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16. Abstract

In recent years, an increase in the amount of information that is available on advanced flight decks has raised concerns about potential problems such as data overload, a failure to notice important changes/events due to masking, and prohibitive information access costs. To better understand the (effects of the) changing information landscape on modern flight decks, the main goals of this research were to (1) assess the type and quantity of information available to airline pilots on different generations of commercial aircraft, (2) examine how pilot tasks have changed as a result of new information management requirements, and (3) explore the impact of data-rich flight decks on pilot performance as well as mitigations to address information management vulnerabilities. Specifically, we compared the information that is presented on two aircraft pairs – the Boeing B737-500 and B787, and the Airbus A320 and A350. Next, we conducted four online interviews with aviation stakeholders regarding their experiences with changes in the amount and nature of flight deck information. The final chapter of this report discusses potential human factors implications of observed and reported changes. Overall, the project confirms the often-made claim that the amount of (primarily visual) information has increased on advanced aircraft. The report discusses both benefits and challenges associated with this trend and highlights issues that should be considered in the evaluation of proposed display designs, procedures and training approaches.

17. Key Words

Human factors; information presentation; information management; flight deck; flightpath management

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Information Management on the Flight Deck of Highly Automated Aircraft

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August 2024

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ACRONYMS

AC	Advisory Circular
ACARS	Aircraft Communications Addressing and Reporting System
ADF	Automatic Direction Finder
AFDS	Autopilot Flight Director System
AFE	Above Field Elevation
ALT	Altitude
ALT HOLD	Altitude Hold
AP	Autopilot
APP	Approach Mode
APU	Auxiliary Power Unit
ASA	Autoland Status Annunciator
ATC	Air Traffic Control
AUX	Auxiliary Information
B/CRS	Back Course Localizer
BARO	Barometric Setting
CCD	Cursor Control Device
CCR	Common Core Resource
CCS	Cursor Control Selector
CDI	Course Deviation Indicator
CDL	Configuration Deviation List
CDU	Control Display Unit
CHKL	Checklists
CLB	Climb
CLB DIR	Climb Direct
CLR MSG	Clear Message
COMM	Communication
CPDLC	Controller-Pilot Data Link Communications
CRZ	Cruise
CWS	Control Wheel Steering
DES	Descent
DES DIR	Descend Direct
DME	Distance Measuring Equipment
DSP	Display Select Panel
DU	Display Unit
EADI	Electronic Attitude Director Indicator
ECL	Electronic Checklist
EDB	EFB Document Browser
EFB	Electronic Flight Bag
EFIS	Electronic Flight Instrument System
EGPWS	Enhanced Ground Proximity Warning System
EGT	Exhaust Gas Temperature
EHSI	Electronic Horizontal Situation Indicator
EICAS	Engine Indicating and Crew Alerting System
EIS	Engine Instrument System

ENG	Engine
ETA	Estimated Time of Arrival
FAA	Federal Aviation Administration
FAC	Final Approach Course
FCC	Flight Control Computer
FCOM	Flight Crew Operating Manual
FD	Flight Director
FIS	Flight Information System
FLCH	Flight Level Change
FLT DIR	Flight Director
FMA	Flight Mode Annunciation
FMC	Flight Management Computer
FMS	Flight Management System
FPM	Flightpath Management
G/P	Glidepath
GLS	GBAS Landing System (Global Navigation Satellite System)
GPS	Global Positioning System
GPWS	Ground Proximity Warning
HDG SEL	Heading Select
HUD	Head-Up Display
IAN	Integrated Approach Navigation
IAS	Indicated Airspeed
IGS	Instrument Guidance System
ILS	Instrument Landing System
IM	Information Management
INBD	Inboard
INFO	Information
ISDF	Integrated Standby Flight Display
LDA	Localizer Type Directional Aid
LNAV	Lateral Navigation
LOC	Localizer Only
LVL CHG	Level Change
MCP	Mode Control Panel
MFD	Multi-Function Display
MFK	Multi-Function Keyboard
MM	Moving Map
NAV	Navigation
ND	Navigation Display
NDB	Non-directional Beacon
OIS	Onboard Information System
OPT	Onboard Performance Tool
OUTBD	Outboard
OVHT	Overheat
PCP	Proximity Compatibility Principle
PFD	Primary Flight Display
PROG	Progress

PWS	Predictive Windshear Alert System
QRH	Quick Reference Handbook
RA	Resolution Advisory
RADALT	Radar Altimeter
RDMI	VOR/ADF Radio Distance Magnetic Indicator
RNAV	Area Navigation
RNP	Required Navigation Performance
RTE	Route
RTO	Rejected Takeoff
RVR	Runway Visual Range
SATCOM	Satellite Communication
SDF	Simplified Directional Facility
SELCAL	Selective Calling
SID	Standard Instrument Departure
STAR	Standard Terminal Arrival
STNDBY	Standby
SYS	System
TA	Traffic Advisory
TCAS	Traffic Collision Avoidance System
TCP	Tuning Control Panel
TOGA	Takeoff/Go-Around
TWIP	Terminal Weather Information for Pilots
V/S	Vertical Speed
VFR	Visual Flight Rules
VNAV	Vertical Navigation
VOR	VHF Omnidirectional Range Navigation
VSD	Vertical Situation Display
VSI	Vertical Speed Indicator

ASSUMPTIONS AND LIMITATIONS

- The aircraft comparisons focus primarily (though not exclusively) on information related to flight path management.
- The comparison of the two Airbus aircraft is incomplete due to the lack of formal documentation for assessment.
- Some select interfaces (e.g., HUD, portable devices) are described at a fairly high level, using examples only, because these interfaces can differ significantly between airlines.
- Little empirical data exist regarding the impact of changes in the type and amount of information on advanced flight decks on pilot tasks, strategies and performance. Chapter 5 is therefore necessarily based on anecdotal evidence, comments made by aviation stakeholders during our focus groups, the state-of-the-art in human factors/human perception/human cognition, and widely accepted display design principles and guidance.

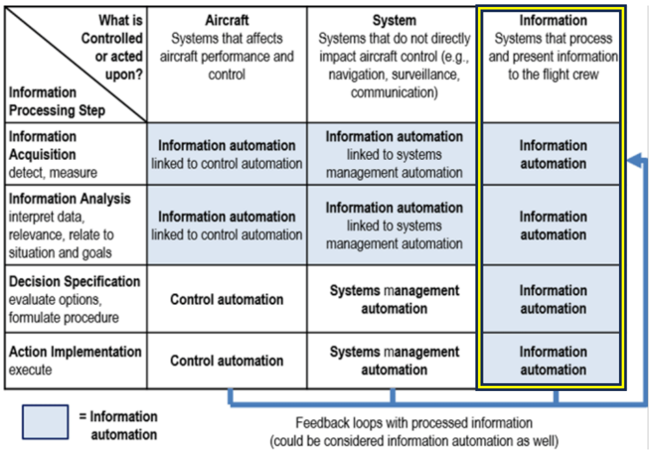
EXECUTIVE SUMMARY

In recent years, an apparent increase in the amount of information on commercial flight decks has raised concerns about problems like data overload, the failure to notice important changes/events, and prohibitive information access costs. The goal of this research was to characterize and better understand the (effects of the) changing information landscape on highly automated aircraft. To this end, we (1) compared the nature and amount of information available to airline pilots on select airplanes of different generations, (2) examined how pilot tasks are affected by changes in information volume, and (3) explored mitigations to address information management vulnerabilities. Specifically, we assessed the information that is presented on the flight decks of the Boeing B737-500 versus the B787, and on the Airbus A320 versus the A350, with a focus on flight path management (FPM). Next, we conducted four online interviews with aviation stakeholders regarding their experiences and perspectives on information management. Participants highlighted that, with advanced aircraft, information management starts well before pilots arrive at the airport, due to their ability to use portable devices for accessing and reviewing flight-related data. Once pilots arrive on the flight deck, information management consists largely of locating and verifying uploaded information (rather than entering it manually). With the introduction of multifunction electronic displays, information presentation on advanced flight decks has become more flexible. Display elements can be (de)selected, and entire displays can be moved between interfaces, manually and automatically. Work-flow and position-based procedures and techniques have been developed to support pilots in handling this flexibility. Finally, participants pointed to new tools that are beneficial for information management (such as electronic checklists) but also voiced concerns, such as inadequate training for visual scanning and some new interfaces (such as the Electronic Flight Bag) as well as a lack of research findings and 'best practices' for information management. The final chapter of this report explores human factors implications of observed and reported changes to flight deck information. Topics covered in this section include display clutter, monitoring strategies and vulnerabilities, information access costs, data propagation, and crew communication and coordination. Overall, the project confirms the often-made claim that the amount of (primarily visual) information has increased on advanced aircraft. However, our findings suggest that qualitative changes, such as dynamic reconfigurations of flight deck displays, affect pilot tasks and performance as much as quantitative changes (i.e., the amount of information). Also, the addition of more and new kinds of information to the flight deck creates both benefits and challenges. For example, the ability to tailor the presentation of information to flight phases and pilot preferences affords increased flexibility; at the same time, the resulting loss of spatial dedication of information can interfere with top-down attention allocation and require effortful information search instead. Taken together, the findings from this project provide a balanced view of trends in information management and help inform the evaluation of proposed display and flight deck designs, procedures and training approaches.

1. INTRODUCTION

The amount of information that is presented on flight decks has increased steadily and significantly over decades, turning information management (IM) into a progressively more demanding task for pilots. IM involves the use of various communication, navigation, and surveillance (CNS) technologies and, depending on aircraft type, systems and displays such as the Flight Management System (FMS), the Primary Flight Display (PFD), the Moving Map (MM) or Navigation Display (ND), a Head-Up Display (HUD), data communications via the Aircraft Communications Addressing and Reporting System (ACARS), Controller-Pilot Data Link Communications (CPDLC), Electronic Flight Bags (EFBs), Crew Alerting (such as the Engine Indicating and Crew Alerting System (EICAS)), the Onboard Information System (OIS), the Traffic Collision Avoidance System (TCAS), and the Enhanced Ground Proximity Warning System (EGPWS). The listed technologies represent examples of information automation which refers to systems that "*…integrate data from multiple sources, convert data to information, and summarize, distribute, format, abstract, prioritize, categorize, calculate, process, and present information…*" (FAA, ACT ARC Recommendation 20-1, 2020).

Dudley et al. (2014) similarly describe information automation as "…systems …responsible for collecting, processing, analyzing, and presenting information to the flight crew to support their task performance, decision making, and position awareness". They propose a two-dimensional framework (see Figure 1) that relates four human information processing stages - information acquisition, information analysis, decision and action selection, and action implementation (Parasuraman et al., 2000) - to the three categories of automation proposed by Fadden (1990) and Billings (1997): information automation ("automation devoted to the management and presentation of relevant information to flight crew members"; Abbott et al., 2013), control automation (controls flightpath (trajectory) and energy) and management automation (supports mission/operations planning tasks and efficient mission completion).



What is Controlled or acted upon? **Information Processing Step**	**Aircraft** Systems that affects aircraft performance and control	**System** Systems that do not directly impact aircraft control (e.g., navigation, surveillance, communication)	**Information** Systems that process and present information to the flight crew
Information Acquisition detect, measure	**Information automation** linked to control automation	**Information automation** linked to systems management automation	**Information automation**
Information Analysis interpret data, relevance, relate to situation and goals	**Information automation** linked to control automation	**Information automation** linked to systems management automation	**Information automation**
Decision Specification evaluate options, formulate procedure	**Control automation**	**Systems management automation**	**Information automation**
Action Implementation execute	**Control automation**	**Systems management automation**	**Information automation**

▭ = **Information automation**

Feedback loops with processed information (could be considered information automation as well)

Figure 1. Framework to distinguish types of automation (adopted from Dudley et al., 2014)

Not only has the amount of information available on flight decks increased but so has the number of interfaces and sources of information as well as the extent to which information is being pushed to the flight deck (rather than being entered manually by pilots; see section 4). Also, the presentation of information has become more flexible. Pilots can (de)select display elements and move around entire displays at their discretion, and in case of display failures information is automatically re-arranged (as will be discussed in more detail in section 3.2.4 of this report). These trends – an increase in the amount of information, the number of interfaces, the number of information sources/feeds as well as the flexibility of information presentation - have raised concerns in the aviation community about potential data overload and display clutter, confusion due to a loss of spatial dedication of information, forced serial access to highly interrelated data, failure to notice important information due to masking, and prohibitive information access cost and time (e.g., Abbott et al., 2013; Kaber et al., 2008; Moacdieh and Sarter, 2015; Woods and Sarter, 2010). These problems can affect routine monitoring of flight-related data, the search for specific and/or rarely used pieces of information, the integration and interpretation of data, and the noticing of unexpected changes and events, especially during high-workload and/or non-normal events.

To better understand and account for the changing information landscape on modern flight decks, the main goals of this research were to (1) determine the type and quantity of information available to airline pilots on advanced automated aircraft, (2) examine how pilots' tasks have changed in response to new information management requirements, and (3) explore the impact of data-rich flight decks on pilot performance and operational considerations, including mitigations to address information management vulnerabilities. This report first documents the changes in information that is presented on two aircraft pairs – the Boeing B737-500 and B787, and the Airbus A320 and A350. These aircraft exemplify early (B737-500 and A320) versus highly advanced (B787 and A350) flight deck automation. The comparison serves to substantiate often made but rather broad claims of an increase in information on advanced flight decks. It details what information is available to pilots and where and how it is presented to the flight crew. Note that the comparisons focus primarily on information related to flightpath management (FPM) which involves "the planning, execution, and assurance of the guidance and control of aircraft trajectory and energy, in flight or on the ground" (Federal Aviation Administration, AC 120-123, 2022). Next, we share findings from online interviews that were held with aviation stakeholders to learn about their experiences and concerns with information management on advanced flight decks, as well as proposed and already implemented mitigation strategies. Finally, we discuss potential implications of observed and reported differences between earlier and advanced flight decks for information processing and management in terms of challenges created and changes to pilot tasks. This discussion highlights issues that should be considered in the evaluation of proposed designs, procedures and training approaches.

2. COMPARISON OF FLIGHT DECK INFORMATION - B737-500 vs. B787

The following section presents a high-level comparison of the flight decks on the Boeing B737-500 (which entered commercial service in 1990; see Figures 2 and 3) and the Boeing B787 (which entered commercial service in 2011; see Figures 4 and 5), two aircraft that exemplify early versus highly advanced flight deck automation.

Figure 2. Decorative Image of a Boeing 737-500 Aircraft on the Airport Surface (source: https://secure.boeingimages.com/archive/737-500-on-Ground-Following-First-Flight-2F3XC52GZ2R.html)

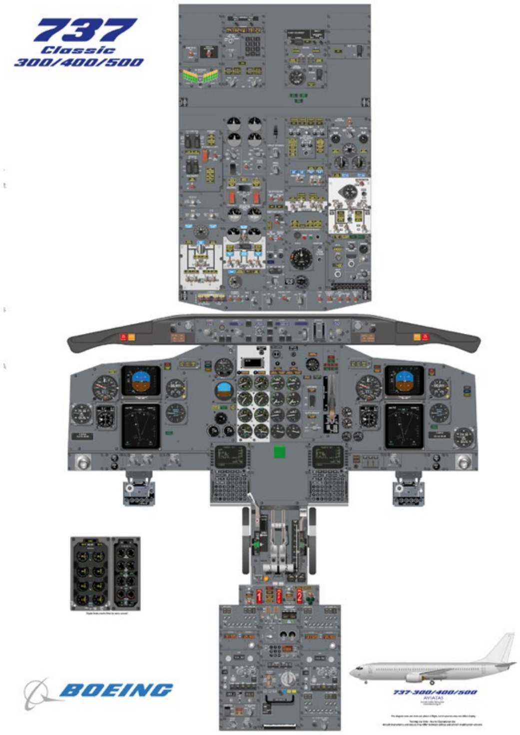


Figure 3. B737-300/400/500 Flight Deck Diagram (source: https://gchadwick.myportfolio.com/boeing-737-300400500-classic)

Figure 4. Decorative Image of a Boeing B787-10 In-Flight (https://secure.boeingimages.com/CS.aspx?VP3=SearchResult&VBID=2JRSN2AKO6BYPV&PN=1&WS=SearchResults#/SearchResult&VBID=2JRSN2AKO6U1ZC&PN=1&WS=SearchResults)

Figure 5. B787 Flight Deck Diagram (source: https://gchadwick.myportfolio.com/boeing-787-8-cockpit)

2.1 METHOD

The comparison was performed by an airline pilot with extensive experience flying, instructing and evaluating on the two aircraft under consideration, in collaboration with the Principal Investigator (PI). Both authors had access to the B737-500 and the B787 Flight Crew Operating Manual (FCOM) and the Quick Reference Handbook (QRH) which, taken together, provide ~7,500 pages of information on the two aircraft. The FCOM contains information on operational limitations, normal and supplementary procedures, and dispatch performance data, systems information, generally subdivided into sections covering controls and indicators, and systems descriptions. The Quick Reference Handbook (QRH) contains all checklists necessary for normal and non–normal procedures as well as in–flight performance data. Note that the comparison is not specific to a particular variant of the B787 (B787-8, B787-9, B787-10). While differences exist between the three variants, they mostly relate to aspects such as dimensions of the aircraft or engine type, rather than to information presentation on the flight deck.

We first describe and compare (1) the overall flight deck layout on the two aircraft, followed by (2) a more detailed analysis of information presented on visual displays related primarily to flightpath management, (3) possible display (re)configurations, (4) portable interfaces, and (5) aural information.

2.2 FINDINGS

2.2.1 Overall Flight Deck Layout

2.2.1.1 Main Instrument Panel

Overall, the information layout of the main instrument panel is similar on the two aircraft, with all parameters necessary for flightpath control presented directly in front of each pilot. Engine, fuel, and gear indications are located in the center of the main panel on both flight decks.

On the B737-500, the main instrument panel (see Figure 6) consists of a combination of traditional round-dial gauges (such as the airspeed indicator and the altimeter) and electronic flight displays, including the Electronic Attitude Director Indicator (EADI) which depicts attitude and speed information, with an airspeed speed tape on the left and glideslope/radar altimeter information located on the right side. Also part of the main instrument panel is the Electronic Horizontal Situation Indicator (EHSI) which shows lateral navigation information. In contrast, on the B787 (see Figure 7), the main instrument panel consists of 5 multifunctional displays (MFDs). Each of the 5 screens is split vertically into a left and right window. The pilots' inboard and outboard display units can be used to present various selections, such as the Primary

Flight Display (PFD) with a mini-map and auxiliary data around it, a Navigation Display (ND), or the Engine Indicating and Crew Alerting System (EICAS). The lower MFD is a Multi-Function Keypad (MFK) for input to the Flight Management Computer (FMC), Aircraft Communications Addressing and Reporting System (ACARS), and Controller/Pilot Datalink Communications (CPDLC).

