of the final approach to capture the ILS localizer, runway occupancy times, and a spacing buffer for safety. For operations on parallel runways and routes, the lateral separation depends upon the ability of the aircraft to fly close to their desired path centerline.

The established IFR separation minima apply during poor visibility (less than 3 nmi) and/or lower cloud cover ceiling (less than 1000 ft). When the visibility and the ceiling are higher than these conditions, the aircraft fly VFR when the pilots are able to see other aircraft and the runway before turning onto the final approach, a situation called, \textit{see and be seen}. For these visual operations, the aircraft are observed to land with much smaller separations than the established IFR separation minima without compromising any safety, but yielding a much higher capacity. This is because the aircraft are not constrained by the required longer ILS straight-in approaches and a fixed glide slope. Therefore, by flying shorter final approaches and variable glide slopes, the aircraft encounter less impact of wake vortices, and as such could use less in-trail separations. The following future avionics technologies will help reduce the current wake vortex separation minima by permitting aircraft to operate as VFR under all weather conditions. The required navigation performance capabilities in the aircraft will support reduction of lateral separations between routes. A future terminal automation function discussed later will reduce spacing buffers by reducing the impact of flight uncertainties.

\section*{Aircraft Technologies for Electronic VFR Operations}

Although there have been no separation minima established for the current VFR operations, there is sufficient data available to define them, if the aircraft could operate like VFR during IFR conditions. The following technologies will help pilots operate as VFR at night and during poor weather and visibility conditions.

Using ADS-B information from the aircraft in the vicinity of the subject aircraft, the CDTI displays the position of other aircraft on a screen in the cockpit. The head-up display (HUD) is mounted on the aircraft instrument panel below the windshield to monitor the external environment (aircraft and airport). The HUDs provide microwave and infrared (IR) images to the pilots. The use of these wavelengths allows pilots to see the runways in poor visibility by penetrating fog or other adverse weather conditions. The enhanced vision system (EVS) enhances a pilot’s situational awareness during approach and landing, when the visibility is poor, using an IR camera displaying a picture of the surface below.

The synthetic vision system (SVS), with its ability to let pilots see terrain, obstacles, and runways in poor visibility conditions, is designed for use by high-end business jets for situational awareness and safety. A 3-D view allows the pilots to see rendering of terrain ahead using information from onboard obstacle, terrain, and
airport databases and tracked flight path. The navigation display shows the intended aircraft flight path with a view that provides real position over the terrain with respect to the flight plan.

**Required Navigation Performance**

In order to reduce the requirement for lateral separation between aircraft on parallel routes, or to conduct simultaneous approaches to closely spaced parallel runways, the aircraft would need to have a RNP capability. The RNP enables aircraft not only to fly RNAV point-to-point, but also to stay within certified route containment limits with an onboard monitoring and alerting function. This function enhances the pilot’s situational awareness, and alerts the pilot when there is a gross deviation from the route centerline, thereby permitting closer route spacing without ground ATC intervention.

Figure 67.12 shows the RNP concept and the lateral components of the aircraft navigational error. The RNP is a measure of navigation performance accuracy and integrity (i.e., route containment and time to alarm) necessary for aircraft operations within a defined airspace. As shown in the figure, an aircraft certified for a given RNP value, e.g., RNP X, must navigate with a total system error (TSE) not to exceed 2X nmi with a probability of 10^-5 per flight hour, defined as the cross-track containment limit. When exceeding this limit, the monitoring function will generate an alert for the pilot to correct back to the desired course. The RNP X value defines the bound of lateral deviation with a probability of 95% of flight time.

The TSE is the deviation of the aircraft’s true position from the desired course or the centerline of the route of the flight path programmed in the FMS. The TSE is a combination of errors from the following contributing factors:

- Navigation system error
- RNAV computation error
- Display system error
- Course error and flight technical error (FTE).

