THE INTEGRATED MODE MANAGEMENT INTERFACE

Edwin Hutchins
Department of Cognitive Science
University of California, San Diego

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1. Introduction

Mode management is the processes of understanding the character and consequences of autoflight modes, planning and selecting the engagement, disengagement and transitions between modes, and anticipating automatic mode transitions made by the autoflight system itself. The state of the art is represented by the latest designs produced by each of the major airframe manufacturers, the Boeing 747-400, the Boeing 777, the McDonnell Douglas MD-11, and the Airbus A320/A340 family of airplanes. In these airplanes autoflight modes are selected by manipulating switches on the control panel. The state of the autoflight system is displayed on the flight mode annunciators. The integrated mode management interface (IMMI) is a graphical interface to autoflight mode management systems for aircraft equipped with flight management computer systems (FMCS). The interface consists of a vertical mode manager and a lateral mode manager. Autoflight modes are depicted by icons on a graphical display. Mode selection is accomplished by touching (or mousing) the appropriate icon. The IMMI provides flight crews with an integrated interface to autoflight systems for aircraft equipped with flight management computer systems (FMCS).

The current version is modeled on the Boeing glass-cockpit airplanes (747-400, 757/767). It runs on the SGI Indigo workstation. A working prototype of this graphics-based crew interface to the autoflight mode management tasks of glass cockpit airplanes has been installed in the Advanced Concepts Flight Simulator of the CSSRF of NASA Ames Research Center.

This IMMI replaces the devices in FMCS equipped airplanes currently known as mode control panel (Boeing), flight guidance control panel (McDonnell Douglas), and flight control unit (Airbus). It also augments the functions of the flight mode annunciators. All glass cockpit airplanes are sufficiently similar that the IMMI could be tailored to the mode management system of any modern cockpit. The IMMI does not replace the functions of the FMCS control and display unit.

The purpose of the IMMI is to provide flight crews with a shared medium in which they can assess the state of the autoflight system, take control actions on it, reason about its behavior, and communicate with each other about its behavior. The design is intended to increase mode awareness and provide a better interface to autoflight mode management.

This report describes the IMMI, the methods that were used in designing and developing it, and the theory underlying the design and development processes.
2. Theoretical stance.

Every designed device instantiates a theory about the nature of the operator and the task(s) to be done with the device. The present generation of interfaces is based on a model of cognition in which the person takes in information, codes it symbolically, and operates on the internal symbolic representations. Such a model of cognition predicts that operators will be able to make use of external representations that are already symbolic codes. All current mode management interfaces represent autoflight modes as text strings. Many other instruments in the "glass-cockpit" do the same.

The need to provide operators with the right information at the right time, and to avoid overwhelming the operator with too much information is widely recognized. This need has led to many efforts to manage information displays in various clever ways. However, simply controlling what information is presented when is not enough. How information is represented is also important. In fact, it may be more important than efforts to reduce the "amount" of information presented.

The study of culturally-elaborated, naturally-occurring distributed cognitive systems leads us to consider how people accomplish cognitive work by establishing coordination with structure in the environment. This view puts more emphasis on the role of perception and action in cognition than on centralized symbolic processing (See Clark, in press). Recent work in embodied and situated cognition question the fundamental status of symbol processing as a model of internal cognitive processes. In the place of symbolic processing, we see processes in which internal structure is brought into coordination with environmental structure. The theory that is instantiated in the IMMI is the theory of distributed cognition. (Hutchins, 1995a).

A new understanding of the role of cognitive artifacts has emerged in the last decade. Rather than amplifiers of abilities, cognitive artifacts are seen as elements that participate in cognitive functional systems that transcend the boundaries of the individual. (Cole and Griffin, 1981; Hutchins, 1995a; Norman, 1993; Hutchins, in prep). In these functional systems, cognitive work is done via the propagation and transformation of representational state. Symbolic rules provide one way to transform representational state, but this is a relatively expensive sort of process for humans. To establish coordination between text representations of autoflight modes and conceptual representations of those modes takes considerable effort (Sherry and Polson, 1996).

The analysis of the use of speed bugs in a modern airline cockpit (Hutchins, 1995b) has lessons for the design of airspeed instruments and the IMMI as a whole. Traditional round-dial speed instruments give the pilot perceptually salient structure that corresponds to important conceptual states. This is lacking in the existing tapes (and in existing interfaces in general).
These material structures provide the operator with the perceptual raw materials for the construction of coherent conceptual understandings. Conceptually important conditions should be perceptually distinguishable from one another. This means more than simply using graphics instead of text.