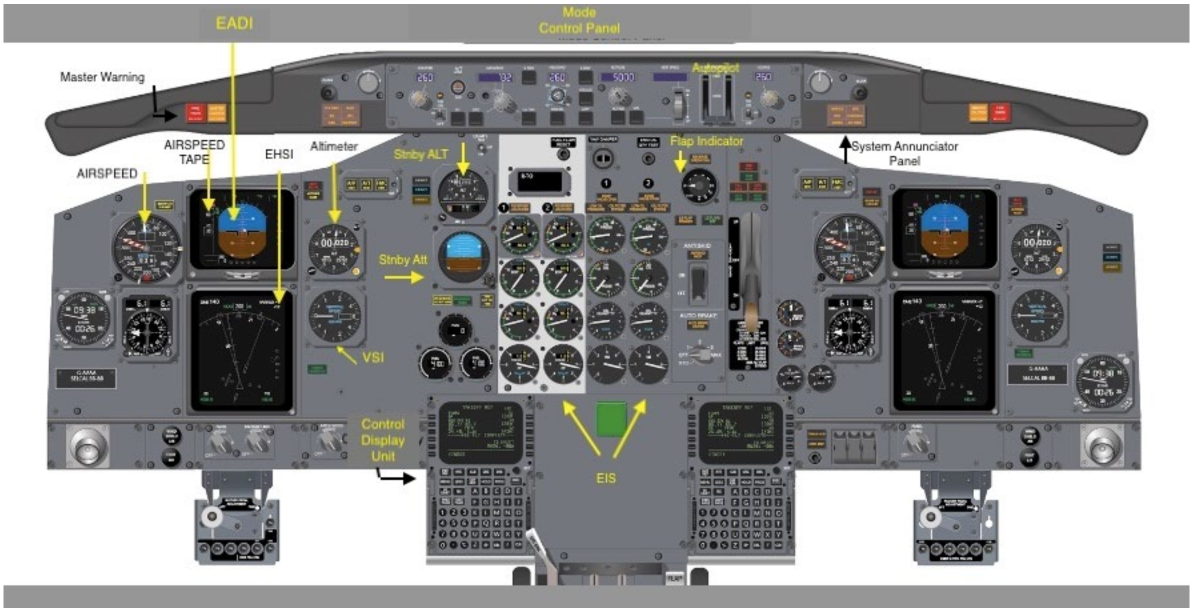


Figure 6. B737-500 Main Instrument Panel (source: pmflight.co.uk)

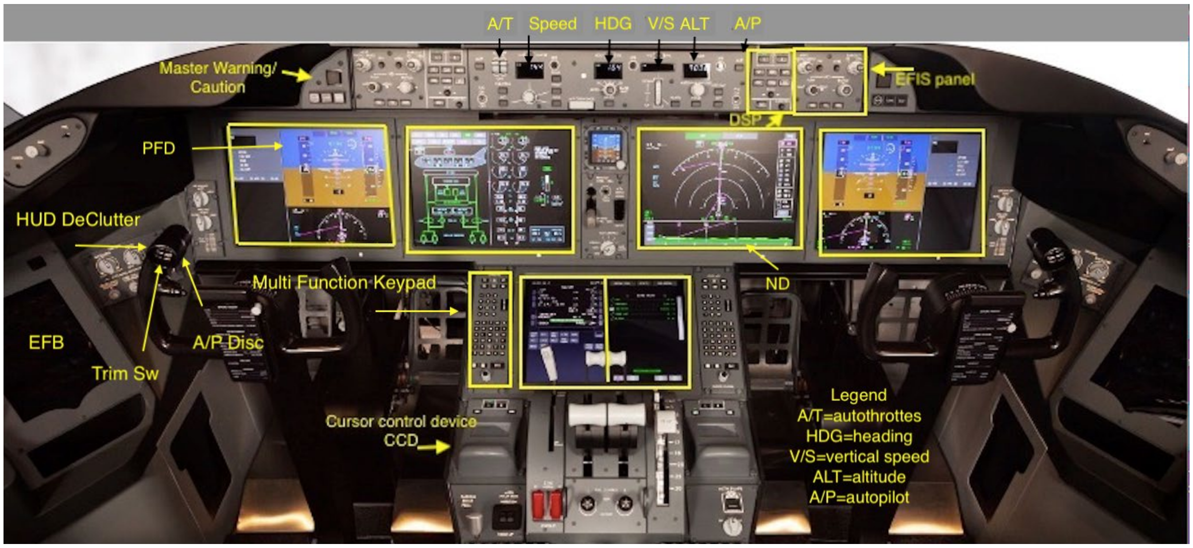


Figure 7. B787 Main Instrument Panel (source: https://flightdecksolutions.com/our-fleet/B787)

The two most significant changes between the two aircraft are (1) the addition of electronic checklists on the B787 and (2) the capability to view and monitor system schematics on the B787. Some items are no longer present on the B787 main instrument panel, including brake accumulator information (the B787 has electric brakes, so accumulator information is not necessary) and the anti-skid on/off selector (anti-skid is automatic on the B787 when autobraking and RTO (rejected takeoff) is selected). Other B737-500 flight deck instruments, displays, and indicators were relocated to a different location on the B787 flight deck. For example, the Vertical Speed Indicator (VSI) has moved to the PFD; VOR bearing and distance are now shown on the ND if selected from the ND drop-down menu; and items such as the flap and landing gear position, thrust reverser indications, autopilot and auto-throttle disconnect lights, and all engine indications now appear on EICAS.

2.2.1.2 Glareshield

Both aircraft have a glareshield with a Mode Control Panel (MCP; discussed in section 2.2.2.4) in the center. Pilots use the MCP to manage (i.e. (de)select, enter targets, etc.) the autopilots, flight directors and/or autothrottle and enter corresponding modes to maneuver the aircraft in altitude, heading, lateral navigation, vertical navigation, and airspeed. The MCP supports coupled autopilot and flight director guidance to conduct a range of flight operations, including instrument approach procedures. On the B737, the MCP is surrounded on both sides by system annunciator light panels and the Master warning and Master caution lights (Figure 8).

Figure 8. B737-500 Glareshield
(source: https://i.ytimg.com/vi/yk5CIptqHm8/maxresdefault.jpg)

The B787 has more extensive glareshield controls (see Figure 9) that include an EFIS (Electronic Flight Instrument System) panel which allows pilots to change settings on the PFD (such as approach minimums, select flightpath vector or adjust barometric pressure) as well as select the mode and range of the Navigation Display (ND; discussed in section 3.2.2). Note that the B737-500 also has an EFIS control panel but it is located on the aisle stand (described in section 2.2.1.4).

On the B787, a CPDLC (Controller-to-Pilot Datalink Communications) function switch is included on the outer sides of the glareshield, as are Display Select Panels (DSPs) used to control the Multi-Function Display (MFD) for the on-side inboard DU. Each DU has a left and right selector and only one can be selected at a time. The currently selected MFD window (left or right) is indicated by an illuminated green annunciator light above the corresponding display switch (L or R). After a MFD side (L or R) is selected, the corresponding display is selected with the Upper Display Switches (SYS, CDU, INFO, CHKL, COMM, or ND). Finally, the B787 glareshield also includes ND weather, traffic, and terrain selections, a push-to-talk communication switch, a single combined Master Caution/Warning button, and an EICAS transfer switch (which toggles the EICAS display between the inboard half of the Captain's and First Officer's inboard DUs).

Figure 9. B787 Glareshield
(source: https://imgproc.airliners.net/photos/airliners/3/6/9/2734963.jpg?v=v40)

2.2.1.3 Control Stand

For the most part, the control stands do not differ between the two aircraft (see Figures 10 and 11, respectively). Both contain throttles with auto-throttle disconnect switches and reversers, take-off/go-around switches (TOGA), flap handle, parking brake, speed brake lever, start levers, stabilizer trim cut-out switches and the CDU (Control Display Unit).

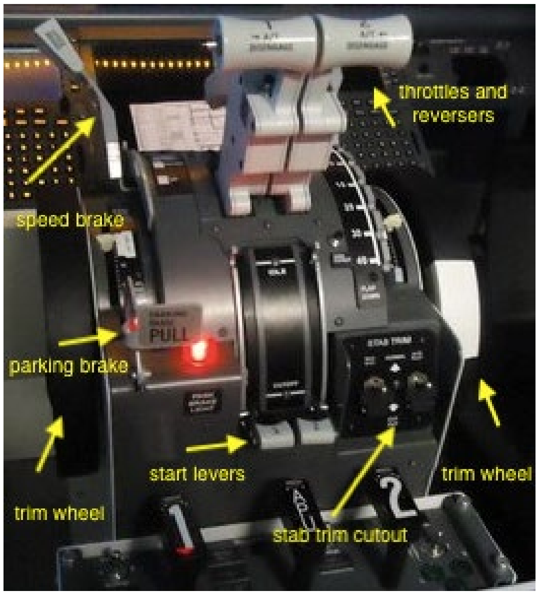


Figure 10. Control Stand B737-500
(source: https://media-cdn.tripadvisor.com/media/photo-s/05/2b/10/fe/aeroteca.jpg)

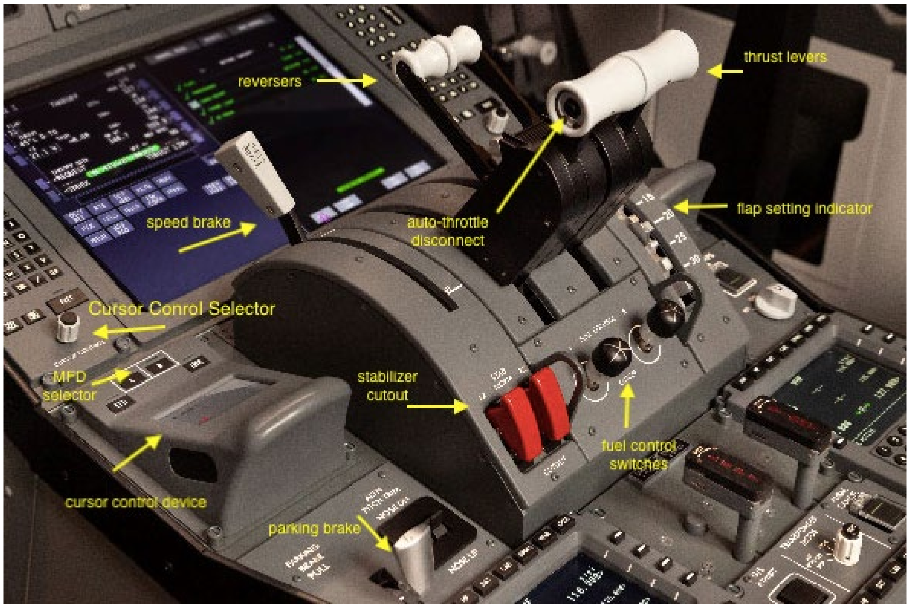


Figure 11. Control Stand B787 (source: https://flightdecksolutions.com)

One significant difference between the two aircraft is the addition of a Multi-Function Keypad (MFK) on the B787 outboard of each pilot's respective virtual CDU (see Figure 12). The MFK is used to enter information to the upper and lower DUs. Also added were a "touchpad" Cursor Control Device (CCD) and a rotary knob Cursor Control Selector (CCS) to the B787 control stand (see Figure 12). These devices perform the same function and are used to move typed or selected data from the CDU scratchpad to a desired location. The left (Captain's) CCD and CCS control the left inboard display unit and the lower display unit cursor position and operation. The right (First Officer's) CCD and CCS control the right inboard display unit and the lower display unit cursor position and operation. Only one destination for data can be selected at a time. Finger application on the CCD pad moves the cursor and the left and right side of the CCD pad has an activation switch when pressed enters the selected data to the desired location. Similarly, rotating the CCS knob moves the cursor on the CDU and pushing the knob selects the location for that item.

Additional control stand differences include the removal of the trim wheel on the B787. The 787 has only trim switch buttons on the yoke (available also on the B737-500) which work through the PFCs (Primary Flight Computers) to maintain a trim reference speed. Also, the B737-500 has a red light indicating that the parking brake is set whereas, on the B787, this information is presented in text form on the EICAS display. The 787 Alternate Trim switch buttons do the same thing as the trim wheel on the 737 although the 737 is mechanical and electric vs the 787 which trims through the PFCs (Primary Flight Computers) to maintain a trim reference speed.

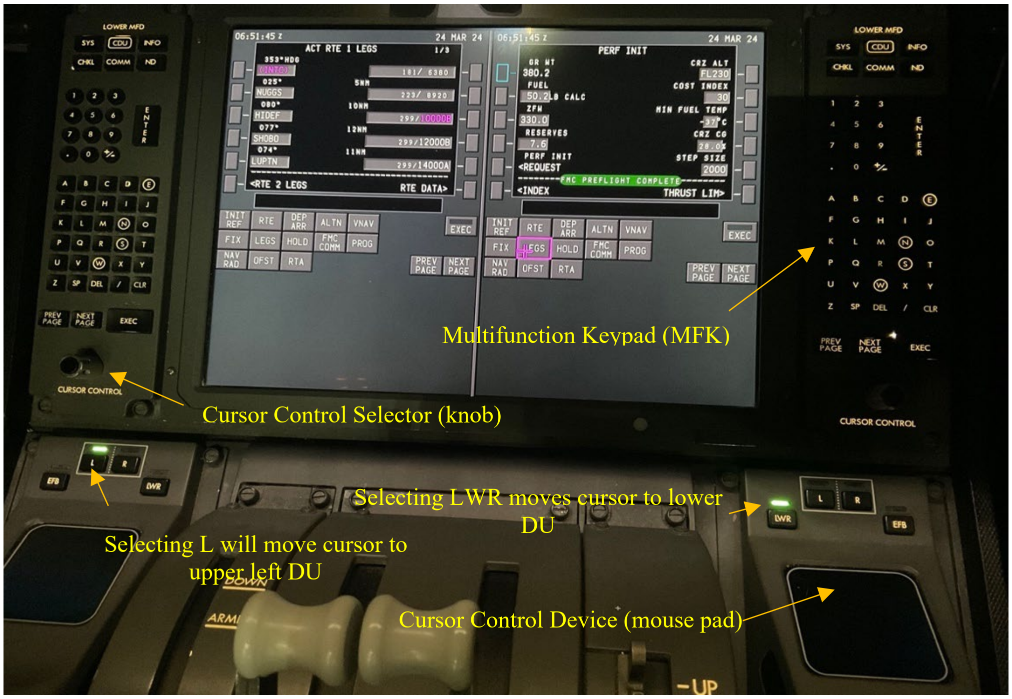


Figure 12. B787 Cursor Control Device (CCD) (source: personal photo)

2.2.1.4 Aisle Stand

The main aisle stand components are fairly similar and are in the same location on both aircraft; however, their appearance is different. The most significant change on the B787 is the introduction of two TCPs (Tuning and Control Panel; one for each pilot). TCPs consolidate and reduce the number of independent control panels traditionally used for VHF, HF, SATCOM, Cabin Interphone, Weather radar panel, GPWS gear and terrain override, and transponder. Also, the rudder trim indicator is now shown on EICAS, and the stabilizer trim cutout switches were moved to the control stand.

2.2.1.5 Overhead Panel

The overhead panel on both aircraft contains controls to operate most onboard systems, such as fuel, electrical, pneumatics and air conditioning panels. The layout of the overhead panel has not changed significantly but most switches on the B737-500 are dedicated toggle switches while the B787 uses push buttons which present indications of system configuration or status, such as ON, FAULT, or NORM.

Some of the B737-500 indicators have moved to the B787 EICAS display, such as thrust reverser, flap and leading-edge device indications. Other system indications are now included in the system schematics themselves, such as cabin and cargo door indications (shown on the DOOR synoptic), APU, hydraulic, liquid cooling and oxygen levels (shown on the SYS STAT page). The IRS (Inertial Reference System) display has moved to the TCP. Removed from the overhead panel on the B787 were the Pitot Static Heaters (probe, engine and wing anti-icing is automatic on the B787; no switches required), the PMC Panel (Power Management Control), and the Spoiler, Flight Control and Yaw Damper switches. Additions to the B787 Overhead Panel include the HUD (head-up display) Control, the APU and Cargo Fire Handles, the CCR (Common Core Resource), and the Fuel Jettison System.

2.2.2 Select Interfaces

2.2.2.1 Electronic Attitude Display Indicator (EADI) / Primary Flight Display (PFD)

The Primary Flight Display (PFD) on the B787 combines important flight information traditionally displayed on several electromechanical instruments onto a single electronic display. It is located on the outboard DU for each pilot, centered in the pilot's primary field of view. The B737-500 has a scaled-down less integrated version of the PFD which is referred to as the Electronic Attitude Director Indicator (EADI). It is located above the navigation display.

The B737-500 EADI (see Figure 13) shows a wide range of speed-related information on a tape display, including the current and selected airspeed, minimum maneuvering speed, V reference speeds for takeoff and landing, stall speed indication, indications for overspeed of aircraft and maximum/minimum/overspeed for flap settings, as well as stick shaker and maximum operating speeds. Below the airspeed tape, Mach and groundspeed are displayed when the aircraft exceeds .40 Mach. Also shown on the EADI are bank indicator/ scale, horizon line and pitch scale, pitch limit indicator, glideslope and localizer pointers and deviation scales, flight director command bars, decision height, radio altitude, rising runway, slip indicator, and radio alert height.

Figure 13. B737-500 EADI (source: 737b.blogspot.com)

The B787 PFD (see Figure 14) presents all of the above information, plus items such as the FMC selected approach with identifier/course/DME, navigation performance scales for Required Navigation Performance (RNP; on the B737-500, RNP-related information is shown on the CDU, the EHSI and the forward instrument panel), navigation source reference such as the Flight Management Computer (FMC), and information regarding the Autopilot Flight Director System (AFDS) and its operating status and landing capabilities (LAND2, LAND3, NO AUTOLAND). Altitude and vertical speed information are shown on tape instruments that are integrated with the PFD (as opposed to the B737-500 where this information must be obtained by scanning the two separate round-dial electromechanical gauges to the right of the EADI). In addition to the PFD, the B787 outboard DU contains a top-down view mini-map below the PFD and an Auxiliary Information (AUX) Display to the side of the PFD (see Figure 14). The minimap has a fixed range of 20 nm and depicts items such as the flightpath, flight plan waypoints with arrival time and distance, altitude and airspeed profile points, winds, TCAS traffic advisories (TAs) and resolution advisories (RAs), weather radar, and terrain. The AUX display is separated into two halves. The upper area is the Flight Data Block which contains information specific to the aircraft (e.g., aircraft tail number, transponder code, elapsed flight time). The lower half of the AUX Display is the Air Traffic Control (ATC) Data Block which contains information such as ATIS (Automatic Terminal Information Service) and CPDLC (Controller Pilot Data Link Communications) messages.

FLT • B0E001
MIC FLT
XPDR 1200
SELCAL GR-AB
TAIL • JA802A
01:13:41
UTC TIME 14:56:36z
DATE 02 APR 22
ELAPSED TIME 01:02

Figure 14. The B787 PFD in takeoff configuration, with mini-map
(source: https://www.thresholdx.net/news/ff7879)

Autoflight system status and flight mode annunciations (FMAs) are displayed along the top of both the B787 PFD and the B737-500 EADI. FMAs indicate to pilots the active and armed auto-throttle, pitch, and roll modes of the autoflight system. On the B737-500, the autopilot status (FD (flight director), CMD (autopilot), or CWS (control wheel steering)) is located to the right of the roll mode whereas on the B787, the autopilot status (FLT DIR (flight director) and AP (autopilot)) is displayed directly below the roll mode FMA.

2.2.2.2 Navigation Display (ND)

The navigation display on both aircraft - called EHSI (Electronic Horizontal Situation Indicator) on the B737-500 and ND (Navigation Display) on the B787 - presents a color top-down view of the flight's progress along its route. The route shown on the ND is loaded from the FMC (flight management computer) via the CDU pages. Pilots can view the entire route - including departure, enroute portion and the arrival -, or they can use the Planview mode to step through each waypoint of the route via the LEGS page of the CDU. Information presented on the navigation display include the position of the airplane, its heading/track, the route of flight, distances and estimated times of arrival (ETAs), wind direction and velocity, and surrounding airports/navaids/waypoints. Both navigation displays can be used in various modes of presentation, including the MAP view (track- or heading-up oriented depiction of the airplane's position relative to the FMC flight plan and/or FMC data base waypoints and navaids), PLAN view (North-up map, used to step through the entire flight route via the CDU Legs page), and full rose or expanded Navigation, VOR, or ILS modes. Pilots can select the map mode, its range and map elements via a control panel which is located on the aisle stand on the B737-500 and either side of the glareshield on the B787.

Some functions are available on the B787 ND only. For example, the display can be reduced to a range of one-half mile and used in full moving map mode to depict the aircraft's position on airport and taxiways. Also, the ND can be viewed in full or normal mode. In normal mode, the ND is half the size of the full mode as it shares the display unit with EICAS. The pilot flying (PF) typically uses the full display while the pilot monitoring (PM) selects the normal display.

Flaps speed profile point and settings are shown on the B787 ND to indicate the approximate map position for FMC calculated flap and speed settings. Position and settings are calculated to be on speed, on path and on time at the final approach fix. The dropdown menu allows the selection of weather radar information to be presented on the ND while terrain can be displayed on the mini-map. Finally, the B787 OFFPATH DES page on the CDU can be used for analyzing/predicting descent performance with and without the use of speed-brakes. The use of this feature results in the appearance of circles on the ND which provide descent information to a reference waypoint on the Legs page. The outer blue circle represents a descent at idle power and no speed brakes. The inner white circle represents a descent at idle power and full use of speed-brakes. The OFFPATH DES page shows distance to go to the entered waypoint. If the aircraft is inside the outer circle and a negative number appears on the OFFPATH DES page under "TO CLEAN", then speed-brakes must be used for the descent.