The airborne equipment accounts for data and computational latencies, equipment response time, and navigation sensor error characteristics for its interfaces. The TSE value assumes a flight director or an autopilot operation that allows the use of either GPS or DME/DME as navigation sources for position determination. The aircraft are capable of RNP 0.3 aided by a flight director in the aircraft, and RNP 0.11 with a coupled highly accurate automatic flight control system (AFCS). The en route path lateral separation requirement could be reduced to 4 nmi from the current 8 nmi for aircraft with RNP 1. RNP 0.11 would permit independent parallel runway operations with significantly reduced runway spacing.

**Automation Functions to Improve Flight Efficiency and Reduce Delays**

The current TFM function balances air traffic demand against airspace constraints and airport capacity taking into consideration the forecasted weather conditions [67.20]. A variety of flow control actions are used to deal with the airport capacity constraints. These include weather avoidance routes, miles in-trail (MIT) restrictions to deal with traffic congestion at fixes and the ground delays generated by the ground delay program to establish expected departure clearance times (EDCT) for flights. Planning for these actions requires predictions of both the traffic demand and the airspace (sector) capacity. Since the TFM decisions are typically made 30 min to several hours in advance of the anticipated congestion, these predictions are subject to significant uncertainty. However, the magnitude of this uncertainty is not known, presented, or understood. As a result, traffic management decisions are often overly conservative, and may be taken at inappropriate times depending upon the accuracy of prediction data. The traffic demand uncertainties arise from many sources. The flight schedules undergo constant changes in response to daily events, and such changes often occur between the time of demand prediction and the time for which demand is predicted. These include flight cancelations, departure time changes, and initiation of previously unscheduled
flights. This latter category is increasing in the USA, as air taxi and executive jet operations are becoming more prevalent.

Several new techniques and technologies are required to provide probabilistic TFM decision support. First, prediction uncertainty must be known and quantifiable. Second, a metric is needed for rating the goodness of the candidate solutions. Third, decision-making algorithms are needed to develop congestion management solutions, given the prediction uncertainty and the goodness metric. Finally, there are significant human factors issues to be resolved due to the combination of information uncertainty and complex automated processes.

Effective TFM decision making in the presence of uncertainty or probabilistic TFM, should have the following characteristics:

1. Rather than attempting to resolve all possible congestion problems, incremental actions are taken to keep traffic congestion risk at an acceptable level, while retaining flexibility to take further actions as the situation becomes more certain.
2. Predicted traffic congestion areas are continually reevaluated for further control action.
3. NAS users are informed of predicted congestion, so that they can proactively reduce schedule risk if desired (e.g., by replanning flights through less congested airspace).
4. Probabilistic congestion predictions are presented to traffic planners and users in an intuitive way, in order to maintain good situation awareness.

**Multicenter Traffic Management Advisor.** The TMA function implemented in the en route automation host computer systems (HCS) regulates or meters traffic arriving from different directions within a single ARTCC to a major airport. The development of multicenter traffic management advisor (McTMA) led by NASA is being built upon the TMA hardware and software baseline. The McTMA is an automation decision support function, which extends time-based metering from a single ARTCC/single airport arrival traffic flow planning to multi-ARTCC operations dealing with traffic flow problems at critical bottlenecks in the en route
airspace and merging of departure traffic with overflights. This function employs a distributive scheduling algorithm to develop flexible collaborative metering plans taking into consideration the ATC constraints at airports and in the en route/transition airspace spread across a region comprising a number of ARTCCs. The distributed scheduling provides a dynamic look-ahead capability and a provisional landing slot reservation system to continuously monitor and feedback upstream adjustment of flight times. This is required to deal with demand/capacity imbalance at the point of congestion [67.21].

**Departure Planning and the Role of Airport Surface Automation.** Most of the traffic flow management constraints are applied at the airports when the traffic demand exceeds either the en route capacity or the capacity at the flights’ destination airport. Consequently, these restrictions are imposed on departing flights so that a particular flight departs at a specific time in order to fit into a specific place in the stream of traffic, or to fit into a specific arrival time slot at the destination airport. The management of these departure time constraints can make the airport surface air traffic control task much more complex. A surface automation function is needed to take all of these constraints into account for efficient departure planning. The airport surface automation system will also help reduce airport accidents, although small in number (13 from 1997 to 2007), by providing timely and accurate information on aircraft positions both to the ground system and the cockpit.