Designing perceptual distinctions that mirror conceptual distinctions accomplishes several goals at once. First, it puts reasoning into the interaction with the external world where it can be accomplished by fast robust perceptual processes rather than by slow, vulnerable conceptual processes. It makes visualizing the consequences of mode engagements easy to do. Second, it supports reasoning as an activity undertaken jointly by crew members sharing the activity.

When we move the boundaries of the unit of analysis out to encompass functional systems that transcend the boundaries of the individual, we not only find processes at work that we might not have suspected, but we also find new places to locate designed activities. It suggests designing crew activities rather than designing just objects or artifacts.

A popular strategy in AI in general and in cockpit automation is to use automation to build intelligent agents or expert assistants to help human operators. This strategy recreates a number of already difficult problems with communication (and intent inferencing.) A different strategy is to use computing power to create worlds where operators get to be smart while using simple cognitive processes. An examination of existing highly culturally elaborated action environments shows how they work to make us smart. Section 3 below shows how we can use these ideas as design criteria.

In the next section, I will use this theory to interpret the significance of observed problems.

As a final note, it is important to focus on what goes right in current operations as well as on what goes wrong. The existing aviation system is very robust and error tolerant (Palmer, et.al, 1994). Many things really do go right in modern mode management. It is as important to understand these phenomena and to capitalize on the principles underlying them as it is to see why things go wrong.
3. Observed problems.

Mode management is a problem. The fact that flight crews are sometimes surprised by autoflight system behaviors is well documented in Wiener's (1989) study of the 757 flightdeck. When flight crews ask "What's it doing now?" and wonder how to make the plane do certain things, there is a problem. Problems with mode management are also easy to see in ASRS reports. Vakil, et.al. (1996) surveyed reports for the years 1990-1994 and found 184 reports in which crews reported automation surprises. Palmer, et al. (1994) in a study of altitude deviations reported to ASRS document several cases in which flight crew uncertainty about the behavior of glass cockpit automation led to altitude busts.

Symptoms of this problem show up in a variety of places in the aviation industry. For example, many Boeing customers who come to Boeing for training, ask that their crews not be taught the VNAV functions of the FMCS. These airlines instruct their crews to make all of their altitude changes in Flight Level Change (FLCH) mode. United Airlines does not teach VNAV operation in its training center1. In both cases, the reason given is that VNAV is too complex to teach. In both cases, it is expected that the competence required to use this aspect of the system will be acquired "on the line" as a consequence of learning (and teaching) in actual operations. Another major carrier (Southwest) has placed metal covers over the VNAV and LNAV mode select switches on their 737 mode control panels to prevent crews from using those modes.

Jean Pinet, president of Airbus Industrie subsidiary Aeroformation describing new A-320 training program called Aircrew Integrated Management (AIM), recently said,

"We took a prudent approach when we saw the proliferation of flight modes and configurations on the A320 and other modern aircraft....We did not want to teach all of the combinations; we kept a 'classic' approach where the training emphasis was on those configurations that seem the best adapted to each of the flight procedures." (Lenorvitz, 1992)

1 I believe that the manufacturers have a special responsibility to provide the very best training possible. The operators look to the manufacturer as the source of training concepts as well as hardware. An America West training captain complained that American West does not provide conceptual training in the use of the FMCS because none is available from Boeing.
The authors of the AIM program should probably be congratulated for their operations-centered approach to training. Still, the proliferation of modes is perceived as a problem, and the solution taken has often been to teach only a subset of the full system capabilities. Presumably this is because the entire system is thought to be too complex for the instructional designers to describe, too complex for the instructors to teach, too complex for the pilots to learn, or all of the above.

Autoflight logic is too complex to be easily understood, even, apparently, by the engineers who created it. The logic diagrams that describe the behavior of the system in all anticipated conditions typically span dozens of pages. Much of this complexity arises from rarely encountered conditions. Still, the actual behavior of the autoflight system in operational circumstances can be baffling (Wiener, 1989). In spite of this complexity, pilots should and do develop simplified models of what the autoflight system is doing.

The decisions to avoid teaching some parts of the autoflight system are symptoms of serious problems with the new generation of highly automated aircraft. Granted that vertical navigation involves the constant interaction of thrust, flight path and speed, there is no need for it to be this difficult. The engineers have created a system of great utility, but the interface to it is conceptually so difficult that operators have given up trying to train their crews to operate and trust instead to the pilots, as a community, to discover and transmit ways of using it in flight. The difficulties that pilots have with mode management are understandable given the nature of the current system. This goes for all major airframe manufacturers. The differences between Boeing and Douglas mode controls is insignificant. Airbus has a different philosophy, but it may actually be more challenging to the pilot than the American systems because even more is hidden from the pilot in the Airbus airplanes.