2.2.2.3 Vertical Situation Display (VSD)

The B787 (but not the B737-500) has a Vertical Situation Display (VSD; see Figure 15) which is shown below the ND moving map. The VSD assists with vertical flightpath management and energy management by presenting a computer-generated profile view of the airplane and its environment, including terrain, waypoint information, navigation fixes, recommended profile speeds for approaches, and fix programmed speeds from the FMC.

Figure 15. B787 Vertical Situation Display (VSD; below the moving map) (source: personal photo)

When using the full ND mode, the full VSD is presented in the bottom third of the screen while in normal ND mode, a compacted VSD is shown because of the need to accommodate the EICAS display. The altitude reference scale is linked to the VSD range and is not independently adjustable. This ensures that a consistent 3° glidepath is depicted up to an 80 nm range. The selected altitude shown on the VSD is the same as the selected altitude shown on the on-side PFD.

2.2.2.4 Mode Control Panel (MCP)

The Mode Control Panel (MCP) on both aircraft (see Figures 16 and 17 below) has been referred to as a 'tactical' interface that pilots use to enter individual targets for the autopilot, flight director, and auto-throttle systems. This is in contrast to the more 'strategic' sequences of instructions entered via the CDU (as discussed in section 3.2.5). Autopilot, flight director, and auto-throttle switches on the MCP allow pilots to (dis)engage these three components of flight deck automation. The B787 has three autopilots, versus only two for B737-500, which allows the B787 to perform an Autoland landing with lower minimums than the B737-500.

Figure 16. B737-500 Mode Control Panel (MCP)
(source: http://www.b737.org.uk/images/glare-500.jpg)

Figure 17. B787 Mode Control Panel (MCP) (source: personal photo)

In addition to entering airspeed, heading/track, altitude and vertical speed targets, pilots use the MCP also to select and activate associated Autopilot Flight Director System (AFDS) modes. These modes are HDG SEL (Heading Select), LNAV, VNAV, FLCH (Flight Level Change) on the B787 versus LVL CHG (Level Change) on the B737-500 (both modes have the same effect, namely idle power descents or full power climbs), CWS (Control Wheel Steering; on the B737-500 only), ALT HOLD, V/S (Vertical Speed)/FPA (Flightpath Angle), and the Approach Mode (APP).

On the B737-500, the APP mode can be used only for flying ILS (instrument landing system) approaches. In contrast, the APP button on the B787 affords many additional precision and non-precision approach options, including B/CRS (Back Course Localizer), GPS (Global Positioning System), LDA (Localizer Type Directional Aid), LOC (Localizer Only), NDB (Non-Directional Beacon), RNAV (Area Navigation), VFR (Visual Flight Rules; Visual Approach), and VOR (VHF Omnidirectional Range Navigation). Also, the APP button on the B787 is a dual-function switch. Pushing this button will intercept the ILS/GLS or, for an RNAV approach, it will intercept the final approach course (FAC) and glidepath (GP). This is similar to selecting LNAV and VNAV for an RNAV approach on the B737-500. On the B737-500, the final approach course is selected by the pilot with a knob on the MCP panel while the B787 final approach course is automatically selected, and the FMC automatically tunes the ILS or GLS once the desired approach is selected in the CDU.

On the B787, airspeed can be managed with the MCP speed intervention button located directly beneath the airspeed window. Pushing the speed button changes the mode from FMC speed to a selectable speed on the MCP panel (an optional feature on the B737-500). Both track and heading can be selected on the B787 (versus only heading on the B737-500). This additional feature is most useful for engine failure procedures requiring the aircraft to fly a particular track versus a heading. Finally, the speed and altitude transfer switch (on the B787 MCP only) is used to make CPDLC-uploaded ATC changes to speed or altitude the active values.

2.2.2.5 Control Display Unit (CDU)

The Control Display Unit (CDU) enables the flight crew to interface with the FMC and create navigation routes that are followed in LNAV, provide airspeeds for climb-out and descents in VNAV, and enter charted speed restrictions for Standard Instrument Departures (SIDs) and Standard Terminal Arrivals (STARS), among other functions. On the B737-500, the CDU is a physical device while it is virtual on the B787.

The CDUs on the two aircraft are similar in that they both have a scratchpad area at the bottom of the screen area for entering data and six buttons on either side of the screen to line-select/move the entered data to the appropriate line on the CDU page. Both CDUs have buttons below the screen area such as RTE (route), HOLD, PROG, and DEP/ARR that will take the pilot directly to the respective page. The B787 has combined the CLB (climb), CRZ (cruise), and DES (descent) buttons into one single button labeled VNAV. Once on the VNAV page, the pilot can navigate to the CLB, CRZ or DES page by scrolling left or right.

On the B737-500, pilots enter data via a dedicated physical keyboard whereas on the B787, pilots interface with the CDU via a Multi-Function Keypad (MFK). The MFK contains an alphanumeric keypad and a rotary cursor control selector (CCS). Below the MFK is a touchpad-based CCD (Cursor Control Device). Pushing the Cursor Control Device (CCD) activates the area of the screen that the cursor is currently in. Gestures on the touchpad are used to move the cursor on the selected display. The CCS performs the same function of moving the cursor to a desired location. It is the preferable interface in turbulence when it can be difficult to use the CCD to select a particular item.

The B787 airplane communications system enables two–way datalink communications between the FMC and airline operations by pushing the COMM button at the top of the CDU

MFK. A manual or automatic downlink occurs when data is transferred from the FMC and transmitted through the airplane communications system to a receiver on the ground. Data (such as takeoff and landing performance data, or route changes from ATC) can also be uplinked from a ground station as input to the FMC at the discretion of the airline operations dispatcher or in response to a downlink request. Last, the B787 (but not the B737-500) CDU provides a HELP window on both the COMM and CDU displays at the bottom of the MFD to assist in resolving data entry errors and to display FMC information messages.

2.2.2.6 Engine Indicating and Crew Alerting System (EICAS)

EICAS (Engine Indicating and Crew Alerting System) is the primary means of displaying engine parameters and alerting the flight crew to system configurations or faults. The various EICAS display elements are presented in fixed locations on the screen. For example, engine indications will always appear in the top left corner of the EICAS screen, secondary engine indications will be shown bottom left of screen, and EICAS messages will be shown on top right.

There are four types of EICAS messages that are color-coded and automatically disappear when the respective condition no longer exists:

1. Alerts (warnings, cautions, and advisories) that indicate non-normal conditions.
2. Comm (communication) messages that direct the crew to normal communication conditions and messages. All communication messages require some pilot action and cannot be canceled.
3. Memo messages that remind the flight crew of selected normal conditions (such as Parking Brake Set, APU running, Pass signs ON). Reminders can be entered manually by the pilots (such as crew rest wakeup or fix crossing times).
4. Status messages that indicate equipment faults which may affect the airplane dispatch capability.

EICAS alerts can take the form of warnings, cautions or advisories. EICAS warnings are shown in red and alert pilots to a non-normal operational or system condition that requires immediate corrective action. EICAS cautions are shown in amber and indicate non-normal conditions that require timely attention and action but are less urgent than warnings. Finally, EICAS advisories are shown in blue or white and inform pilots about a system status or condition that may or may not require corrective action. This message prioritization and corresponding presentation on the EICAS screen assists the flight crew in making decisions and properly sequencing actions on the Non-Normal Menu checklist page when more than one EICAS alert is displayed.

A white box to the left of an EICAS alert message indicates the existence of an electronic checklist for that item. Pushing the checklist display switch on the DSP brings up the checklist page where three types of checklists can be displayed:

1. Normal checklist (such as Pre-flight, Before Push Checklist, After Start checklist, etc.)
2. Non-normal checklist associated with an EICAS message (such as FIRE ENG L, HYD PRESS SYS L, etc.)
3. Non-normal checklist not associated with an EICAS message (unannunciated; such as runway change, driftdown, fuel jettison)

2.2.2.7 Electronic Flight Bag (EFB)

In this report, we use the term Electronic Flight Bag (EFB) to refer to an information management device that is installed in a fixed location on the flight deck. It contains, in digital format, all documentation and forms traditionally carried by pilots in printed form – such as aeronautical charts, manuals for fault reporting and operations, minimum equipment lists and logbooks. In addition, the EFB can host various software applications to automate other functions normally conducted by hand. For example, the Onboard Performance Tool (OPT) application calculates takeoff and landing performance using a combination of pre-loaded and manually-entered data for a specific aircraft configuration under current conditions. The EFB is located in a fixed position, below the Captain's and First Officer's tiller, near the respective pilot's knee (see Figure 18).

Once the flight is initialized via the CDU pre-flight procedure, the pilot can turn on the EFB and the flight information propagates to the EFB, including departure and arrival airport, GPS information, flight number, performance data points for performance calculations. Using the EDB (EFB Document Browser) the pilot can navigate throughout the document finder to locate critical information, and the 'Edit Chart Clip' page allows the pilot to select chart types for airport taxi pages, SIDs (standard instrument departures), STARs (standard terminal arrival routes) and instrument approach procedures.

Figure 18. Location of the Electronic Flight Bag (EFB)
(source: http://www.lb.boeing.com/commercial/aeromagazine/articles/2012_q1/3/)

An ‘Enroute Moving Map’ on the EFB uses the airplane location data to enable live airplane tracking along the route. The application may be used to load and modify routes as well as search for navigational objects and retrieve their details. Also available on the EFB is a full navigation page with the capability to depict navigational aids, waypoints, airports, airways, and FIR (flight information region) boundaries among other items.

2.2.2.8 Head Up Display (HUD)

Two independently operated Head-Up Displays (HUDs; see Figure 19) are located above the glareshield, one in front of each pilot. Installation and use of dual HUDs eliminates (left) seat dependent tasks. Both are drop-down type HUDs that can be pulled to stow or extended forward for use by releasing a latch device. Flight data symbology is projected onto a glass combiner screen from a monochromatic green LCD projector. For the most part, the HUD displays the same information as the PFD and aids in low visibility takeoffs and landings. In addition, the HUD takeoff system provides lateral guidance on the HUD for takeoff roll and rejected takeoff. Selecting a HUD TAKEOFF departure in the FMC and turning on either flight director enables the guidance and sets HUD TO/GA as the active FMA roll mode.

Figure 19. B787 Head-Up Display (HUD)
(source:http://www.lb.boeing.com/commercial/aeromagazine/articles/2012_q1/3/)

The HUD provides flight director (FD) guidance which is either FMC- or MCP-generated, or possibly a combination of both. The HUD also includes a flightpath acceleration symbol. It indicates the inertial acceleration (or deceleration) of the airplane along the flightpath. In addition, there is a speed error tape which shows the difference between the indicated airspeed and the MCP-selected airspeed or the FMC-commanded airspeed.

A full mode and a de-clutter mode are available for the HUD. The de-clutter mode removes the airspeed and altitude tapes and substitutes the information with digital values. The de-clutter mode also provides calculated runway edge lines at 1000 ft that disappear at 60 ft, with tic marks at the touchdown aim point. The declutter mode helps direct the pilot's eyes toward the runway which is especially useful in high crosswind conditions where the nose of the aircraft is not directly lined up with the runway.

2.2.2.9 Thrust Levers and Trim

Both aircraft are equipped with two thrust levers, one for each engine. Located on the thrust levers are auto-throttle disconnect buttons inside the handle of the levers. With auto-throttles armed, the TOGA (Take-off/Go-Around) switches, if depressed automatically, add power in takeoff or go-around conditions. Thrust reverser positions for both aircraft include full or partial reverse (selected by the pilot), idle reverse and reverser stow positions.

An engine failure would necessitate the disengagement of the failed engine auto-throttle on either aircraft. However, on the B787, two auto-throttles switches (left and right) control the respective engine thrust lever. In case of a single engine failure, the operating engine auto-throttle would remain engaged and allow the crew to conduct a single engine auto-landing in low visibility situations to as low as 300 RVR (runway visual range). In contrast, the B737-500 has only a single auto-throttle switch. An engine failure would require disabling the auto throttle and auto-land would be prohibited.

The B787 normally lands with both auto-throttles engaged throughout landing and roll-out. The auto-throttle maintains the selected speed throughout landing and flare. The B787 also has an 'Automatic Activation' mode for the auto-throttle. If the airspeed decreases to near stick shaker activation, the auto-throttle automatically activates in SPD mode and advances thrust to maintain the minimum maneuvering speed (approximately the top of the amber band) or the airspeed set in the IAS/MACH window, whichever is greater.

The B737-500 has a black rotating trim wheel located on the First Officer side. The trim wheel moves in response to manual trim changes or automatic trimming by the autopilot. In contrast, the B787 has no trim wheel and there is no sound when trimming occurs either by the pilot or by the autopilot. Trim indications for the B787 are significantly different from those on the B737-500. The B787 shows exact trim position on EICAS versus the green band on the B737-500 trim wheel which is only an approximate setting.

2.2.3 Aural Information

Both aircraft present aural warnings for terrain and obstacle alerting, predictive and reactive windshear, traffic conflicts, and improper takeoff or landing configuration.

The **B787 provides additional aural alerts** including EICAS caution and warnings for systems such as the **Ground Proximity Warning System (GPWS)**; **speed brake warnings** on rollout if the speedbrakes do not deploy automatically or in flight if speed brakes extend with power above idle; **low airspeed**; **flight control malfunctions**; **incomplete electronic checklists**; and the **crew alertness monitor** (both visual EICAS message and an aural warning). The Crew Alertness Monitor is enabled/disabled and configured by the airline. When enabled, the FMC continuously monitors for switch actions on the MCP, EFIS control panel, display select panel, CDUs, and radio transmitter microphone switches. If a predefined time (e.g., 30 minutes) elapses after the last switch action was detected, a visual EICAS advisory message PILOT RESPONSE is displayed. If there is still no switch action after a brief time, the EICAS caution message PILOT RESPONSE appears. As configured by the airline, if there is still no switch action, a siren, Master Warning lights and the red EICAS warning message PILOT RESPONSE may be displayed.

3. COMPARISON OF FLIGHT DECK INFORMATION - A320 vs. A350

The following section presents a comparison of the flight deck layout, the information presented on various flight deck interfaces, and the flexibility of information presentation on the flight decks of the first-generation Airbus A320 (first introduced into airline operational service by Air France in 1988; see Figure 20) and the Airbus A350 (first introduced into airline operational service by Qatar Airways in 2015; see Figure 21).

Figure 20: Decorative Image of an Airbus A320-200 In-Flight (source: https://www.aircharterserviceusa.com/aircraft-guide/group/airbus-europe/airbusa320-200)

Figure 21: Decorative Image of an Airbus A350-900 In-Flight (source: https://de.wikipedia.org/wiki/Airbus_A350)

As with the preceding comparison of the two Boeing aircraft, the information and interfaces discussed in this section are those that have the most direct impact on flightpath management, which the FAA defines as: “the planning, execution, and assurance of the guidance and control of aircraft trajectory and energy, in flight or on the ground." (Federal Aviation Administration, AC 120-123, 2022).

3.1 METHOD

The comparison was performed by an experienced helicopter pilot and active-duty officer in the U.S. Coast Guard, in collaboration with the Principal Investigator (PI). Please note that this comparison was prepared without having access to the Airplane Flight Manuals (AFMs) and Flight Crew Operating Manuals (FCOMs); instead, it is based on publicly available information, including unofficial aircraft manuals, flight crew training manuals, simulator training guides and flight deck videos of aircraft or simulator flight. First, the overall flight deck layout on the two aircraft will be compared, followed by a more detailed analysis of information presented on individual displays, a discussion of information propagation and a review of display reconfiguration options.

3.2 FINDINGS

3.2.1 Overall Flight Deck Layout

3.2.1.1 Main Instrument Panel

The A320 has six 7.2" x 7.25" display units (DUs) on the main instrument panel. Both pilots each have a set of two side-by-side DUs for the Primary Flight Display (PFD) and Navigation Display (ND), respectively. In the center of the instrument panel, two DUs are vertically stacked and display engine-related information, warnings, cautions and alerts, as well as the status for aircraft systems (see Figure 22). In addition, the A320 has two Multipurpose Control and Display Units (MCDUs) on the center pedestal, between the pilots' seats, for flight plan and aircraft information entry.

The A350 has six 12" x 8" DUs on the main instrument panel (see Figure 23). The screen directly in front of each pilot normally displays the PFD and ND, while the outboard screens show the Onboard Information System (OIS) which serves as an Electronic Flight Bag (EFB), among other capabilities. The vertically stacked screens in the middle of the instrument panel display engine information, warning details, and the status of aircraft systems. In addition, the pilot in the left seat and the one in the right seat each have a slide-out keyboard for information entry and a laptop (not pictured) which is capable of displaying Onboard Information System (OIS) information.

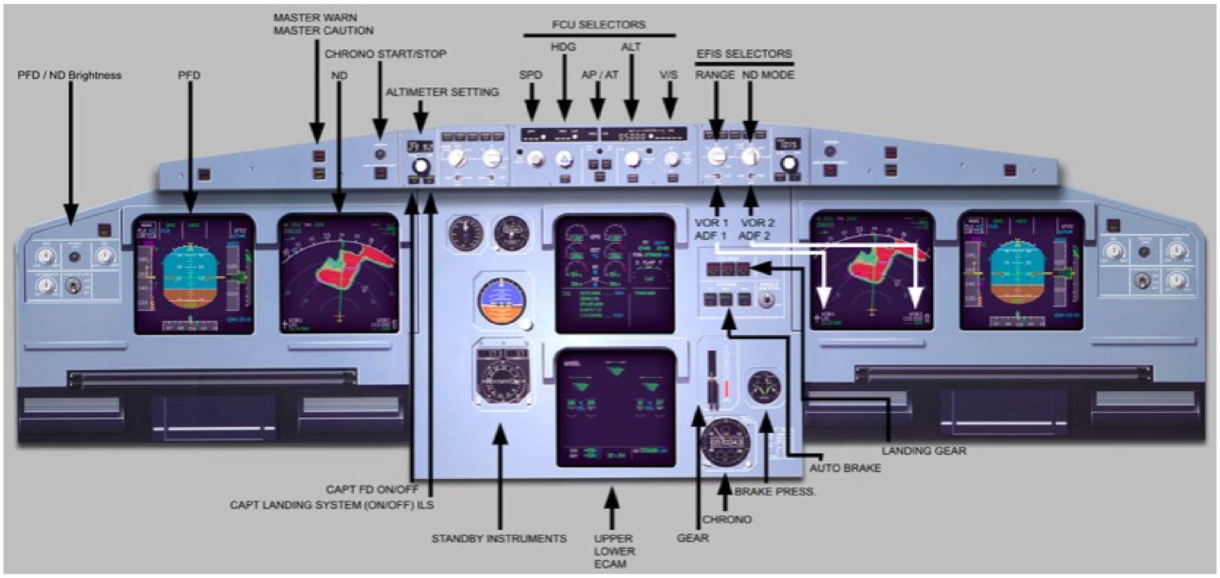


Figure 22: A320 Main Instrument Panel (source: Airbus, 1998)

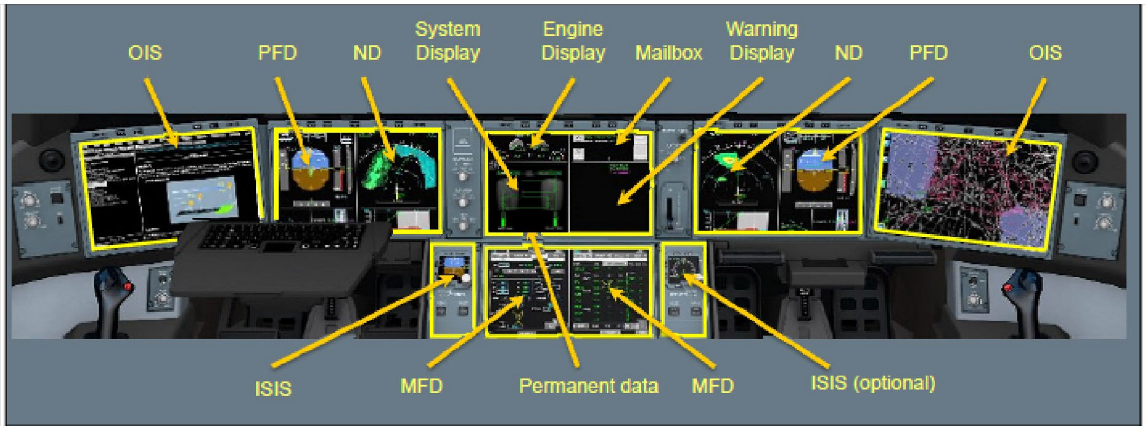


Figure 23: A350 Main Instrument Panel (source: Airbus, 2011)

While the total number of screens (six) on the A320 equals that on the A350 used in normal operations, the split-screen viewing capabilities of the A350's DUs effectively support 10 separate displays. The information layout is, in a broad sense, preserved between the two aircraft with PFD and ND information directly in front of each pilot, engine and system information in the center of the main instrument panel, and flight planning information on the lowest central screen. The most significant change with respect to layout is the addition of the OIS displays on the A350. Other notable layout changes on the center instrument panel of the A350 include:

- MCDUs are located in the center pedestal on the A320; they are presented on a split screen display on the lowest central instrument panel screen on the A350 (referred to as the MFD).