Figure 67.13 illustrates the exchange of information between the various facilities to manage departing flights in order to use capacity at major airports effectively. The airport ramp control tower provides each aircraft with a clearance to push back from the gate. The desired airport runway configuration to use is given by the tower, so that each departing flight could exit the ramp at an appropriate time. The ATCT is responsible for providing clearances for the aircraft to taxi safely from the ramp area to the departure runway, and to take off at appropriate times so as to meet all traffic flow constraints and safe separation requirements. The TRACON provides the ATCT with the relevant traffic flow constraints upstream, as does the ARTCC. The AOC provides the initial flight plan and manages the dispatch of each flight under its control.

The airport departure capacity is a function of the sequencing of flights to each departure runway. Aircraft in the heavy weight class require more spacing behind them than smaller aircraft. Therefore, clustering heavy aircraft together could significantly increase runway capacity. Dynamically managing arrivals and departures, by building extra arrival runway slots when necessary to absorb extra arrival demand, also improves the overall effective use of airport capacity.

In order to facilitate all of the above interrelated decisions, the airport surface automation system should provide the following four functions, and the information generated must be provided in real time to all of the decision-makers shown in Fig. 67.13:

- Surface aircraft and vehicle surveillance
- Automated transfer of controller clearance and flight intent information
- Detection of potential airport surface conflicts
- Automation decision support function to assist the ramp control tower and the ATCT to best use the available runway and taxiway capacity.

Surface aircraft and vehicle surveillance, as well as the automated clearance and intent information transfer, are the two key functions that enable the other two functions listed above. Information about the current position of each aircraft and the vehicle located on an airport’s taxiways and runways, integrated with the positions of the aircraft immediately around the airport, provide the ATCT and the ramp control tower with the ability to see all of these objects, even when the physical line of sight is obstructed by low airport visibility conditions (fog). They also provide the necessary input to the surface conflict detection function, which uses the known positions of each aircraft and vehicle and infers the future path of each aircraft and vehicle (e.g., the cleared taxi path), in order to detect potential conflicts. When a conflict is predicted, the automation function generates an alarm for the controller to alert the pilot to take an action to avoid the conflict.

The surface automation decision support function provides the traffic flow managers and the air traffic controllers in the ATCT and the ramp control tower with recommendations on actions such as:

- When to change the runway configuration to minimize the loss of capacity during the changeover
- In what order to best maximize the taxing aircraft movement through the exit spots at the edge of the ramp area
- In what order to best queue aircraft to maximize runway capacity given the traffic constraints, the size of the aircraft, and other factors
- How best to introduce arrival slots between the departure slots to minimize arrival and departure delays.
The approaches to develop these automated decision support functions have already been discussed in detail [67.22, 23].

**Terminal Automation for Arrival Planning and Control [67.24].** Over the years, two terminal automation functions, viz. metering and spacing (M&S) and the final approach spacing tool (FAST), were developed and went through extensive validation and field testing. However, these functions were not accepted by controllers, because the automation-generated information was either too constraining or inconsistent with the human decision process. These functions were intended to complement en route metering function (TMA) to accurately establish landing sequences and times to enhance airport capacity. The crux of the problem was a discrepancy between the TMA-planned nominal flight trajectories and the actual trajectories flown by aircraft tactically changed by TRACON controllers to achieve desired separations between aircraft.

The TMA establishes desired meter fix times for the traffic going to an airport while they are still in the en route airspace by establishing landing sequences and times based on prestored aircraft trajectory data and wind information over the terminal airspace. The en route controllers try to meet these meter fix times within a specified tolerance (1 min) by maneuvering the aircraft before they reach the meter fixes. Once the aircraft enter the terminal airspace, the terminal controllers merge traffic generally coming from four different directions to maintain the required separations, as well as guide the unequipped aircraft in the terminal maneuvering areas, if there are no navaids. As such, they end up changing the en route metering system planned paths and landing time schedules. This affects the flight planning and operational efficiency for aircraft all the way to touchdown by first getting delayed in the en route airspace and then getting further delayed in the terminal area.