### 3.1. Autoflight modes

An autoflight mode is a means of linking a performance target (speed, or path) to a control axis (pitch, roll, thrust). It has been said that the flight management computer system (FMCS) has replaced the autopilot in the current generation of flightdecks (Robert Dorsett, sci.aviation). This is a

Just what it is that pilots are inventing to deal with automated flight modes that are not taught in schools is a very interesting topic that deserves systematic study.
misconception. The autopilot remains as an alternative to the human pilot as a way of manipulating the control surfaces of the airplane. What has changed is the way of specifying and computing the targets that autopilot may be asked to achieve. The FMCS provides new classes of abstractly specified targets for the Autopilot flight director system (AFDS) which can then be achieved either by the pilot acting on the controls to track flight director cues or by the autopilot servos acting on the controls.

The introduction of automation is not often driven primarily by cognitive considerations, but it inevitably has powerful effects on cognition. Automation on the flightdeck is changing both the cognitive tasks that are faced by individual crew members and changing the cognitive properties of the flightdeck itself as a cognitive system.

Although cockpit automation has touched all aspects of flightdeck operations, it has probably had more impact on flight path management than on any other aspect. Through the years there has been a continual process of upgrading and adding new devices and new functions in support of aircraft flight path control. The innovations have come in waves as technologies have matured and made new sorts of operations possible. Unfortunately, the consequence of this process has been the accumulation of a set of poorly integrated devices and functions for flight path management.

### 3.2. Flightdeck Automation

Consider a brief history of flightdeck automation beginning with the Boeing 727.

The 727 flightdeck\(^3\) is a "round-dial" or "steam-gauge" system. The instrumentation is based on electromechanical gauges. Flight path is controlled primarily through the flight controls: control column, rudder pedals, thrust levers, flap handle, trim switches, spoiler lever, landing gear handle, etc. There is a rudimentary autopilot which is capable of holding an already established altitude, maintaining a heading, tracking a VOR radial, and holding an attitude. There is an altitude alerting system, which provides warnings on approaching or deviating from a selected altitude, but it is not connected to the autopilot system and the airplane is not capable of capturing an altitude. Horizontal situation (heading and positional relation to a specified VOR radial or localizer course) are displayed on a Horizontal situation indicator. DME (distance measuring equipment) provides information about distance from station. Considerable cognitive processing is required to construct and maintain situation awareness in this sort of flightdeck. The representations that are provided by the instrumentation

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\(^3\) I use the 727 as a representative of a class of airplanes. The 737 models prior to the -300, and the older DC-9 models prior to the MD-80 are comparable.
must be coordinated with other representations in the form of air navigation charts.

The DC-10 represents another step in flightdeck automation. It is still a "round-dial" flightdeck, but it contains several new features. The autopilot is much more capable. It can not only hold an altitude or track a VOR radial, it can capture a specified altitude and capture a radial or a localizer. The autopilot is capable of controlling pitch to produce a specified target vertical speed. There is also an autothrottle system which is capable of controlling engine thrust in two modes: a thrust reference mode in which a particular thrust parameter (e.g., N1) is tracked, and a speed mode in which thrust is varied to track an airspeed target. The control of the autopilot and the autothrottle are brought together on an autopilot panel mounted in the glareshield. The airspeed, altitude, heading and vertical speed targets to be provided to the autoflight systems are entered on this panel. Modes of operation are armed for engagement or selected by button presses and switch throws on this panel. The selected, armed or engaged modes of flight control are annunciated on a Flight Mode Annunciator panel. Some of the longer-range models of the DC-10 were also equipped (retro-fitted?) with RNAV (inertial navigation) systems that are capable of flying off-airway tracks to distant navigation fixes specified by latitude and longitude.

The MD-80 added to this a "performance box" which can be used to fly more fuel efficient climbs, cruises and descents. This Performance Management System (PMS) is a precursor of the current VNAV functions of the FMS. The computations of the performance system can be coupled to the Flight Director and to the autopilot if desired. Inputs to the performance system are made with a small limited keyboard (digits 0-9 plus characters N, E, S, W, and /) and PMS data entry and computed data are displayed in a 4 line 24 character per line display. The MD-80 also has coupled autopilot approach and autolanding capability to Category III minimums.

The Boeing 767/757 marked another jump in flightdeck automation. In this airplane, the performance box expanded to become the Flight Management Computer system. This coupled a comprehensive navigation data base with autotuning of navigation radios and automatic position updating. A two-dimensional color lateral navigation display replaced the HSI. CRT displays driven by symbol generators provide great display

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4 Early versions of the Boeing 747 and the McDonnell Douglas DC-9 have comparable flightdeck designs.