- Reduction of information displayed on the A320 autobrake panel and gear position indicator. Landing gear position indicators and brake temperatures moved to the landing gear system page on the A350 ECAM system page.
- A350 autobrake selector switch changed to send indications to the Flight Mode Annunciator (FMA).
- Removal of A320 brake pressure accumulator triple gauge. Brake pressure information is consolidated into the A350 Electronic Centralized Aircraft Monitoring (ECAM) system page.
- Removal of analog clock from A320 center panel. On the A350, clock functions are managed via the MFD "FMS Position/Time" page and displayed on the permanent data section of the ECAM.
- Consolidation of the A320's standby attitude indicator, standby airspeed indicator and standby altimeter into a single Integrated Standby Instrument System (ISIS).

3.2.1.2 Glareshield

The center section of both aircraft's glareshields contain a Flight Control Unit (FCU) as well as an Electronic Flight Information System (EFIS) panel for each pilot. The switches and pushbuttons on each aircraft's panels have minor differences but with largely the same functions (further details in 3.2.2 Navigation Display). The outboard sections of both glareshields contain visual alerts and indicators for warnings, cautions, sidestick priority and autoland. Some components added to the A350 glareshield as compared to the A320's are loudspeaker sound controls, an indicator for datalink messages from ATC, and a Head-up Display (HUD) control panel. Figures 24 and 25 show the respective aircraft glareshields.

Figure 24: A320 Glareshield (source: *Opencockpits*)

Figure 25: A350 Glareshield (source: *MK First A350-941*)

3.2.1.3 Center Pedestal

Many components of the A320's center pedestal exist in a similar but updated form and in a similar relative position on the A350. Figures 26 and 27 contrast the respective layouts. Below is a list of the most significant changes on the A350.

- The thrust levers remain in the center of the panel laterally but are relocated to the front of the panel.
- Instead of an MCDU and keyboards, the A350 has Keyboard and Cursor Control Units (KCCU) that interface with the MFD, ND, Mailbox and OIS (rather than just the MCDU on the A320).
- The ECAM control panel has additional push buttons and is moved from forward of, to aft of the thrust levers.
- The radio management panels are upgraded and digitized to now have their own small display screens on the A350. A third radio management panel is also added as a spare.
- The A320 center pedestal includes rotating pitch trim wheels that sandwich the thrust levers. On the A350, there are instead rocker type switches located aft of the flaps lever.
- The radar management panel was updated to take into account the increased surveillance and overlay capabilities of the A350. It is now located in between the flaps and speed brake levers and controls radar, Traffic Collision Avoidance System (TCAS) and the Terrain Awareness and Warning System (TAWS).

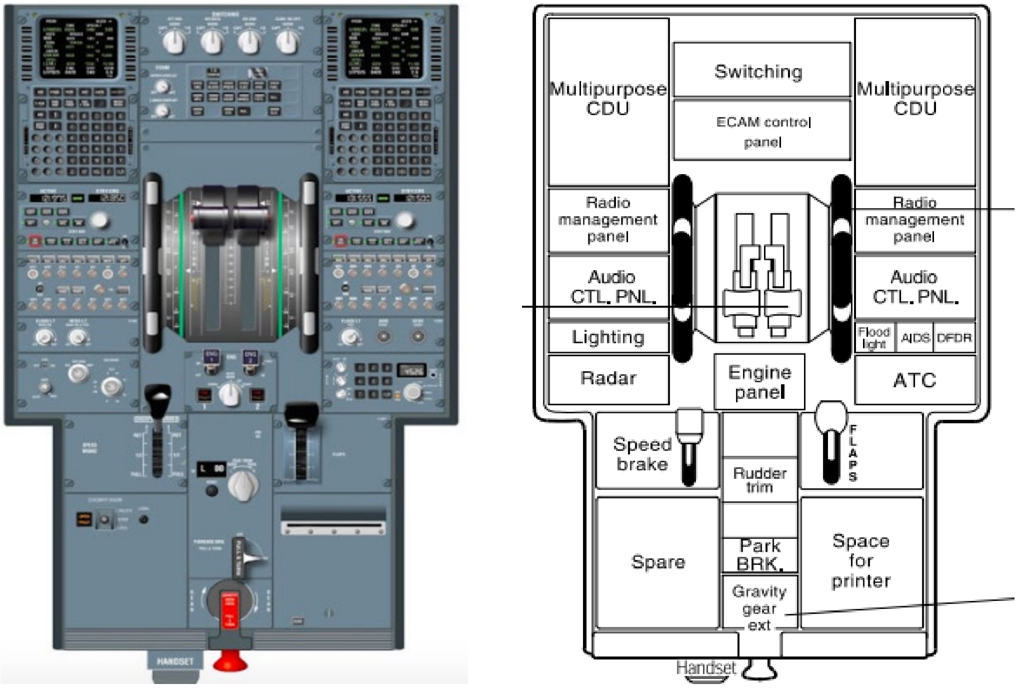


Figure 26: A320 Center Pedestal – Photo (on the left) (source: Airbus, 1998) and Text-Based Schematic (on the right)

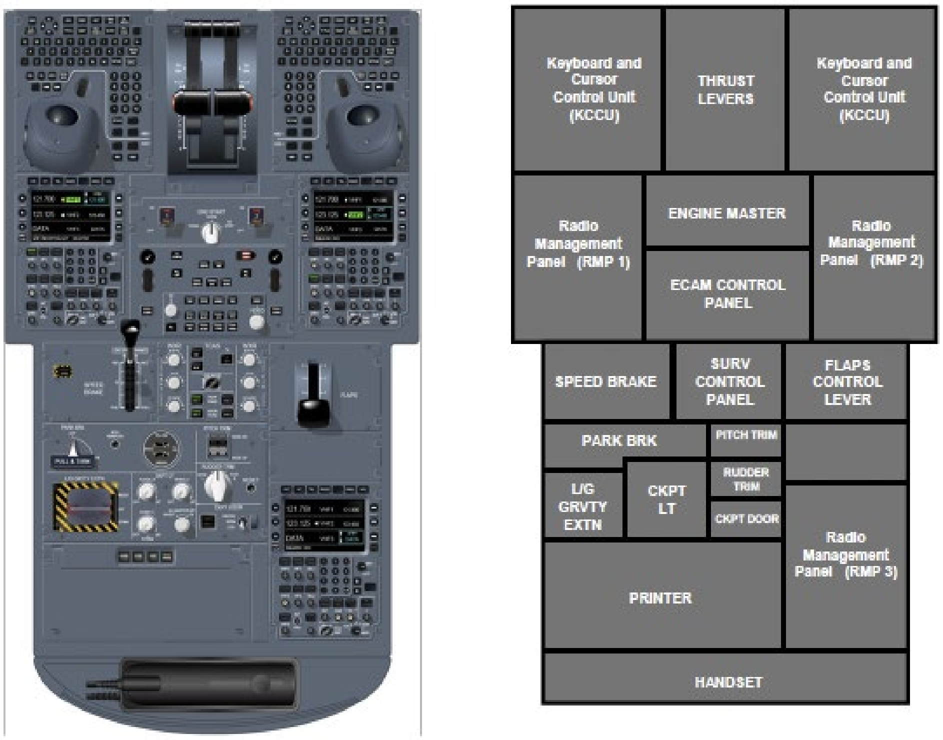


Figure 27: A350 Center Pedestal – Photo (on the left) (source: Airbus, 2011) and Text-Based Schematic (on the right)

3.2.1.4 Overhead Panel

On the two aircraft, controls for the primary aircraft systems - fire suppression, hydraulics, fuel, electrics, air conditioning, auxiliary power unit, and cabin pressure - have remained in the same locations relative to one another, on the center column of the overhead panel.

There are some differences due to changes in equipment between the A320 and A350. The most significant change is the addition of the maintenance panel in the aft section of the center column on the A350. This panel displaced all the circuit breakers that were previously located in this place, to the two lateral rows.

Overhead panel controls do not directly relate to pilots' flightpath management tasks; therefore this review will not go into further detail on minor differences between the two aircraft. Figures 28 and 29 depict the two aircraft overhead panels.

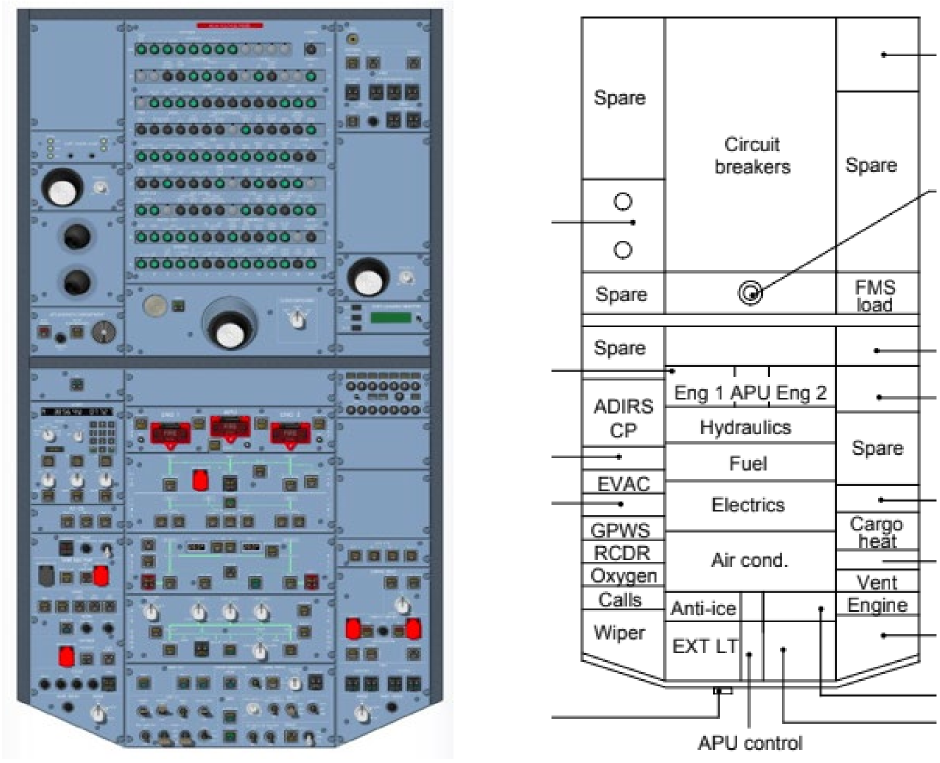


Figure 28: A320 Overhead Panel – Photo (on the left) (source: Airbus, 1998) and Text-Based Schematic (on the right)

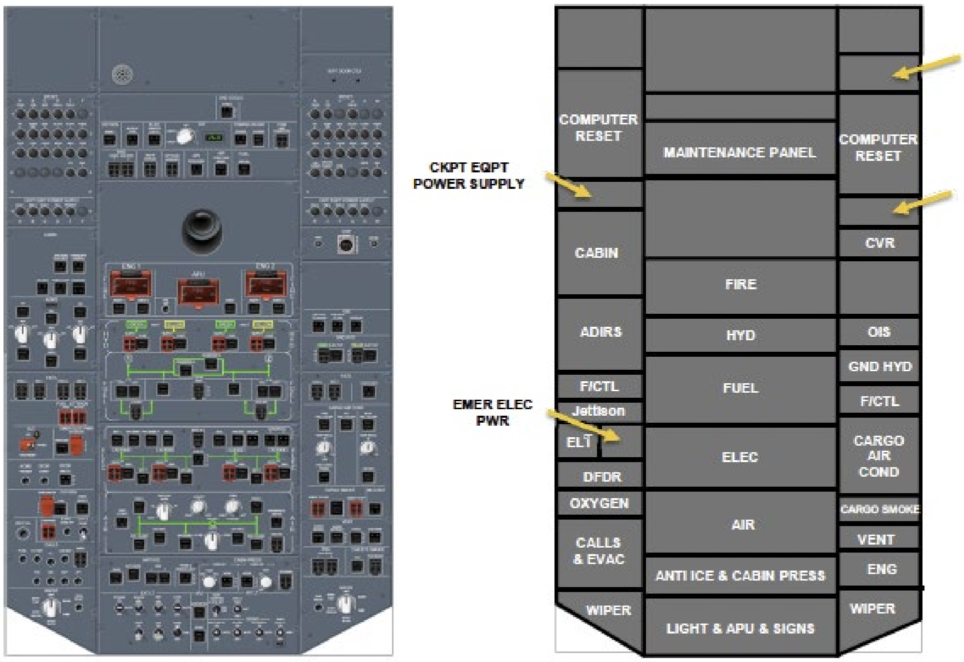


Figure 29: A350 Overhead Panel – Photo (on the left) (source: Airbus, 2011) and Text-Based Schematic (on the right)

3.2.2 Select Interfaces

3.2.2.1 Primary Flight Display (PFD)

The Primary Flight Display is the pilot's primary reference for information necessary to fly the aircraft. The A320's PFD consolidates the "standard T" consisting of an attitude indicator, heading compass, altitude and airspeed instruments into a single display. The airspeed tape (left side of the PFD; see Figure 30) uses a vertical grey scale with an overlay of white numbers and symbols with various colors to provide airspeed indications to the pilot. Actual indicated airspeed is represented by a horizontal yellow line. Speed trends are represented by the yellow vertical arrow (see arrow near 160 knots in Figure 30). The index line displays what the indicated airspeed might be in 10 seconds if the airplane maintains a constant acceleration or deceleration. The magenta triangle (to the right of 170 knots in the figure below) is a target airspeed symbol that is calculated by the flight management guidance computer (FMGC) when a pilot engages the SPEED mode (autopilot function). The A320 PFD also incorporates flight mode annunciations at the top, a vertical speed indicator, radar altitude, flight director guidance bars and approach and navigation information. Figure 30 shows the A320's PFD in an approach configuration.

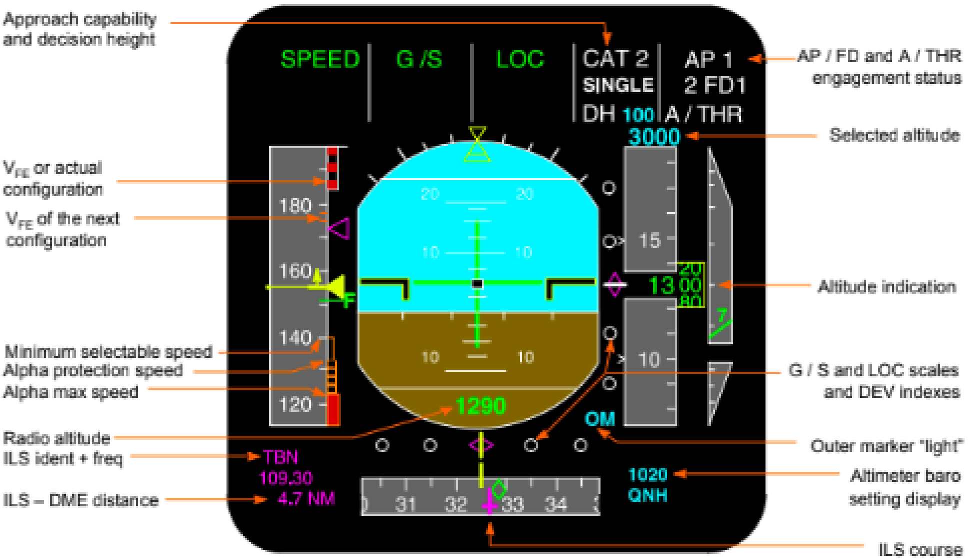


Figure 30: A320 PFD in Approach Configuration (source: Airbus, 1998)

On the A350, new display areas for flaps and thrust lever settings were added. Also, the stand-alone PFD and ND displays on the A320 were combined into a single display unit viewed as a split screen on the A350. Figure 31 shows just the PFD side of the A350 PFD/ND split screen display.

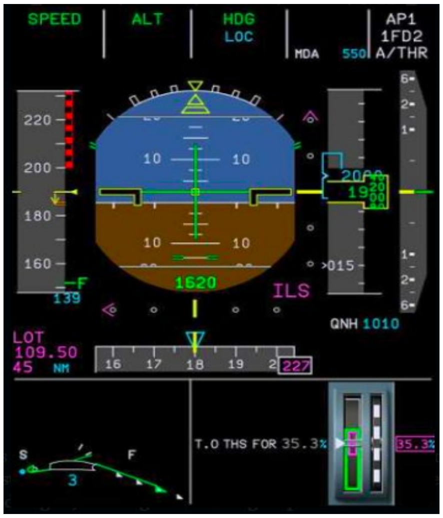
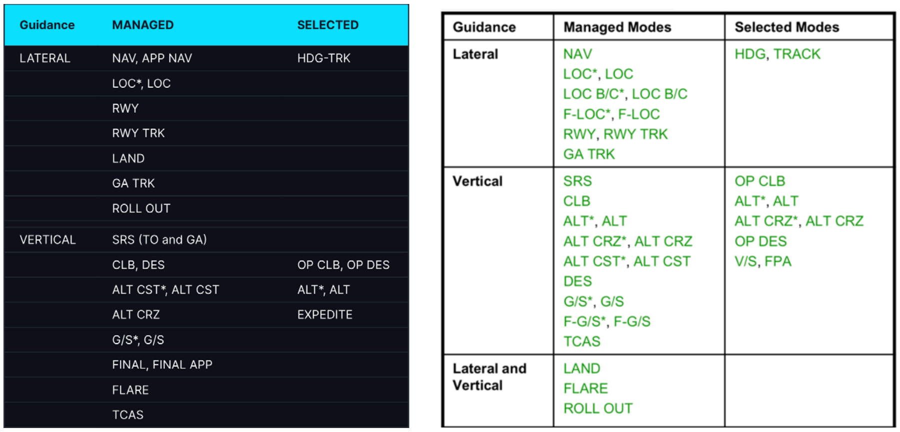


Figure 31: A350 PFD (source: Airbus, 2011)

The following sections compare various components of the A320 PFD and the A350 PFD.

<u>- Flight Mode Annunciator:</u> The upper-most section of the PFD (see Figure 31) contains five columns displaying information about active and armed flight guidance modes (columns 1-3), the aircraft's approach capabilities (column 4) and the status of the autopilot, flight director and autothrust system (column 5). The first column on the left shows autothrust modes while the second and third columns present vertical and lateral modes, respectively (for a side-by-side comparison of lateral and vertical modes on the two aircraft, see Figure 32 below). Active modes are shown in the top row, in green, while armed flight modes appear in row 2, in cyan.