A terminal automation arrival planning and control function is needed to complement the en route planning function in order to predict arrival schedules accurately. This is essential for realizing maximum efficiency benefits for the users by flying optimum paths, and for the service providers to manage diverse aircraft traffic with minimum air-ground communications. This function should minimize the variations between the aircraft flight planning and actual operations by first defining routes all the way to touchdown and then establishing landing sequences and schedules using accurate flight time estimates.

The basic requirement for establishing an efficient terminal area flight plan for each aircraft is that it should be based on minimum flying time from the entry (meter) fix to the runway. In order to achieve the earliest permissible landing times:

1. The plans should be based on the shortest paths
2. Continuous descent from meter fixes to touchdown
3. The aircraft are assumed to fly highest permissible speeds over each flight segment
4. The routes from different directions towards final approach(s) are adequately separated to avoid conflicts during merging of traffic
5. The landing times for successive aircraft ensure adequate separations based on wake vortex considerations.

Once the landing times are established, they should be integrated with the en route planning of flight times such that, when the aircraft arrive at the meter fixes within a desired tolerance, they should be able to continue on the established 3-D profiles without any need for path deviations to maintain separations. The en route metering process ensures delivery of aircraft at the meter fixes within the expected time variance.

In most major terminal areas today, the aircraft, using four-corner post configuration, navigate over established STARs from the meter fixes to about 10–15 nmi radial distance from the airport. Depending upon the direction of arrival, the aircraft either fly a downwind path and then turn onto a base leg, or turn directly onto the base leg, before intercepting the final approach as shown in Fig. 67.14. Since there are mostly no established routes in the base-leg region, the

![Fig. 67.14 Terminal merge-free route design for flight planning.](image-url)
controllers merge the traffic coming from the opposite directions over the two base legs, and then again merge the traffic flying over the two base legs from the opposite directions onto the final approach to a single runway. Merging of aircraft at two or three points, while keeping them separated, results in inefficient, large path deviations and significant workload for both the pilots and the controllers.

In order for most of the aircraft to stay on the minimum path for maximum flight efficiency with short delays, aircraft-derived speed control should be used as the primary means to compensate for aircraft performance deviations and wind forecast uncertainties. In order to achieve this, the terminal route design should eliminate the need for the controllers to merge traffic at multiple points except on the final approach(es). As such, the routes should not only be the shortest, but all merge points should also be eliminated. As shown in Fig. 67.14, the aircraft arriving from the direction opposite to the direction of landing (meter fix 1) fly a downwind path from the end of the STAR turning onto a base leg 5 nmi long before intercepting the localizer course. For smooth capture of the localizer, the aircraft intercept the final approach course at an angle of 30° or less over a path segment of 2.5 nmi to allow for smooth turns from the base leg to the localizer course. The aircraft also need to capture the localizer for final approach course about 2 nmi from the outer marker in order to be stabilized over the glide slope to the runway. This defines the minimum path in the base-leg region. The aircraft arriving from the other direction (meter fix 2) turn directly onto the base leg before capturing the localizer course. In order to create a merge-free route design, the base legs are separated by 6 nmi to keep the aircraft not only safely separated when arriving from different directions, but also to allow for some margin of airspace to deal with pop-up aircraft, missed approaches or large aircraft deviations (as shown dotted in the figure). A mirror image of the design in Fig. 67.14 could be applied to the other two fixes, either to the same runway or to a parallel runway. The figure also shows a path in case the runway assignment is changed. In the future, if some other ILS precision landing guidance is available, the base-leg and final approach paths could be shortened for curved approaches customized for each aircraft depending upon its avionics capabilities.

After entering the terminal area, most aircraft are required to reduce speed to 250 kt before they attain an altitude of 10,000 ft. From there on, depending upon the aircraft performance characteristics, the aircraft typically go through two speed reductions (speed 1 and speed 2 in Fig. 67.14) before reducing to their final approach speeds. The automation function could determine timing or location of these speed reductions to compensate for flight time variances from the desired landing times without requiring the aircraft to divert from the above-defined minimum paths.