Guidance	MANAGED	SELECTED
LATERAL	NAV, APP NAV	HDG-TRK
	LOC*, LOC	
	RWY	
	RWY TRK	
	LAND	
	GA TRK	
	ROLL OUT	
VERTICAL	SRS (TO and GA)	
	CLB, DES	OP CLB, OP DES
	ALT CST*, ALT CST	ALT*, ALT
	ALT CRZ	EXPEDITE
	G/S*, G/S	
	FINAL, FINAL APP	
	FLARE	
	TCAS	

Guidance	Managed Modes	Selected Modes
Lateral	NAV LOC*, LOC LOC B/C*, LOC B/C F-LOC*, F-LOC RWY, RWY TRK GA TRK	HDG, TRACK
Vertical	SRS CLB ALT*, ALT ALT CRZ*, ALT CRZ ALT CST*, ALT CST DES G/S*, G/S F-G/S*, F-G/S TCAS	OP CLB ALT*, ALT ALT CRZ*, ALT CRZ OP DES V/S, FPA
Lateral and Vertical	LAND FLARE ROLL OUT	

Figure 32: Lateral and Vertical Flight Guidance Modes on the Airbus A320 (on the left; source: https://docs.flybywiresim.com/pilots-corner/advanced-guides/flight-guidance/overview/#available-guidance-modes) and the Airbus A350 (on the right) (note: in managed modes, the autopilot follows the constraints set in the flight management computer; in selected modes, it follows targets chosen by the pilot)

Of particular interest is the TCAS mode as it is new on the A350 and operates differently from other mode types. If a TCAS alert reaches the highest level - called a "resolution advisory" - while the autopilot is in use, the flight director will automatically engage the HDG-V/S display mode (not TRK-FPA) and activate a resolution maneuver. This will occur regardless of flight mode selection status prior to the advisory. If the autopilot is not engaged, the flight director will display the command bars on the PFD, and it will be up to the pilot to fly the maneuver. "TCAS" will be displayed in green on the FMA while it is engaged just as with any other flight director mode. The aircraft will return to the prior AP/FD configuration once the "resolution advisory" is resolved.

- Attitude Indicator: The same shape and color scheme is used for ground and sky on the attitude indicator along with the same gradations on the pitch and roll scales. The sideslip indicator also remains unchanged.

- Airspeed, Altitude, Vertical Speed & Heading Indicators**:** For the most part, the modalities and functions of these indicators remain similar. There are some changes in symbology, such as color and lines of text, but with the information available to us, it is not possible to determine the details of these changes.

- Flight Director Guidance: There are two different flight director guidance modes on both aircraft, "HDG V/S" and "TRK-FPA." The "HDG V/S" mode provides a traditional PFD view with perpendicular sliding horizontal and vertical command bars. In contrast, the "TRK-FPA" mode provides an indication of the aircraft's actual flightpath in relation to the ground. The flight director can be coupled to the autopilot in either mode.

During a precision approach, the FMGS provides a vertical deviation scale along the right-hand side of the attitude indicator and a horizontal deviation scale below the attitude indicator. The associated indications remain the same between the two aircraft.

- Flightpath Vector (FPV): The flightpath vector shows the track and flightpath angle of the aircraft in relation to the ground via a circular green display on the PFD, commonly called the "bird". The bird appears only when TRK-FPA is selected on the FCU. It responds with a delay as it is affected by the inertia of the aircraft during maneuvers. FPV can be used in all flight phases, except during takeoff and go-around. It is specifically recommended for non-precision approaches and visual flying. On the A350's so-called 'harmonized Primary Flight Display' (hPFD), the "bird" is surrounded by additional indicators (right side of Figure 81). These include a speed line, energy chevrons and a flight director, represented by a magenta ring. This symbology mirrors what is presented on the A350 head-up display (HUD) to make head up-head down transitions easier for pilots. Figure 33 shows the differences between the two aircraft for a coupled flight director in the FPV mode.

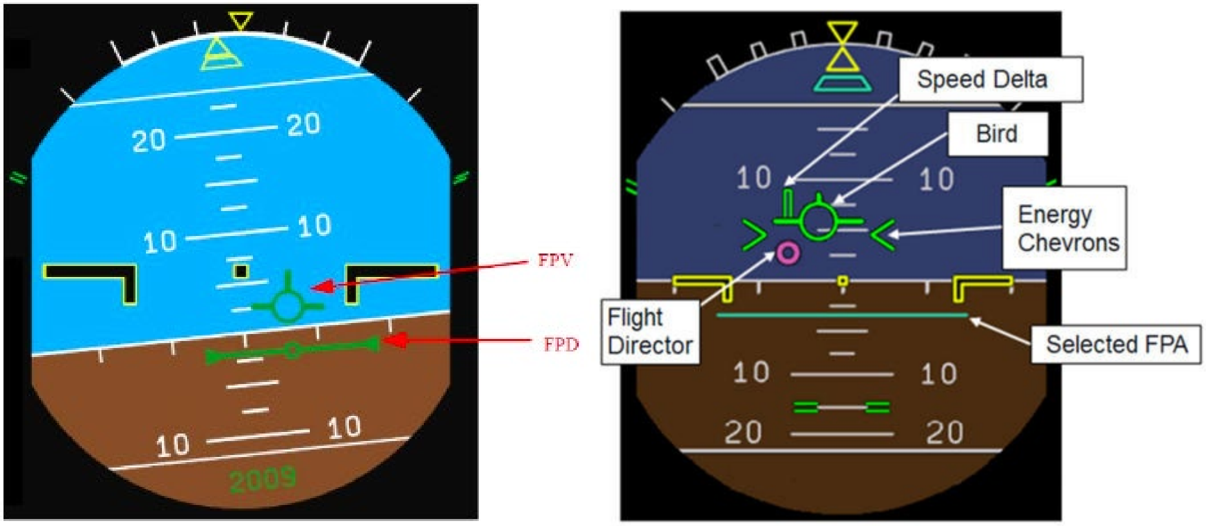


Figure 33: A320 (left; source: JeeHell, 2020) & A350 (right; source: https://www.airbus.com/en/products-services/commercial-aircraft/wide-body-aircraft/a330neo-cockpit-commonality-with-a350) Coupled Flightpath Vector (FPV) on the PFD

<u>- Additional PFD Elements:</u> The most evident change on the A350's PFD is the addition of two side-by-side displays at the bottom of the display, underneath the heading tape. The lower left portion of the screen details the commanded flap setting and the actual flap position. This information was previously part of the upper ECAM display on the A320. The lower right side of the display depicts the required thrust setting for the particular phase of flight, or the actual thrust setting given the thrust levers are resting in a managed detent.

There are new safety protections built into the functions of the slats and flaps on the A350 to prevent inadvertent extension or retraction based on phase of flight. Each precaution method, extension setting and failure type has unique indications on the slats/flaps display. This is an increase in the amount of information available from the A320, as well as a change in the presentation of information in a more prominent location directly in front of each pilot. Figure 34 shows many of the slat/flap display options of the A350's PFD, compared with the limited display on the A320's upper ECAM screen (shown on the right side of the figure).

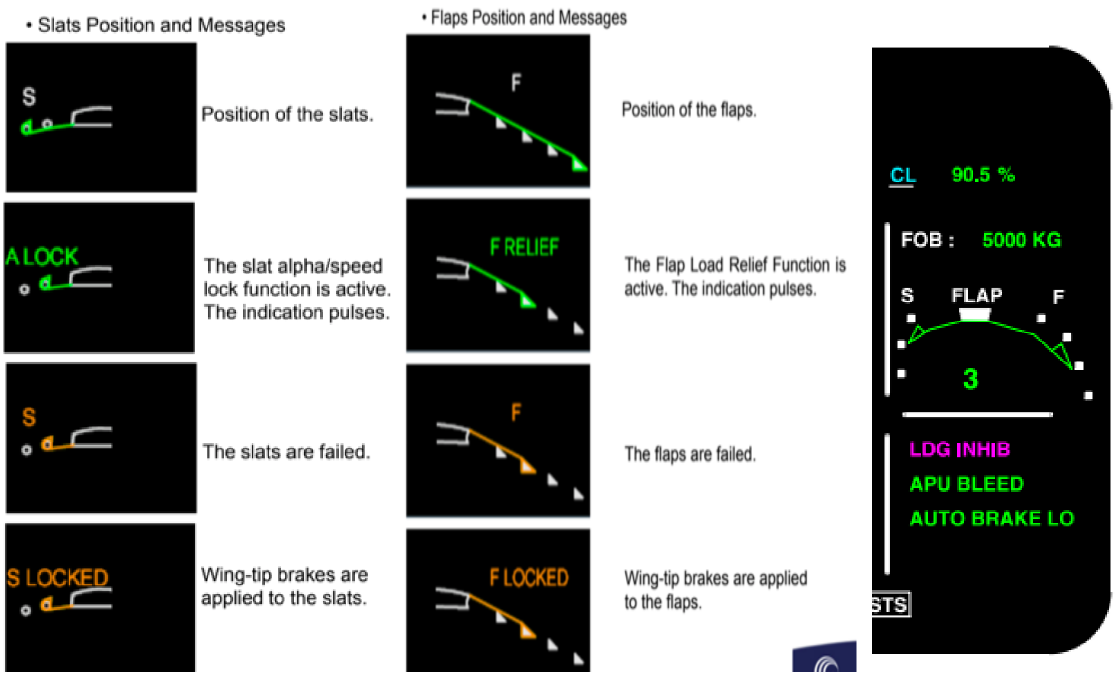


Figure 34: A350 (left two columns) (source: Airbus, 2011) vs. A320 (right column) (source: Airbus, 1998) Flaps and Slats Indications

<u>- External Taxiing Aid Camera System (ETACS):</u> While not a separate flight display, another capability added to the PFD on the A350 is the ETACS. It provides a split-screen view to aid in taxiing, consisting of an overhead view of the aircraft looking aft (Figure 35) and a view of the nose wheel looking forward. ETACS is made available to each pilot via a “Taxi” pushbutton on their respective EFIS control panels.

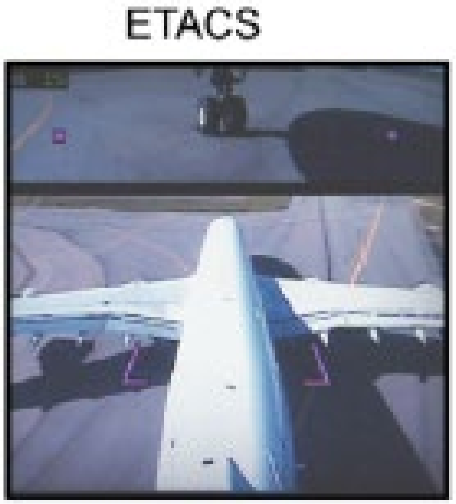


Figure 35: A350 ETACS on the PFD (source: Airbus, 2011)

The ETACS can also be viewed on the system display portion of the ECAM screen. This is accessed via the "video" push button on the central pedestal's ECAM control panel and the rotating "video" knob to cycle through the three available cameras (cabin, flight deck door, ETACS).

3.2.2.2 Navigation Display (ND)

The Navigation Display presents pilots with a color top-down view of the flight's progress along its route. Information presented on the navigation display can include the position of the airplane, its heading/track, the route of flight, distances and ETAs, wind direction and velocity, and surrounding airports/navaids/waypoints.

A significant difference between the A320 and A350 is that the ND changed from a stand-alone screen to a combined screen, split side-by-side with the PFD. Within the ND, a Vertical Display (VD) section was added to the lower screen area. The VD spans the width of the screen and contains most of the same navigation, weather and surveillance information that is available on the ND but displays it in a profile view. Figure 36 depicts differences in the displays. This new profile view provides the pilots quick reference altitude planning for obstacles, clearances and terminal procedures through interaction with the FMS that otherwise would require integration of information from multiple sources.

Figure 36: A320 ND in ARC Mode (left) (source: Airbus, 1998) vs. A350 ND & VD in ARC Mode (right) (source: Airbus, 2011)

- ND/PFD Controls: Figures 37 and 38 show the differences in the Electronic Flight Information System (EFIS) control panels for the PFD and ND.

Figure 37: A320 Left Seat Side EFIS (source: https://wiki.ivao.aero/en/home/training/documentation/Navigation_Display_-_ND)

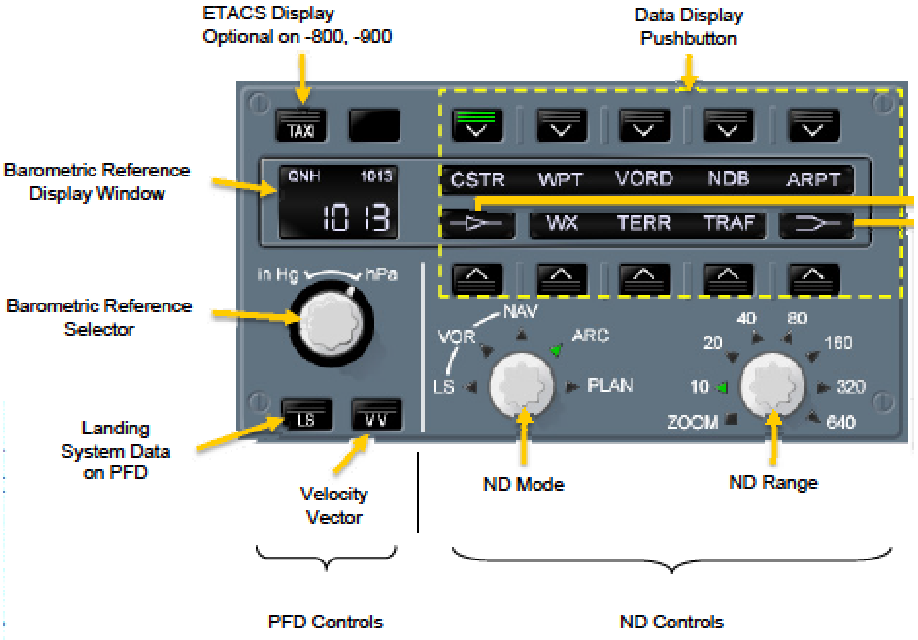


Figure 38: A350 Left Seat Side EFIS (source: Airbus, 2011)

Both designs split PFD controls to the left side and ND controls to the right side, but the A350's panel has different selectors, display methods and added controls to access new ND capabilities. These changes and new capabilities are summarized in the following list:

- VOR/ADF selectors 1 and 2 changed from three-way switches to pushbuttons for overlay selection. There is no longer a way to track an ADF with an overlay needle.
- The overlay selection options expanded from five to 10 options. Added overlay options on the A350 are weather (WX), Terrain Awareness and Warning System (TAWS) and Traffic Collision Avoidance System (TCAS).
- The pushbuttons for selecting overlays are now adjacent to the desired overlay (as opposed to on the center pedestal on the A320).
- The rotating knobs for selecting barometric reference, ND modes, and ND range changed to circular knobs with large edge knurls.
- The selected ND mode and ND range are now indicated with a green light, rather than a pointer on the rotating knob.
- ND display range was extended from 320 NM to 640 NM.
- Instead of the "FD" push-button under the barometric reference selector on the A320, the A350 features a "VV" (velocity vector) push-button (in the center of the FCU), which enables or disables the flight director guidance bars on either pilot's PFD.

- Enhanced ND capabilities are listed below:

    - Weather radar enhancements include improved localization for predictive windshear and turbulence detection, as displayed in figure 39. When detected, windshear and turbulence information is automatically displayed on the A350, instead of having to be selected manually on the A320 radar control panel.

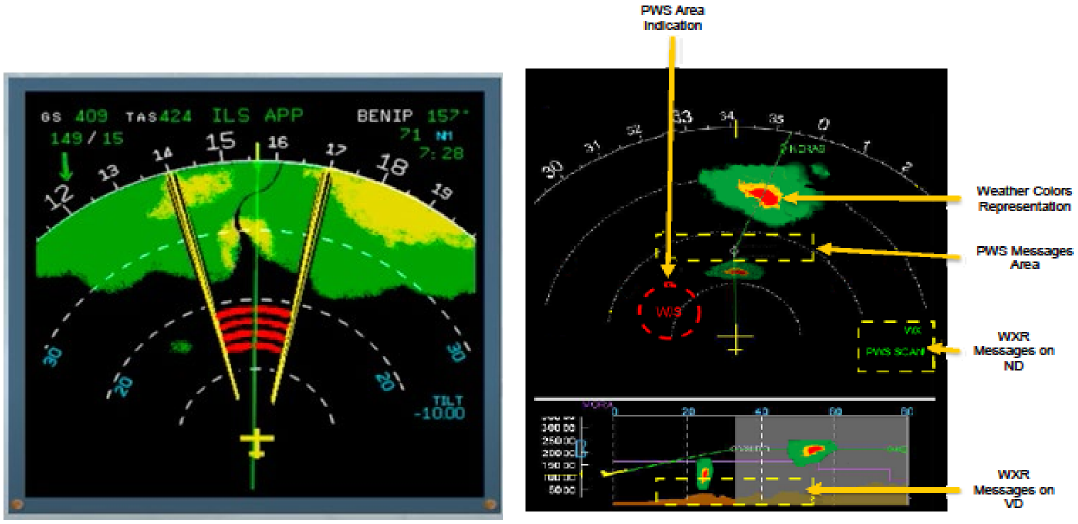
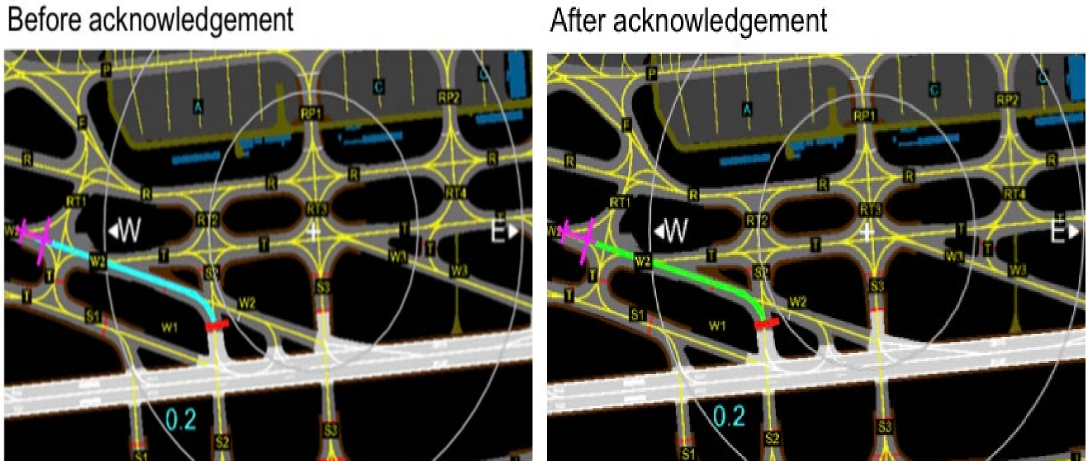


Figure 39: A320 (left) (source: Weather Radar Presentation - A320 Family, 2021) vs. A350 (right) (source: Airbus, 2011) Weather Radar Displays

- There are two new functions in the Terrain Awareness and Warning System (TAWS): Ground proximity warning and terrain awareness on the ND and VD. The A350 also allows filtering of the display to provide TAWS between weather and/or terrain as well as a decluttering pushbutton to display only traffic alert information.
- The A350 presents intuitive images of TCAS contacts, rather than a generic shape, to allow quick identification and orientation of other aircraft in addition to their standard position, relative altitude, and vertical trend information.
- An “Airport Navigation" display shows the aircraft's position relative to runways and taxiways as well as other aircraft on the ground. Additional features are a runway proximity advisory system and a taxi path clearance indicator that changes colors to correspond with clearances and clearance limits when paired through a controller/pilot datalink communication system. Figure 40 shows an A350 color-coded taxi clearance path.


Before acknowledgement

After acknowledgement

Figure 40: A350 Data-linked Ground Clearance Display (source: Airbus, 2011)

3.2.2.3 Multi-Function Displays (MFD)

Generally, Multi-Function Displays (MFDs) are electronic instrument panels that consolidate multiple flight-critical information sources into a single display unit. They can display a wide variety of information, including navigation data, flight parameters, weather data, engine performance, and system status.

On the A320, the central screens are referred to as the upper and lower ECAM Display Units, while on the A350 the upper central screen is called the ECAM and the lower display is called the MFD. Each aircraft has two central screens stacked vertically, but with split-screen layouts. The A320 effectively has five display sections used in normal operation while the A350 has seven. Typical layouts are shown in figure 41.