The NextGen concept for the future air transportation system considers 4-D navigation as one of its core elements. In order for the aircraft to operate in a 4-D navigation mode, a 3-D flight profile is established from take-off to landing with estimated times of arrival at key decision points along the path. The aircraft are required to stay on the predefined 3-D paths and meet the times at these points by adjusting speeds along the flight segments using the onboard required time of arrival (RTA) function with automated thrust management. Because of the time compression at the end of flight during the arrival/landing phase, any path deviation along the way would be counter to the goals of 4-D navigation.

**Air/Ground Automation with Aircraft**

**Self-Separation to Reduce Workload**

Air traffic controllers today are involved in a number of routine ground–air communications, such as changing frequency, when the aircraft transition from one controller airspace to another’s. In the future, the ground automation system will directly communicate routine information over a data link to the aircraft FMS. In addition, the primary responsibility of the controller to separate aircraft could be shared with the appropriately equipped aircraft, which could self-separate under certain situations as discussed below. The increased use of automation both in the ground system and in the aircraft cockpit will help reduce workload for both the controllers and the pilots.

Before aircraft are committed to the final approach, the controllers direct the aircraft to maintain specific in-trail spacing when following each other, or when the aircraft merge from different directions on a common point in airspace, and then follow each other in a single stream of traffic. This process requires a series of clearances, as well as monitoring of aircraft conformance to the directions from the ground. This is workload intensive for both the pilots and the controllers. In the future, with the aircraft equipped with ADS-B, CDTI, FMS, and RNP, including a monitoring and alerting capability, the aircraft will have the ability to maintain separation from other equipped aircraft. Flight-deck-based merging and spacing concepts are being explored in which a strategic setup is estab-
lished by the ground system followed by cockpit-based self-separation [67.25].

NASA has defined an automated airspace concept that uses ground-based automated airspace computer system (AACS) to generate conflict-free air traffic control advisories and send trajectories via a two-way data link to the FMS of equipped aircraft. With traffic situational awareness provided by CDTI, the pilots could assume separation assurance responsibility during certain traffic conditions. Although the selection of data link and data transmission protocols to meet these requirements is uncertain at this time, mode S, ADS-B, and VDL2 are likely candidates for this concept. The automation of separation assurance function will also mitigate a number of ATC constraints that limit the efficiency and capacity of the current ATM system [67.26].

The joint FAA/Eurocontrol Cooperative Research and Development Committee defined the principles of operation for the use of airborne separation assurance systems (ASAS) taking into account US and European perspectives for global applications [67.27]. The primary guiding principle is based on cooperative involvement of both the pilots/aircraft systems and the controllers/ATM system in assuring separation among aircraft. Four specific ASAS applications defined are:

1. Airborne traffic situational awareness to enhance pilots’ knowledge of surrounding traffic
2. Airborne spacing to permit pilots to maintain a given spacing with designated aircraft
3. Airborne separation when the controller delegates separation assurance responsibility to the pilots
4. Airborne self-separation when the pilots achieve separation from other aircraft in accordance with the desired separation standards and rules of flight.

These concepts make use of aircraft capabilities-based performance to establish different control mechanisms for different segments of airspace. The equipped aircraft assume responsibility for self-separation and for monitoring and alerting in most airspace, except where there are high-density traffic operations. Most FMS using GPS for navigation alert the pilots when navigation performance exceeds RNP criteria. This UNABLE RNP alert is based on probability and not on measured error, and is only a part of the required monitoring and alerting process. A flight technical error relative to the computed path is displayed to the pilot for monitoring lateral and vertical deviations. A corrective action is required if either the lateral or vertical deviation exceeds the lateral RNP limit, or 75 ft in vertical, respectively. The GPS meets the monitoring and alerting requirements of accuracy and integrity through RAIM alerts tied to the RNP value for each phase of flight. This means that the separation assurance responsibility is ground based in the airspace where the traffic density and flight uncertainties are high, whereas some separation assurance responsibility could be delegated on a pairwise basis to aircraft during light traffic. In other airspace segments, both the aircraft and the ground automation share responsibilities, with the aircraft responsible for tactical flow management and separation assurance, while the ground system is responsible for strategic traffic flow management.