Figure 41: A320 Upper ECAM (left) (source: Airbus, 1998) vs. A350 Upper ECAM (right) (source: Airbus, 2011)

The primary engine indications (see Figure 42) remain on the top left corner of the ECAM screen for both models, but on the A350 display, there is no N2 and fuel flow information. The A350 still displays N1 information, but only the numerical readout as compared to a dial-type N1 gauge on the A320. A generic '0-10' scaled gauge labeled "THR" (thrust) has been incorporated in the A350 engine display. Its versatility allows it to be adapted to all engine types, rather than requiring aircrew interpretation depending on which engine is installed on a particular aircraft model. The Exhaust Gas Temperature (EGT) gauge remains very similar on both aircraft. Both have a numerical readout within a semicircular dial, but the numbers surrounding the dial have been removed to help declutter the display on the A350.

A mailbox section in the top right corner of the ECAM is new to the A350. This is where messages from ATC received via Datalink can be read, acknowledged and requests can be sent.

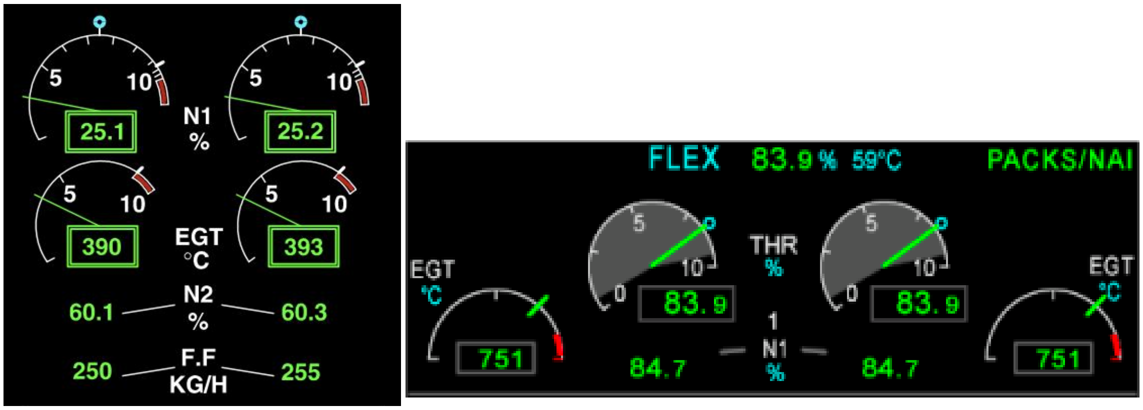


Figure 42: A320 (left) (source: Airbus, 1998) vs. A350 (right) (source: Airbus, 2011) ECAM Engine Data

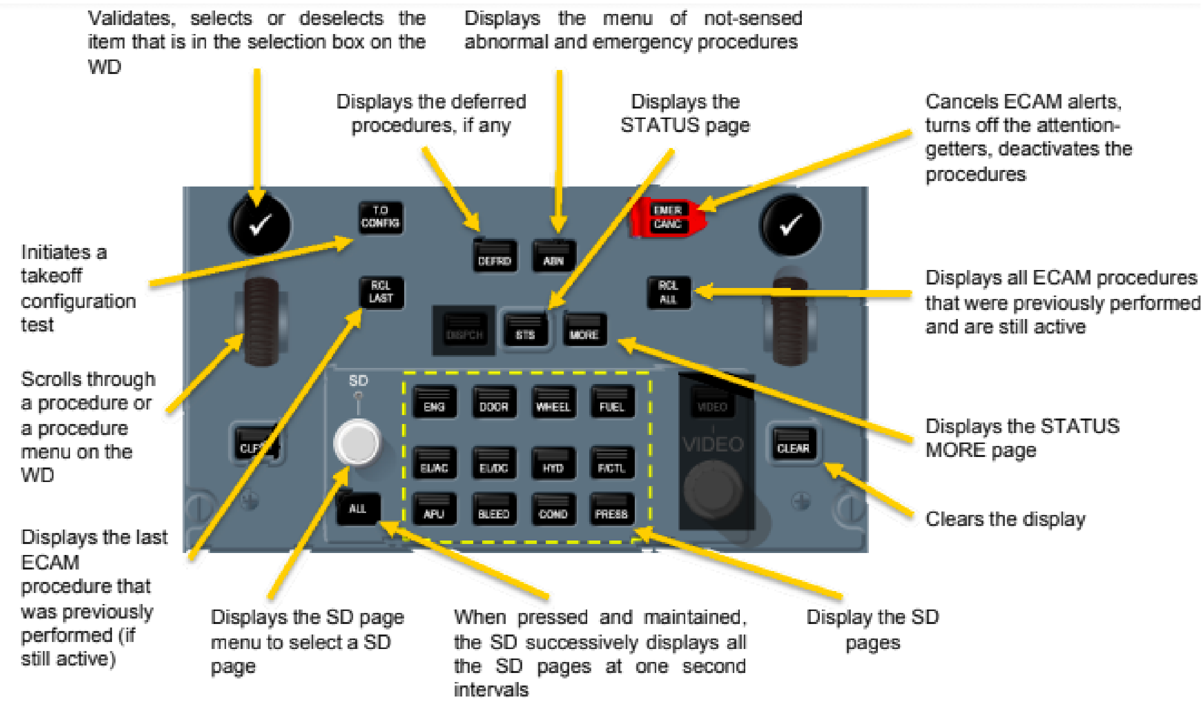
The information available on the A320's lower ECAM moved to the System Display section of the A350's ECAM. The A350 has all the same system display pages as the A320 as well as one additional page that shows all the system circuit breakers. These system screens are accessed in similar manners, either through an automatic switching function based on the phase of flight or via a pushbutton selector on the ECAM control panel.

The dedicated warning display section of the A350 remains in the lower right-hand side of the ECAM but is much larger than that of the A320. The permanent data section in the lower left corner of the A350's ECAM displays temperature and pressure data, gross weight, center of gravity and total fuel information. With the exception of fuel on board, this data was previously only viewable when not on the cruise System Display or through the MCDU on the A320.

With the lower ECAM screen data of the A320 now contained within the upper ECAM on the A350, the lower screen is available for flight management data for both pilots. This frees up the space on the center pedestal that was occupied by the MCDUs on the A320 for the Keyboard Cursor Control Units on the A350 that function across multiple display screens.

- <u>MFD Controls:</u> There are many differences between the A320 and A350 ECAM control panels, which are shown in figures 43 and 44 and listed below:

Figure 43: ECAM Control Panel for A320 (source: Airbus, 1998)



Validates, selects or deselects the item that is in the selection box on the WD

Displays the menu of not-sensed abnormal and emergency procedures

Displays the deferred procedures, if any

Displays the STATUS page

Cancels ECAM alerts, turns off the attention-getters, deactivates the procedures

Initiates a takeoff configuration test

Displays all ECAM procedures that were previously performed and are still active

Scrolls through a procedure or a procedure menu on the WD

Displays the STATUS MORE page

Clears the display

Displays the last ECAM procedure that was previously performed (if still active)

Displays the SD page menu to select a SD page

When pressed and maintained, the SD successively displays all the SD pages at one second intervals

Display the SD pages

Figure 44: ECAM Control Panel for A350 (source: Airbus, 2011)

- Addition of a scrolling wheel for navigating the ECAM’s warning display menu on the A350. On the A320, pilots would push the CLR button to move to the next page of items.
- Addition of a “check” pushbutton used along with the scroll wheel to select, deselect or validate items in the A350’s warning display.
- Removal of display brightness rheostats on the A320’s ECAM panel to the center instrument panel on the A350.
- Rearrangement of aircraft system selection pushbuttons and the addition of a circuit breaker system page for the A350.
- Addition of a System Display (SD) rotating knob selector for a secondary method of choosing a particular SD.
- Separation of electrical system pages on the A350: one for DC and one for AC.
- Addition of a “DEFRD” pushbutton to quickly recall deferred checklists or procedures.
- Addition of a second “RCL” (recall) push button that allows a distinction between recalling all previous ECAM procedures with just the most recent one (“RCL ALL” and “RCL LAST " respectively).
- Creation of a “MORE” push button to display overflow information from the status page.
- Addition of the “VIDEO” pushbutton and rotating knob for selecting an ETACs to display on the upper ECAM screen.

3.2.2.4 Integrated Standby Instrument System (ISIS)

The update of the Integrated Standby Instrument System (ISIS) for the A350 consolidated three instruments into a single display to closely mirror the function and presentation of information of the PFD while maintaining independent data sources for backup navigation (see Figure 45). The main display is called the Standby Flight Display (SFD) and is located on the left-hand side of the A350's lower central MFD. An optional Standby Navigation Display (SND) can also be installed on the right side of the MFD.

A major enhancement to the A350's standby system display is the track deviation indicators to allow completion of an ILS approach all on standby instrumentation. The standby "wet compass" remains present and unchanged in location or function between the A320 and A350.

Figure 45: Standby Instrumentation on A320 (left) (source: A320 EC-KNM Iberia Cockpit, 2011) and ISIS SFD on A350 (right) (source: Airbus, 2011)

3.2.2.5 Onboard Information System (OIS)

The A350 OIS is an additional full display screen in front of each pilot (two screens total). This system represents an electronic flight bag, presenting performance calculations, charts, weather reports and forecasts, and flight plans. It has maintenance support capabilities, aids in cabin management and helps replace all former paper documentation and charts.

The display depicts information that is derived from laptops stored in the lateral panels by each pilot and can be controlled through the Keyboard and Cursor Control Unit (KCCU; see more details below) or a stow-away keyboard and pointer on the same side of the flight deck as the screen. The aircraft systems share information with the OIS for display, but OIS data is not automatically incorporated into the aircraft's navigation or flight systems.

3.2.2.6 Keyboard and Cursor Control Unit (KCCU)

The A350's KCCUs provide a major change from the legacy A320 MCDU keyboard. Each KCCU incorporates computer style navigation methods with a scrolling wheel, mouse ball, full "QWERTY" keyboard and a click button selector (see Figure 46).

Many of the function keys at the top of the KCCU are carried over from the page selection keys of the legacy MCDU but with the addition of "MAIL BOX", "MFD", "ND" and "OIS" selectors. These illustrate the flexibility of the KCCU which can control message functions on the ECAM, flightpath management details on the MFD or ND and electronic flight bag information on the OIS. This is a significant change from the keyboard of the A320 which has dedicated use to only the MCDU immediately adjacent to it.

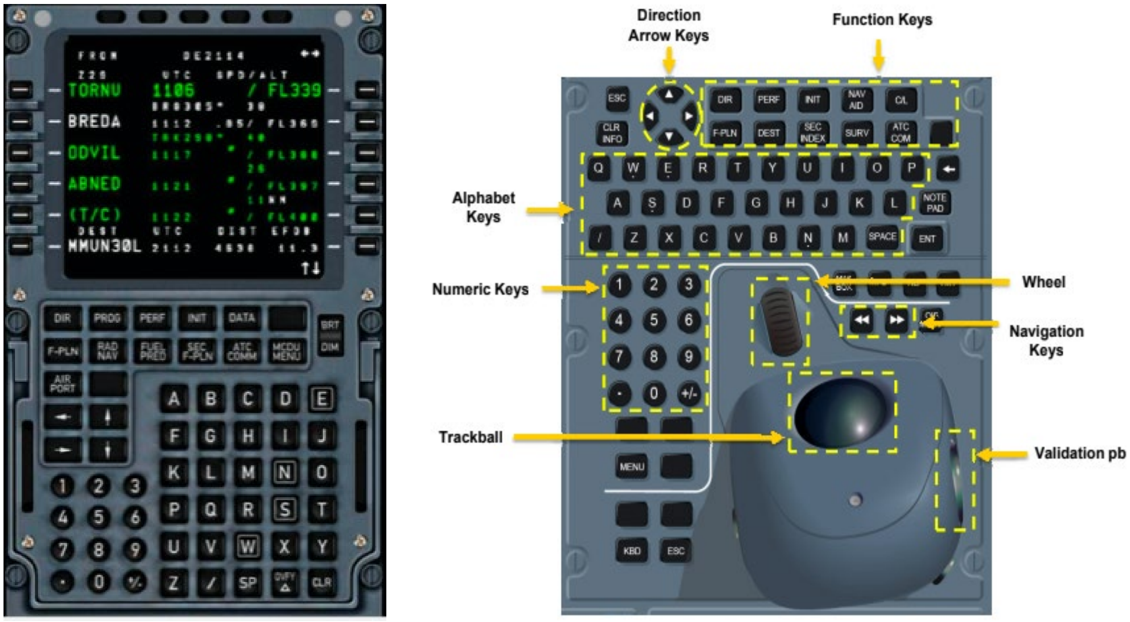


Figure 46: A320 Legacy MCDU (left) (source: A330 MCDU Text Hard to Read - Flight Model \ AP \ FMS - AEROSOFT COMMUNITY SERVICES, 2019) and A350 Left Seat KCCU (right) (source: Airbus, 2011)

3.2.2.7 Head-up Display (HUD)

A Head-up Display (HUD) is a 'see-through' transparent display that presents information to the pilot in their primary field of view (FOV). The primary benefit of a HUD is the enhancement of situation awareness for flight in limited (or night) visibility, especially in the vicinity of terrain, water, ground-based obstacles or other aircraft.

The Head-up Display (HUD) was added to the A350 as a new feature. The A320 did not have a HUD originally but has since been retrofitted by some operators to include one. The HUD contains much of the same information available on the PFD, including the FMAs, attitude indicator, airspeed, altitude and heading tapes, vertical speed, approach guidance and message alerts in textual form (see Figure 47), with modern HUD implementations presenting increased amounts of information. Minor differences between the HUD and PFD are that the HUD incorporates wind indications that are otherwise displayed on the ND (not the PFD), the roll indicator is a truncated version of that on the PFD, and the heading tape on the HUD does not have a numerical readout. As illustrated in Figure 47, HUD symbology differs to some extent from PFD symbology.

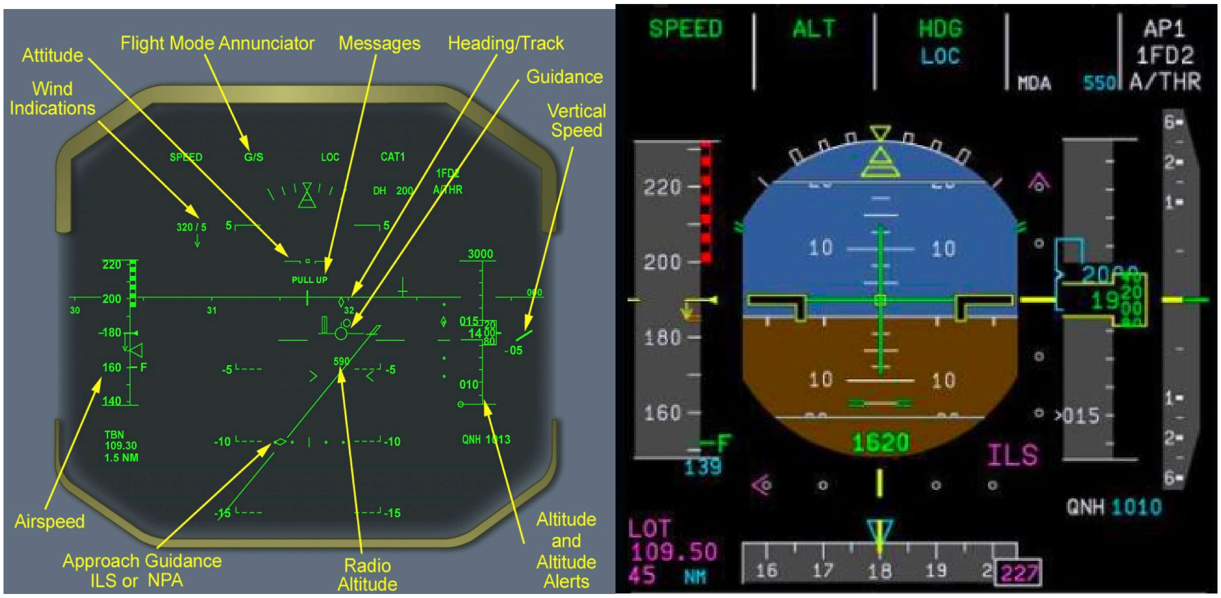


Figure 47: A350 HUD (left) & PFD (right) (source: Airbus, 2011)

3.2.3 Information Propagation

The A350 maintains much of the same architecture to its flight management system as the A320. Some minor differences include:

- Nomenclature (for example changing from a Flight Management Guidance Computer (FMGC) to a Flight Guidance (System)).
- Interface methods - removal of the MCDU so the pilot’s main interaction is via the KCCUs.
- Technology updates - new flight director modes.

The main interface between the pilots and the FMS is the MFDs. Flight planning information entered into the MFD is shared with the FMS computers, OIS, FPD, ND, and ECAM system pages. In addition, much data that is picked up automatically by sensors on the aircraft is directly distributed throughout the system. It is sent via the FMS to the PFD as a visual display, to the Flight Guidance system in order to make the appropriate adjustments to meet flight plan targets, to the OIS to make available comparison calculations from current airspeed, to the FADEC for throttle adjustments, and to the Flight Guidance system as feedback on commanded vs. actual speeds (note that, due to the unavailability of the Airplane Flight Manuals (AFMs) and Flightcrew Operating Manuals (FCOMs), this is not an all-inclusive list). The data pilots enter through the MFD serve as the reference points against which those systems adjust.

One of the largest changes in information management between the A320 and the A350 is the introduction of the Onboard Information System (OIS), which integrates aircraft-sensed data, pilot-entered data through the MFDs, as well as externally accessed weather data (and other capabilities). These integrated data allow pilots to perform real-time calculations and test options for modifying flight routes. The data flow is always one-way, from the aircraft to the OIS; none of the scenarios tested on the OIS will ever lead to a change to the aircraft's configuration, flight route, or flight director mode. Those changes need to be entered by the pilot.

Similarly, there is almost always a "wall" between sensed data or pilot-entered data and any automatic aircraft action. The following is a list of examples of "pseudo" automatic aircraft action:

- Flight director modes can engage from an "armed" state but must first be selected by the pilot.
- The aircraft can automatically land itself, but the appropriate flight director modes must first be selected by the pilot.
- Changing the barometric altimeter setting when a barometrically referenced vertical flight director mode is active will cause the aircraft to climb or descend.
- FMS will automatically advance navigation radios as well as select landing instrument frequencies when approaching the terminal environment. These will change the displays on the ND, the Radio Management Panel and the PFD. However, this only occurs when the pilot has previously entered all the necessary flight plan data into the MFD for managed flight guidance. Manual inputs will also always override automatic changes.
- The flight guidance system uses auto-pilot, auto-thrust, and the flight director in tandem with FADEC logic and FMS info to keep the aircraft within a normal operating flight envelope and on the desired flightpath. But these functions remain overridable by manual input.
- Possibly the truest example of automatic action without pilot input is the previously referenced "resolution advisories" based on TCAS threat sensing.

3.2.4 Manual and Automatic Display Reconfigurations

3.2.4.1 Normal Operations

During normal operations (i.e., standardized procedures and guidelines established for routine flight operations), display reconfigurations can be triggered by pilot input. The A320's ND and PFD on the left and right side can be swapped via a pushbutton on the outboard portion of the panel (but cannot be swapped across sides from the left to right side or vice versa). The ECAM system display on the lower center screen can also be exported manually to the ND on the left or right side via a transfer knob on the central pedestal. However, this is not typically done in normal operations because it is a display replacement, not a display swap, meaning the ND screen information on the chosen side of the instrument panel will be lost. Figure 48 below animates the PFD and ND screen swap.

Figure 48: A320 PFD / ND Normal Operations, Manual Reconfiguration (animated)

Display reconfigurations on the A350 in normal operations allow swapping the OIS display from either the left or right side with the MFD displays on the lowest center instrument panel screen. If this swap occurs on the left side, the pilot in the right seat then gets the option to cycle through the displays on their OIS in order to view MFD data without needing to look across the instrument panel at the left side screen. This process is shown via the animation in figure 49.

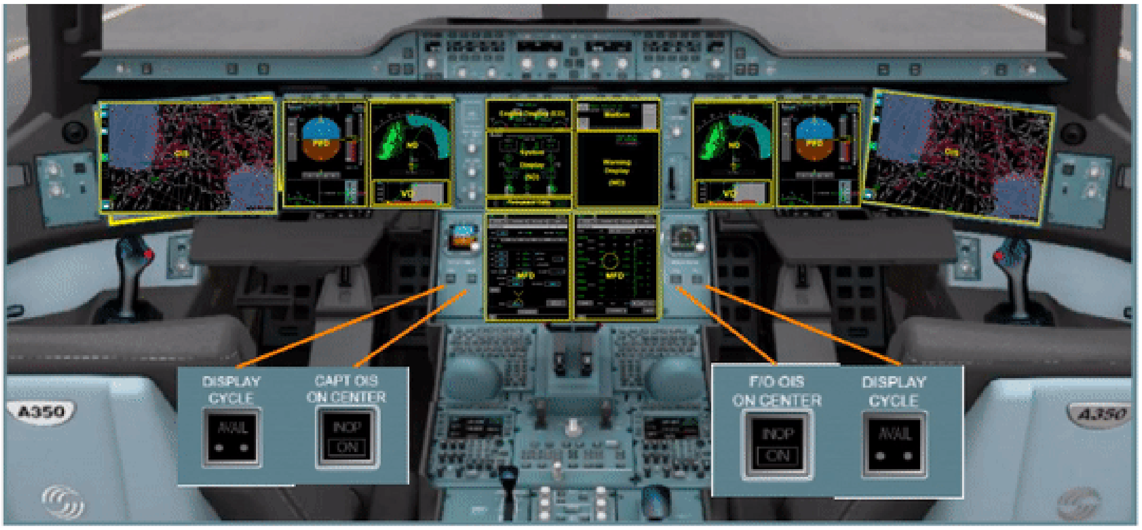


Figure 49: A350 Normal Operations, Manual Reconfiguration (animated)

3.2.3.2 Off-Nominal Operations

During off-nominal operations, both manual and automatic display reconfigurations can occur. The A320 display management gives priority to the PFD and upper ECAM display screens. If the PFD fails, its display will automatically relocate to the ND screen. Figure 50 animates this automatic action.

Figure 50: A320 Automatic Reconfiguration with PFD Failure (animated)

Similarly, if the upper ECAM DU fails, its information will automatically display on the lower ECAM DU. At this point, two options are given to the pilots for manual reconfigurations. One is to export the displaced lower ECAM system data to either pilot's ND by rotating a knob on the

ECAM "switching panel." Figure 51 animates this action. The other option to view the lower ECAM DU information is to depress and hold the push-button of the desired system on the ECAM control panel. This will display that system's information instead of the Engine/Warning data while the push-button is depressed. If the lower ECAM DU fails, the pilots have the same two options for viewing the lost information.

Figure 51: A320 Automatic Reconfiguration following Engine/Warning ECAM Failure, plus Manual Reconfiguration (animated)

If both of the center ECAM screens are lost, the pilot's only option is to display the Engine/Warning data on either pilot's ND and hold down the ECAM system pushbuttons to temporarily view system data. Figure 52 shows an animation of this process.

Figure 52: A320 Dual ECAM Failure with Reconfiguration (animated)

The A350 has more flexibility with respect to display reconfigurations due to the combination of the PFD/ND display onto one "split-screen" and the availability of two laptops to display OIS information. The display logic gives precedence to the engine display, PFD/ND, MFD, and OIS in that order. If a PFD/ND screen malfunctions, its information will automatically display on the OIS screen. The affected pilot may then manually send their OIS data to the lower center MFD and cycle pages between the OIS and MFD data. This process is shown in Figure 53.

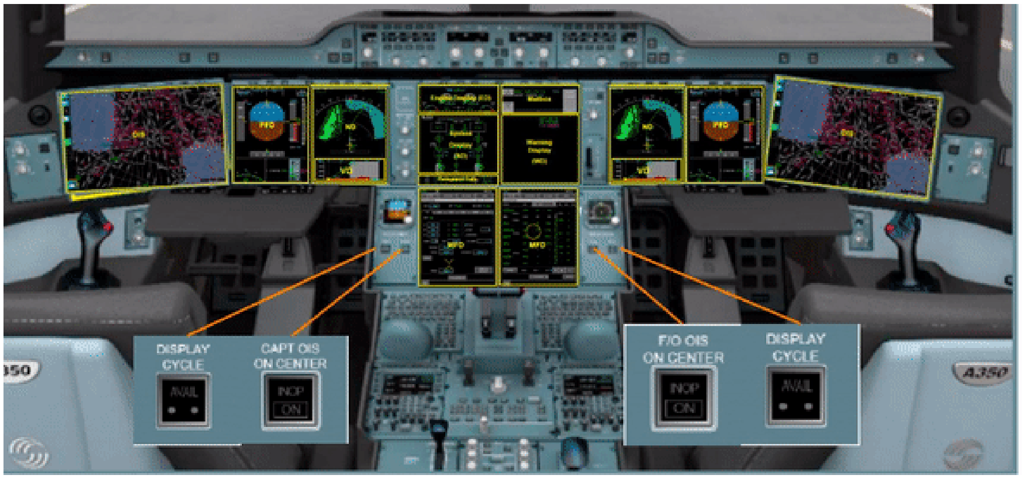


Figure 53: A350 PFD Failure with Automatic and Manual Reconfiguration (animated)

Similarly, if the upper center DU becomes inoperative, its information will automatically be displayed on the lower center MFD. That DU's information will then be available on the OIS screen via the display cycle option described above in "Normal Operations." An example of this display flexibility is shown in the animation of figure 54.

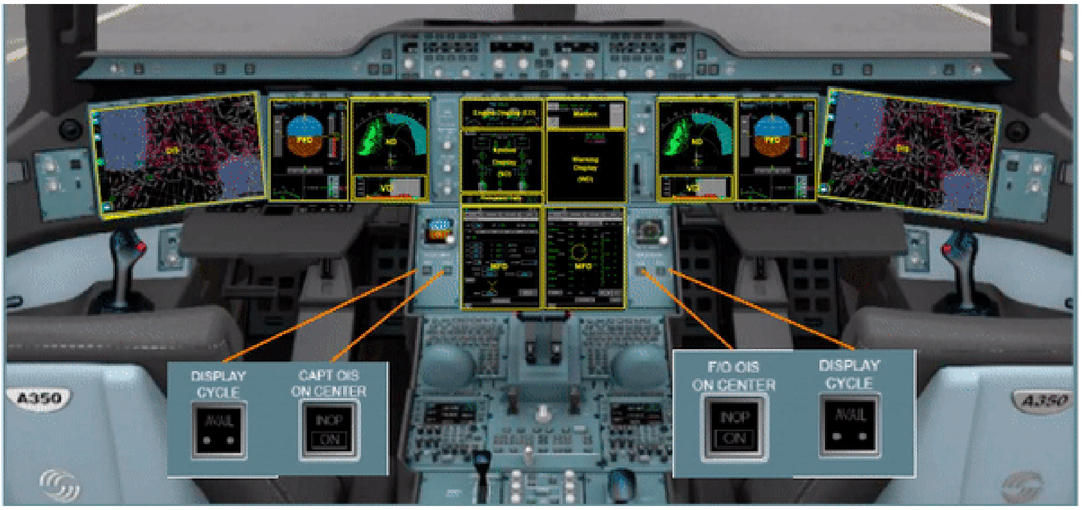


Figure 54: A350 Upper Center MFD Failure with Automatic Reconfiguration (animated)

For any single screen failure, the lost or displaced information can be recovered through screen swapping and using the OIS display as a spare screen. This is possible because when the OIS information is lost or displaced, its information can still be accessed from the two additional laptops available to the pilots or via a push-button switch that cycles between displays on either the OIS or lower center MFD. This is not true for the A320 as its screens do not have the same degree of display flexibility. On the A320, any PFD or ND screen failure will allow some navigation information to be viewed only on one side of the flight deck. In contrast, on the A350, at least two screens would need to fail before that limitation is encountered. Based on the information currently available to us, it is unclear what would happen if both the upper and lower center display units were to fail simultaneously on the A350.

4. INTERVIEWS WITH AVIATION STAKEHOLDERS

In October and November 2022, the PI conducted four one-hour zoom interviews with individual aviation stakeholders to explore their experiences with, and perceived changes to information management demands on advanced automated flight decks. The University of Michigan Institutional Review Board (IRB) reviewed a protocol describing the plan and purpose for these interviews and determined that they were exempt from ongoing IRB review (protocol HUM00220796; July 27, 2022).

The participants in the interviews were all senior airline pilots who, at the time of the interview, held some managerial position in their company. The following table shows the most recent aircraft flown by each participant and their managerial role:

Table 1. Participants in Online Interviews

Past and Current Aircraft Flown	**Managerial Role**
B757/767 – A350 – A320	Chief Pilot, Flight Operations Safety
A319/320	Line Check Airman
B737	Director, Fleet Technology and Flight Operations Engineering
A320 - B787	Senior Fleet Manager A320

A set of questions were shared with participants in advance of the interview to guide the discussion:

(1) In your experience, what are the main challenges associated with the increasing amount of information displayed on modern flight decks?
(2) How do you/pilots cope with the information management demands on modern flight decks?
(3) What are, in your opinion, the benefits and disadvantages of the increased flexibility in the presentation of information (i.e. the ability to move information between screens; the ability to present information in different forms)?
(4) Are there design features of modern flight deck displays that help or hinder pilots' management and monitoring of information?

(5) Has your role as a pilot changed significantly as a result of the increase in information?
(6) Who/what drives the increase of information presentation on modern flight decks?

In aggregate, the main insights gained from the 4 interviews are:

- When flying advanced automated aircraft, information management starts well before pilots arrive at the airport, largely due to their ability to use portable devices for accessing and reviewing information.
- Once on the flight deck, information management primarily involves verifying automatically uploaded information (as opposed to entering it manually).
- Certain types of information (e.g. weather) can be obtained from multiple, potentially disagreeing sources, requiring coordination between crew members.
- The presentation of information on advanced flight decks has become more flexible with the introduction of multifunction electronic displays. Display elements and entire displays can be (de)selected and/or moved around the flight deck, manually and automatically.
- To help pilots manage this increased flexibility, airlines have developed work-flow and position-based procedures for the various phases of flight.
- Participants highlighted a number of changes that are beneficial for information management (e.g., electronic checklists, VSD).
- Participants also voiced concerns about certain aspects of information management (e.g., EFB training and location, lack of 'best practices').

The following sections expand on each of the above points and provide more detail and supplemental information based on discussions with the airline pilot who collaborated with us on this project.

- Participants highlighted that, with advanced automated aircraft, **information management starts well before pilots arrive at the airport** and enter the flight deck. While airlines differ with respect to the specific procedures and application software they employ for preflight, the following describes a sample scenario for a B787 trans-oceanic flight:
    - Preflight planning begins at the hotel before the van arrives to pick up the crew. The dispatcher completes and loads the flight plan hours before departure time. Once the pilot has downloaded the flight plan to a portable device, they will look at the weight of the aircraft to identify potential performance issues. For example, they will consider whether they have to fly low out of their departure airport because of heavy weight, whether the weight puts them into the tops of weather or thunderstorms or

    turbulence, and whether they have to wait at the gate to get the final weight numbers from dispatch because they cannot taxi over a maximum taxi weight.
    - Next, the pilot will review the departure and flight time, weather at the departure and arrival airports, and the alternate and ETOPS alternate (e.g., distance to alternate).
    - After reviewing the flight plan, they then open their weather app and enter the flight number which pulls up a plan view of the dispatcher-planned routing for the flight. By selecting specific tabs on the weather app they can see if they will encounter areas of turbulence or thunderstorms, whether they will be flying a random northern track over Greenland or whether they will be flying over NAT tracks (Northern Atlantic track system). In the latter case, they have to review the track message attached to the flight plan.
    - Reviewing the weather briefing from the app helps pilots make decisions on possible new altitudes or routings they could discuss with the dispatcher. In the weather app they also look at the vertical turbulence profile from departure to destination so they can brief the flight attendants on when they can expect to be seated for possible turbulence ahead.
    - On the way to the airport, the pilot may use their cell phone to call the dispatcher for a mandatory briefing, or they can call the dispatcher on the SATCOM in the aircraft at the gate.
    - Following the weather review, the pilot returns to the airline's mobile app to accept and sign off the flight plan. They then convert it into a PDF which has the pilot's signature on it.
    - After signing off the flight plan, the pilot opens a navigation app, enters the flight number and downloads the flight plan. This app contains the entire routing from departure to destination. They then enter critical ETOPS points as lat/long positions along the route of flight. These are added as decision points along the route in case of depressurization and are turn-around points to head back to an alternate. The dispatchers ensure there is enough fuel to land at ETOPS alternates. Flight planning is now complete.
    - Flight planning on the B737-500 had to be completed at the airport, in operations, and without the aid of apps, after printing out a hard copy of the flight plan which included weather information.

- Once on the flight deck, during preflight, **automatic uploads (instead of manual entries) of information occur**. This requires pilots to locate and verify this information. Some participants mentioned that, early on, this task can be very challenging.
- New information management demands are not simply the result of more data/information shown on more screens on the flight deck. Instead, **there are more input streams to/sources for the same type of information.** For example, turbulence

information can be found in 4 different places (e.g., CPDLC, SatCom). Also, data from different sources are presented differently and support different decisions.

- There is **more flexibility on advanced flight decks in terms of where information can be presented, and where information can be moved manually or automatically** in response to display failures or to support crew coordination. This increased flexibility can create challenges because on earlier generation aircraft pilots knew where things would reside at all times. This allowed them to monitor and search for information in a top-down expectation-driven fashion. Now information search can be more challenging and time consuming.
- Many airlines have reduced this flexibility through **fleet-approved work-flow and position-based procedures and standards for screen use** to help with CRM and with faster preflight. For example, on some aircraft, during preflight the SMS is supposed to be shown on the center screen in front of both pilots; once they taxi, the SMS is replaced by charts and moves to outboard display units. Task management on some aircraft means that during preflight, the F/O sets up the aircraft (e.g., pressurization, FMS input) while the Captain focuses on the broader picture (e.g., weather, fuel, airport conditions). Once these tasks are completed, then both pilots come back together. These procedures have helped reduce the time needed for preflight. One participant reported that early on, especially for long flights, it took one hour to preflight the airplane because of the need to verify all the information. For short-haul operations, preflight can now be completed in 10-15 minutes.
- Still, one pilot reported that **one of the hardest things to get used to on the B787 are the multifunctional displays**. The pilot said that "I always have to look at my DSP to see which [MFD] is lit up green (left or right) and decide "do I want my screen there?" Or should I display my screen on the inboard right side, "wait, EICAS is on my side so I have to move the EICAS over to the FO side so I can use my inboard screen".

Participants highlighted the following changes as **beneficial for information management**:

- Some **critical information has been moved to/integrated with the Primary Flight Display** (PFD). For example, flap settings and landing gear position are now shown on the PFD.
- The **introduction of electronic checklists was highlighted as a major improvement**. In case of a fault, the correct checklist is displayed automatically; in other cases, links to the appropriate checklist are provided. This means flight crews do not need to remember the correct checklist and are less likely to complete an inappropriate one. At the same time, some participants mention that this feature increases the risk of rushing through checklists.

- The **VSD is considered very beneficial for flightpath awareness and management** as it depicts for pilots their intended vertical path and where the aircraft is relative to that path. Pilots no longer need to compute this information in their head.
- Lower workload and faster responses in case of emergencies were reported because some advanced aircraft **allow pilots to enter 4 alternate flight plans while still at the gate**. For example, if they experience an engine fire in flight and have to divert or return, all the necessary information has already been entered into the system.
- **Important information**, such as checklists and DataLink/ATC clearances, **can be displayed on the forward display units** which supports **shared reference for crew members.**
- Pilots receive **more and better information to plan ahead**. For example, real-time weather data (beyond weather radar which is limited to approximately 20 minutes out) and system-initiated alerts to weather changes, such as expected turbulence, support longer-term flightpath planning and can improve safety because pilots can divert and/or ask passengers to take a seat well in advance of turbulence. Also, real-time taxi data improve efficiency (e.g., if a long taxi time is expected, pilots may delay starting the second engine).
- **Stand-alone portable Electronic Flight Bags (EFBs) give airlines a lot of flexibility** as they can work with third-party developers to create and add their own apps. However, some participants felt that the EFB teams that help develop/introduce apps do not necessarily have the required human factors expertise.
- Participants expressed appreciation for **head-up displays (HUDs)** on advanced aircraft as they **allow them to look up and outside during critical phases of flight**. However, they also mentioned **concerns**.
  - First, a HUD **takes time to get used to**.
  - HUDs are **monochromatic** (as opposed to the color-coded PFD) which can make them harder to read and, in some cases, has led to over-rotation on takeoff.
  - Pilots can declutter HUDs to improve their ability to view the outside scene but when put **in de-clutter mode, information presentation on the HUD changes** (e.g., some flight parameters are no longer shown on tape instruments but rather digital readouts are provided).
  - Finally, some pilots mentioned that the use of a **HUD can be problematic because of its implications for 3D attention**. Pilot's visual attention may focus on the HUD display at the expense of monitoring at a greater distance.

Participants voiced **concerns** about the following changes to information presentation and management:

- **Airlines cannot tailor and/or remove information** they might consider unnecessary or undesirable because of the high level of integration on advanced flight decks.

- **Training for the EFB is not sufficient,** both in initial and recurrent training. EFB training focuses on emergencies but not enough on the routine use of the EFB.
- The **location of installed side-mounted EFBs interferes with CRM**. Participants explained that the EFB location forces pilots to look away from each other and "talk to the window".
- CRM **issues can emerge also when Captain and First Officer have different preferred sources of information**. For example, discrepancies such as different refresh rates for the EFB versus other sources of information can lead to pilots not having the same information.
- The **development of flight deck technology is driven too much by engineers,** with too little input from pilots and airlines.
- **Work-flow based procedures**, such as the use of an electronic flight folder which walks pilots through every step from pre- to post-flight, **reduce pilots' flexibility** and ability to work according to their own preferences.
- Currently, **each airline develops their own approach to information management**. Studies are needed to determine 'best practices' that can be implemented across fleets and airlines.

5. POTENTIAL IMPLICATIONS OF OBSERVED DIFFERENCES BETWEEN FLIGHT DECKS FOR INFORMATION PROCESSING/MANAGEMENT

The previous sections described the changes in information presentation and processing on the flight decks of the Boeing B737-500 versus the Boeing B787, and the Airbus A320 versus the Airbus A350. In this final section of the report, we will discuss possible effects – both positive and negative - of the observed differences between these flight decks on information management. It is important to note that very little systematic empirical data is available on how changes in the information landscape affect how pilots process and manage information. This section is therefore necessarily based on anecdotal evidence, comments by aviation stakeholders during focus groups held as part of this effort, the state-of-the-art in human factors/human perception/human cognition, and display design principles and guidance. The primary goal of this section is to highlight areas that need to be considered in the evaluation of proposed flight deck interfaces, pilot training and procedures.

Our comparisons of the two aircraft pairs confirm the often-made claim that the amount of (primarily visual) information available to pilots has increased on advanced aircraft (see, for example, Table 1 and Figure 82). This was made possible by the introduction of a larger number and size of screens, multifunctional displays, increased overlay options (for example, weather, terrain and traffic overlays added to the A350 ND), installed EFBs and portable devices/tablets, and increased interconnectivity and data links between the aircraft and ground-based systems and services. The trend towards more information has raised concerns among regulators and human factors researchers about potential problems such as data overload and clutter, the failure of pilots to notice unexpected changes or events due to masking, their ability to locate rarely used pieces of information, an increase in the number of information management tasks, and prohibitive information access cost and time, especially during high-workload and/or non-normal events.

One of the main concerns with the documented increase in the amount of information on the modern flight deck is the creation of data overload and **clutter**. This concern is partly based on the traditional, rather simplistic definition of clutter, namely ‘the presentation of large or excessive amounts of information’ or ‘the presence of a large number of objects within a display’ (e.g., Clay, 1993; Horrey & Wickens, 2004; Kroft & Wickens, 2002; Mack & Oliva, 2004; Tufte, 1983; Tullis, 1983; Ververs & Wickens, 1998). More recent definitions of clutter emphasize both quantitative aspects, such as display density, and qualitative aspects, such as display layout, target-background, and task relevance (e.g., Bravo & Farid, 2008; Doyon-Poulin et al., 2012; Rosenholtz, Li, Mansfield, & Jin, 2005; Tufte, 1991; van den Berg et al., 2009). For example, Moacdieh and Sarter (2015) have defined clutter as “the presence of performance and attentional costs that result from the interaction between high data density, poor display organization, and an abundance of irrelevant information.” In the context of aviation, Kaber et al. (2008) describe clutter along four dimensions: global density, feature similarity, feature clarity, and dynamic nature. These definitions highlight that the increase in the number or density of objects/information that was observed in our comparison is, by itself, not necessarily a problem.