67.6 Summary

The current US air transportation system has an excellent record for safety of aircraft flying in accordance with the IFR separation requirements. The NAS relies on VHF for voice communication between the pilots and the air traffic controllers, ground-based VOR/DME systems for navigation, primary and secondary radars for surveillance, and ground-based automation for flight and radar data processing at local, regional, and national ATC facilities. During 2006, over 700 million passengers flew in the NAS, and the cargo revenue ton miles exceeded 40 billion. The NAS manages about 55,000 operations daily, with about 6,500 flights in the air during peak demand. The density of traffic is creating congestion at airways and airports, thereby creating bottlenecks resulting in flight delays, which cost the airlines millions of dollars in lost revenue.

With the demand for air traffic services continuing to increase, future delays will increase significantly unless the NAS is transformed. Satellite-based CNS technologies offer the opportunities to enhance safety, airport capacity, and flight efficiency. The new generation of aircraft has already acquired avionics compatible with satellite-based CNS technologies, with increased automation provided by the FMS. However, the ground system infrastructure needs to be modernized using
satellite-based CNS technologies and automation of decision support functions.

This chapter describes the current CNS and ATM infrastructure, which includes VHF/HF communications, ground-based navigation systems, viz. VOR, DME and ILS, and primary/secondary radars for surveillance. Upcoming satellite-based CNS technologies are also discussed, e.g., VHF data link for data communication, GPS/WAAS for navigation, and ADS-B for surveillance. How these technologies will enhance aircraft operations with direct air/ground communications, RNAV point-to-point navigation, and improved aircraft tracking for automated decision support is elaborated in order to provide an understanding of the major technological transformation expected in future NAS.

The functional role of automation in the aircraft and the ground system is addressed in terms of their limited use today, as most of the decisions in the cockpit and on the ground are human-centric. The two major functions of the ATM system in NAS, viz. TFM and ATC, and their limitations are addressed. Most of the automation functions such as MSAW/conflict alert/URET are primarily used for aircraft safety. Limited automation functional capabilities exist, such as TMA and ETMS, to deal with capacity, flight efficiency, and workload, although a number of newer aircraft have FMS to help aircraft fly efficiently.

The metrics to measure CNS/ATM systems’ performance are aircraft safety, airport capacity, flight efficiency with its impact on delays, and pilot/controller workload. The established government regulations require the aircraft to follow other aircraft with specific separation distance minima in various phases of flight. Because of human decision making, the controllers often plan for larger than the required IFR separation distance rules to ensure safety, although this adversely affects capacity, resulting in increased delays and workload. A detailed explanation of the factors used in defining the above performance measures is provided here to develop a clear understanding of the CNS/ATM system operational elements that the new technologies should improve, and the functions which should be automated for the air transportation system of the future.

This chapter also provides highlights of the future CNS/ATM capabilities for the NextGen system for the year 2025 and beyond, with its goals and objectives. How the enhanced automation could meet the requirements of the future system for increased safety and capacity, as well as for reducing delays and workload, is also discussed.

In order to realize some of the goals of the future air transportation system, research is going on to develop new capabilities such as RNAV, CDTI, and EVS in the cockpit, and automated functions such as PARR, McTMA, probabilistic TFM, and automated departure/arrival management for the ground-based ATM system. The new aircraft technologies will provide the aircraft with an ability to operate in poor-visibility conditions just like they operate in good-visibility conditions to reduce separation minima and increase capacity. The enhanced automation in the cockpit and in the ground system will be better able to deal with the system uncertainties to improve flight efficiency and reduce delays, as well as provide both the pilots and the controllers with accurate and timely decisions to help reduce their workloads. Moreover, some sharing of separation assurance responsibility between the pilots and controllers would result in equitable distribution of workload for ensuring safety of flights.

Because of the limited space here to cover the vast scope of the current air transportation system functions and capabilities and ongoing research to develop the future system, this chapter provides a tutorial at a high level. For specific details of any feature of the current or future systems, it is recommended that the readers seek information on the US FAA or the ICAO websites (www.faa.gov or www.icao.int), respectively.

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