Other factors - such as the proper organization and discriminability of these items, as well as task relevance - may mitigate the performance effects of clutter (Doyon-Poulin et al., 2012).

These performance effects include a substantial increase in pilots' workload as clutter can affect their ability to locate information on displays (Kaber et al., 2008; Dill & Young, 2015). More generally, cluttered displays are known to degrade monitoring and signal/change detection (Schons & Wickens, 1993), delay visual search (Henderson, Chanceaux, & Smith, 2009; Neider & Zelinsky, 2011), increase memory load (Westerbeek & Maes, 2011), instill confidence in wrong judgments (Baldassi, Megna, & Burr, 2006), lead to confusion (Ewing, Woodruff, & Vickers, 2006), and negatively affect situation awareness (Kim & Kaber, 2009) and object recognition (Bravo & Farid, 2006). High degrees of clutter can lead to masking[1] and thus the failure to notice unexpected changed and events. Different aspects of clutter affect information search in different ways. For example, display density can lead to increased search time (e.g., Neider and Zelinsky, 2011) and decreased accuracy. Display layout, on the other hand, including the logical arrangement of display elements, affects users' visual scan path which becomes more random and inefficient with illogical arrangements (e.g., Goldberg and Kotval, 1999).

One challenge for the evaluation of displays remains the measurement of clutter. Simply enumerating the number of visual objects or elements on a display is inadequate. As pointed out earlier, adding display elements that are task relevant and doing so in a well-organized fashion can be beneficial for performance. This is acknowledged in AC 25-11B, 5.7.4.1 which states that: "*....graphic elements should be included only if they add useful information content, reduce flightcrew access or interpretation time, or decrease the probability of interpretation error."*

Yeh et al. (2016) propose a normalized measure of clutter called 'display density'. Display density "is calculated as the total number of characters presented on a display divided by the maximum number of characters that could fit on the display". Clutter in the form of high display density is created, for example, when a compacted display format is encountered (Yeh et al., 2016). A compacted display format is defined as a "reversionary display mode[2] where selected display components of a multi-display configuration are combined in a single display format to provide higher priority information following a display failure" [AC 25-11B, 6.5.1.1].

Other clutter metrics that have been proposed in a variety of application domains (for an overview and more detail see Semizer and Michel, 2019) include:

- edge density (the number of edges in a display), a simple measure which is quite successful at predicting visual search performance
- feature congestion (the local variability in features such as color, orientation, and luminance contrast within an image), the most commonly used clutter metric

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[1] Visual masking refers to the situation where the visibility of a target stimulus is decreased by presenting it in close spatial and temporal proximity to another stimulus, the so-called 'mask'

[2] A reversionary display mode is defined as a secondary means to provide information initially presented on the PFD or MFD by the transfer of information to an alternate display (AC 23.1311-1C, 6.2.nn)

- subband entropy (the number of bits necessary for encoding an image; a high degree of redundancy in an image, and therefore fewer bits required, is considered a sign of low clutter)
- segmentation based clutter (this metric uses a segmentation algorithm which counts the number of regions in an image.

Recommendations for how to avoid clutter and its performance effects have been provided in a number of FAA advisory circulars (AC 23.1311-1C, 17.3; AC 25.1302-1, 5-5.b(3)(e)[3] and c(2)(a), AC 25-11B, F.5.3, AC 27-1B, and AC 29-2C[4]), as summarized by Yeh et al. (2016):

- *The density of information on the display should be compatible with the pilot's ability to recognize essential information and to minimize misinterpretation. Symbols and markings that are displayed during specific phases of flight may be removed at other times to reduce clutter. Establish an information prioritization scheme to ensure the clear presentation of essential information. [AC 23.1311-1C, 17.3]*
- *If overlays are provided, the display format should allow the pilot to overlay weather or other graphics relevant to the flightpath on one display without ambiguity. Each new graphic should be evaluated both individually and with allowed combinations of other weather, terrain, and navigation symbology to guard against confusing the pilot or cluttering the screen. [AC 23.1311-1C, 17.12.a]*
- *The number of overlays should not cause the information displayed to become unusable through cluttering or obscuration. [AC 23.1311-1C, 17.12.c]*
- *To meet the requirements in § 25.1302(b) applicants should show that layering information on a display does not add to confusion and clutter as a result of the color standards and symbols used. Avoid designs requiring flight crew members to manually reduce the clutter of such displays. [AC 25.1302-1, 5-5.b(3)(e)]*
- *Several different types of information may be overlaid onto a display, and the display can become cluttered very easily. In particular, features of the display could be hidden by the overlays and interfere with task performance. Decluttering has the advantage of temporarily removing unnecessary information from view. However, when information is not visible, the pilot may not remember it is available and fail to consider it.*
- *If anticipating clutter, there should be a means provided for manual de-cluttering. Automatic de-cluttering, such as during specific phases of flight, or during certain alerts, may*

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[3] AC 25.1302-1, 5-5.b(3)(e) is relevant and important in this context as it highlights that "To meet the requirements in § 25.1302(b) applicants should show that layering information on a display does not add to confusion and clutter as a result of the color standards and symbols used. Avoid designs requiring flightcrew members to manually reduce the clutter of such displays."

[4] Part 23 relates to Normal Category airplanes and Part 25 relates to Transport Category airplanes; Part 27 relates to Normal Category Rotorcraft and Part 29 relates to Transport Category Rotorcraft.

also be appropriate. [AC 27-1B, Chapter 3 AC 27 MG 19d(4)(i)(C); AC 29-2C, Chapter 3 AC 29 MG 19d(4)(i)(C)]

The above recommendations reflect the more recent and more nuanced view of potential costs and benefits of adding information to the flight deck. They acknowledge that additional information may be beneficial and desired by pilots but that integrating and prioritizing the information for flight crews is critical. The ACs also highlight that manual and automatic declutter options need to be provided. Anecdotal evidence from flight deck and training observations suggests, however, that relying on pilots to manually reduce clutter, as suggested in AC 25.1302-1, 5-5.b(3)(e)*,* can be problematic. For example, pilots sometimes encounter clutter when many or all items from the drop-down menu on the navigation display are selected/added over time (see Figure 55), or when the scale of a depiction is not being adjusted as necessary (see Figure 56). Especially during high-tempo operations, the flight crew may not realize the need, or have time for adjusting the display. It is important to note that this particular problem exists on both earlier and more advanced flight decks.

Figure 55. B787 Navigation Display (with all drop-down menu items selected) (source: personal photo)

Figure 56. B787 Navigation Display (with inappropriate 80NM range selected) (source: personal photo)

Automatic decluttering of a display presents its own challenges. For example, Schvaneveldt et al. (2000) have explored changing display symbology and minimizing or even removing low priority information when high display density is detected. One concern with the latter approach is that potentially relevant information may be missing when non-normal circumstances arise. Another potential issue with decluttering is illustrated by the declutter mode of the B787 HUD which removes the airspeed and altitude tapes and substitutes the information with digital values. As noted in AC 23.1311-1C, 17.5, this can be problematic since "digital read-out presentation of airspeed and altitude should convey to the pilot a quick-glance sense of rate and trend information. For airspeed and altitude, digital read-out alphanumeric displays may not be adequate on the primary display or on the standby instruments….". Finally, eliminating redundancy[5] can be an effective way of decluttering, but Schvaneveldt et al. (2000) found that the redundant presentation of information can help pilots maintain confidence in its accuracy.

While data overload and the creation of clutter are often mentioned as leading concerns with modern flight deck design, other equally important trends emerged as part of our aircraft comparisons and discussions with stakeholders. First, an increased **flexibility** of information presentation was noted. With the move from separate round-dial electromechanical gauges to integrated electronic displays[6], options for manual and automatic reconfiguration of information have increased significantly. On the one hand, this can be considered a benefit as it allows pilots to tailor displays and display configurations to their personal needs and preferences, across different phases of flight. Automatic reconfigurations also ensure the availability of critical information in case of a display failure. At the same time, automatic reconfigurations (as well as uploads to flight deck interfaces) involve the risk of change blindness which refers to the "inability to notice [scene] changes that occur during … transients [such as a display reconfiguration] (Triesch et a;. 2002). And the ability to add/remove data to/from a display, change the scale of presented information, or move information between screens, represents a potential concern as it can create confusion and adds a new interface management task to an already large task set. Pilots may not always realize the need or have time for display adjustments. And when duplicating information on two or more displays, pilots need to maintain awareness of whether these multiple instances are synchronized or independent of each other to avoid making unintended changes to the other pilot's display (see page 62). Airlines have introduced standard procedures and display setups to try and reduce information management demands. Increased flexibility of information presentation also involves the risk of interfering with top-down attention allocation.

Top-down attention allocation refers to monitoring that is driven by expectations and experience (as opposed to bottom-up monitoring where the environment determines a person's

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[5] Redundancy here refers to presenting the same information multiple times, in different form and/or in a different location.

[6] For example, the progression from the traditional 'six-pack' to the B737-500 EADI to the PFD on advanced aircraft; also see the consolidation of the A320's separate standby attitude indicator, standby airspeed indicator and standby altimeter into a single Integrated Standby Instrument System (ISIS)

attention focus, often in an involuntary fashion). This form of attention allocation can mitigate negative effects of an increase in the amount of information on advanced flight decks as it enables pilots to select information based on changing needs (e.g., across flight phases) and expectations (based on scan training and operational experience) while ignoring irrelevant data. Training can be one means of supporting the development of top-down monitoring strategies in the form of effective, standard scanning techniques. However, earlier work (e.g., Sarter, 2024) has shown that visual scanning is currently not a standard element of most pilot training programs, and there is no standard approach or procedure even within one airline due to the diversity of aircraft flown. Presenting information in the same way and in the same location at all times also supports the formation of expectations and thus aids in the fast and reliable location of information. Once information moves around or is hidden, especially when this happens automatically, there is a risk of confusion and a more effortful time-consuming and deliberate visual search may become necessary. This concern was highlighted by pilots participating in the focus groups we conducted as part of this project. They reported that finding information was easier on older aircraft where displays and display elements were presented in a fixed location. One way in which some airlines have addressed the issue is by developing workflow- and position-based standards for the placement of information during various phases of flight, thus in effect reducing the flexibility afforded by modern design. This approach reduces the time and effort required for setting up the flight deck but it was criticized by some pilots in our focus groups because it takes away degrees of freedom.

As mentioned earlier, display reconfigurations can lead to an increase in **information access costs**, i.e., the time and/or effort required to retrieve information. The same problem results when frequently accessed, related sources of information are not positioned in places where the cost of traveling between them – the scanning distance - is minimal. This represents a violation of the Proximity Compatibility Principle[7] (PCP; Wickens and Carswell, 1995). On the B787, information access costs have been reduced, in part, by combining, in digital form on 5 large MFDs, information that was traditionally presented in analog form on multiple distributed round-dial electromechanical gauges. For example, altitude and vertical speed information is now being presented on the PFD in the form of tape instruments in close proximity and to the right of the ADI. The range scale is shown on the ND itself, and the flap and thrust settings appear on the PFD, both leading to a reduction in scanning costs. Electronic checklists are another example of how information access costs have been reduced. In case of a fault, the correct checklist is displayed automatically or links to the appropriate checklist are provided. This means flight crews do not need to remember and locate the correct checklist and are less likely to complete an inappropriate one. While not directly related to flightpath management, electronic checklists thus free up attentional resources to support path and energy management. Another example of reduced information access cost is the use of a HUD on the B787 and the A350 (as well as some A320s).

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[7] The proximity compatibility principle asserts that when a task requires the integration of multiple sources of information, performance will be best supported when that information is displayed in close proximity.

A HUD reduces the need for pilots to alternate their visual focus between the outside view, including monitoring for traffic and looking at the runway, and critical aircraft instruments such as the PFD. A FAA report on Advanced Cockpit Displays describes various potential benefits of HUD (see Table 5):

Table 2. Potential Benefits of HUDs (from FAA, 2022)

Benefit Mechanism	Potential Ops Impact
Display of aircraft state information in pilot's primary FOV	Improved compliance with aircraft operating envelope, possibly leading to a reduction in safety events including loss of control, unstable approach, and over- rotation.
Display of contextual information including extended runway centerline, touchdown zone, and remaining runway	Improved safety by providing the flight crew with relevant contextual information of the runway environment.
Better situational awareness in the approach phase	Reduced flight technical error, which allows for HUD to be used in place of Autoland to use CAT II or CAT III approaches. HUD may provide access to airports during low visibility conditions, possibly manifesting in reduced cancellations, diversions, and delays.

Presenting important information in the pilot's primary FOV, either integrated on one display like the HUD or shown in close proximity on adjacent interfaces, is helpful during routine operations as it reduces scanning and information access costs. It may be even more beneficial when pilots experience a phenomenon called 'startle'. Startle has been defined as "the initial short-term, involuntary physiological and cognitive reaction(s) to an unexpected event that commence the normal human stress response" (IATA, 2018). A startle response has been shown to affect a person's information processing capability for up to 30 seconds and thereby affects situation awareness and decision-making. It can lead to attentional tunnelling which involves a reduction in the utilization of information presented in peripheral vision due to narrowing of the attentional field towards the threat (Easterbrook, 1959; Staal, 2004). Startle has received considerable attention in the aviation domain in recent years as it is assumed to have played a key role in a significant number of Loss-of-Control In-flight accidents.

One final example of reduced information access costs is the addition of a minimap below the PFD and of the VD/VSD to the ND. Not only does the VSD eliminate the need for pilots to integrate and visualize information related to their vertical flightpath in their mind. In other words, it replaces "knowledge in the head" with "knowledge in the world" (Norman, 2013). The placement of the VSD on the ND, below the top-down view of the flightpath, also reduces scanning cost as pilots can easily assess their current and future lateral and vertical position (see Figure 31), and both the ND and the VSD support **predictive aiding** as they help pilots anticipate future states and events which, in turn, requires combining relationships of parameters in dynamic systems – a task that humans tend to have difficulties with. Predictive aiding is supported also by new features such as the OFF PATH DES page on the CDU which indicates to pilots the aircraft's predicted descent performance with and without speedbrakes, real-time turbulence data that allows pilots to request alternate routes sooner and thus provide smooth rides for passengers, and real-time airport data that helps pilots anticipate delays and thus result in fuel savings as they can delay engine starts.

As discussed earlier, many displays on advanced automated aircraft contain more information than their counterparts on earlier generation flight decks. In addition, entirely new interfaces have been introduced, such as the EFB or OIS which contain, in digital format, all documentation and forms traditionally carried by pilots in printed form and host various software applications that allow flight crews to perform a variety of functions that were traditionally accomplished using paper products. In that sense, the introduction of the EFB or OIS does not necessarily represent a significant increase in the amount of information as much as a transition to a different medium. Chilse and Hiltunen (2014) examined safety reports involving EFBs and portable devices and highlight some potential concerns. For example, pilots reported that critical information was sometimes off-screen or difficult to read due to its small size. An unexpected shutdown of the device can make important information (temporarily or permanently) inaccessible to pilots. And the placement of the EFB can have a significant impact on **crew communication and coordination**. The EFB is located in a fixed position, below the Captain's and First Officer's tiller, near the respective pilot's knee. This makes entering large amounts of data (such as an entire route for a thirteen-hour flight with numerous latitude/longitude points) rather slow and cumbersome and requires the pilot to rotate their entire body toward the EFB (and away from the other pilot and instruments in front of them) to complete the task. As discussed by Segal (1993) as early as the 1990s, in the context of electronic checklists, "the constraining relationship between the design of an environment and the behavior of living systems within that environment must be considered." During one of the focus group meetings held as part of this effort, one pilot commented that side-mounted EFBs (see section 3.2.7) get in way of cockpit resource management (CRM) as pilots look away from each other and do not have shared reference necessarily: *"They talk to the window."* Crew coordination on advanced flight decks like the B787 is affected not only by new interfaces such as the EFB but also by new input devices (Yeh et al., 2016). For example, CCD inputs (see section 3.2.5) may go unnoticed by another crewmember because pilot inputs can be accomplished with small finger motions on the CCD [AC 20-175, 3-4.a].

Finally, pilots in our focus groups mentioned that another important aspect of information management on advanced flight decks is maintaining awareness of automatic **data propagation** between flight deck systems and between the flight deck and the ground, as well as **uploads of information** from various sources. For example, some airlines enable pilots to receive turbulence information using the SkyPath application on an iPad, air traffic control (ATC), reports made by other pilots, and weather radar. These sources of information differ with respect to range, reliability and update frequency which can create issues when two pilots do not rely on the same source of information and are therefore not "on the same page". Uploading information via the COMM function and ACARS (rather than manually entering the data) also has the potential to create breakdowns in pilot awareness. For example, pre-departure, once the FMC is initialized by the pilot, the flight route is received via datalink. Pilots load and accept the route, request winds, and select the SID and runway for takeoff. ATIS is obtained via ACARS. So are takeoff weights which are used to calculate takeoff speeds and power settings. Concerns about such automatic data entry are expressed in ACT ARC Recommendation 19-3: “automated flight plan uploads reduce flight crewmember engagement with the planned route of flight, and without diligent verification, risk of reduced navigational awareness is increased.” Other examples include that, accepting a CPDLC “load” clearance on departure drops any previously entered departure, requiring reentry, and adding to workload at an already workload-intensive portion of the flight. And aircraft performance computers may display the landing distance associated with a maximum tailwind component of 5 knots for poor braking action, even if the computed tailwind component exceeds that limit.

6. CONCLUSIONS

The amount of information that is presented on flight decks has increased steadily over decades. This trend has led to concerns among regulators and human factors researchers about excessive information management demands for airline pilots, especially during highly dynamic high-workload phases of flight. During those flight phases, pilots may struggle to divide their attention effectively between the many sources and locations where relevant information may reside. Also, their attention may be unduly focused on interacting with informational tools at the expense of monitoring basic flight instruments and the aircraft surroundings.

The goal of this project was to document and analyze likely effects of the changing information landscape on modern flight decks. To this end, we first compared the type and amount of information that is presented on two aircraft pairs – the Boeing B737-500 and the B787, and the Airbus A320 and the A350. Next, we conducted online interviews with aviation stakeholders to learn about their experiences and concerns with information management on advanced flight decks, and to discuss proposed and already implemented mitigation strategies. Based on the findings from these two research activities, we highlighted potential human factors implications of observed and reported differences between earlier generation and highly advanced flight decks.

Overall, the project confirms the claim that the amount of (primarily visual) information has increased on commercial flight decks. However, our report highlights that the nearly exclusive focus on information quantity in the aviation community fails to acknowledge that qualitative changes in information presentation are as important and can affect pilot tasks and performance to the same extent. For example, with the move from round-dial electromechanical gauges to integrated electronic displays, options for the manual and automatic reconfiguration of information have increased significantly. This allows for dynamic tailoring of information presentation to pilot preferences and flight phases. At the same time, it introduces an additional interface management task, and the resulting loss of spatial dedication of information can interfere with top-down attention allocation and require effortful information search instead.

Our report emphasizes that the trend toward more information on advanced flight decks creates not only challenges but also opportunities. The risk of data overload due to additional information seems to be moderated by the re-location and better integration of important information. For example, moving flaps and thrust lever settings to the Primary Flight Display decreases scanning and information access costs for pilots during takeoff and approach/landing. New tools and interfaces require additional pilot training and monitoring demands. Still, pilots benefit from the introduction of electronic checklists which reduce memory demands and the potential for error. The Vertical Situation Display (VSD) supports improved flight path awareness. And additional airport and weather information helps pilots with long-term flight path planning and improved efficiency.

The trends towards more information, more automation, and more complexity on modern flight decks will likely continue in coming years. These developments have the potential to reduce pilot workload, lower the opportunity for erroneous actions, accommodate expected changes to the national airspace system, and maintain or even improve the safety of flight operations. For these benefits to materialize, however, it will be critical to invest in more empirical research that assesses the actual, and predicts the likely performance effects of ongoing and proposed changes to information technologies.

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