5 The Boeing 737-300, and the McDonnel Douglas MD-88 have comparable flight deck designs

6 An HSI type display can still be presented by the symbol generators that drive the computer displays. There are operational reasons for preferring
plasticity. The inertial reference systems support navigation displays that show motion in either track up or heading up modes. They also permit computation and display of ground speed and true wind - items that were simply not possible to compute in earlier technologies.

The plasticity of navigation displays permits the superimposition of other kinds of information onto the depiction of the aircraft track. Nearby airports, navigation aids, and weather radar returns can all be superimposed on the depiction of lateral flight path. Information about the vertical aspect of flight path can be added in the form of data blocks attached to waypoint icons. LNAV provides facilities for flying complete complex lateral paths that consist of a succession of geographic waypoints. Off airway navigation, complete approach procedures, and autolandings are also supported. Complex vertical profiles can be specified and flown in VNAV modes. The 757/767 also introduced additional autothrottle modes. Altitude callouts were added as part of the newest GPWS systems.

All of these new facilities increased the capabilities of the aircraft autoflight systems, but also created new systems for the crew to monitor and supervise.

The present state of the art in flightdeck design is represented by the Airbus A-320, the McDonnell Douglas MD-11 and the Boeing 747-400. These airplanes have full EFIS. Full EFIS means that the airspeed, altitude and vertical speed instruments are also CRT presentations. This permits soft bugs for altitude and airspeed as well as for heading, decision height and minimum descent altitudes. As an acknowledgment of the importance and difficulty of keeping track of autoflight modes, the Flight Mode Annunciators (FMA) have been improved, and consolidated.

There is no doubt that these innovations have transformed the activities of flight crews, changed the cognitive requirements of flight, and changed the properties of the flight deck as a cognitive system. It is easy to focus on the shortcomings of the automation, but any evaluation of this technology must take full account of the increased functionality and ease of operation provided by these systems. In some cases the automation makes possible things that could simply not be done without it; autoland in zero/zero conditions being perhaps the most striking example. In other cases, crew workload is dramatically reduced; flying a DME arc approach procedure is an example.

Modern flight decks present many alternatives for linking elements of descriptions of the aircraft flight path to autoflight systems. One pilot boasted to me that there are six ways to climb or descend the 737-300. The Operations

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7 All except the standby instruments are now on glass. The Boeing 777 may have even the standby instruments on glass.
manual for the MD-88 lists four ways to climb, but on closer inspection one discovers that there are actually eleven different mode configurations involved in these climb methods.

These alternative methods provide the pilots with functional flexibility, but the space of possible linkages is large and complex. Mode changes occur at pilot command, but also automatically without pilot action under many conditions. Automatic control modes may revert to other modes as a consequence of pilot action, due to changing flight circumstances, and due to equipment or signal failure. It is not always apparent which mode combination will best accomplish the desired goals. Modes of operation carry with them other implications, so that what appears to be a good solution (and may be at the moment) could become an unsatisfactory solution as flight conditions change. For example, in the Boeing airplanes, the vertical speed mode provides no stall protection in climb. A rate of climb that is perfectly safe at low altitude may lead to a stall at high altitude.

Even if a pilot knows which mode to select, it is not always clear how to select the desired mode. Some modes will only arm under certain circumstances and may then only engage when other conditions are met. In most cases, the limiting conditions for mode arming and engagement are not represented anywhere in the flightdeck system (except in the mind of the pilots if they remember the criteria).

As serious as not being able to engage a desired mode is the inability to disengage an undesired mode. This is sometimes an even more subtle problem that mode engagement (Sarter & Woods, 1994) Some methods of engaging one mode may unintentionally lead to the disengagement of other modes (Palmer, et al, 1994).

Even though autoflight modes are annunciated, it is not clear at all times which modes are actually engaged or what the engaged modes imply about aircraft performance. These problems may be due to the following factors: 1) the annunciations are sometimes cryptic (see discussion of mode names below), 2) the annunciated modes combine with each other in complex ways; there are modes for thrust, armed captures, roll and pitch guidance, 3) Mode transitions can occur without pilot intervention and sometimes without apparent change in aircraft behavior, 4) the mode annunciations are not prominently displayed, 5) pilots often take the state of the MCP or FGCP as a mode indicator (which it is not), 6) some modes have very complex behaviors, what Vakil, et.al. (1996) call multi-input multi-output (MIMO) controllers.

The complexity of the autoflight systems requires the crew to reason in a complex space about not only the situation of the aircraft and its flight configuration, but also about the configuration of the automatic systems. This creates situations in which pilots are unsure what is being done by which "intelligent" agents. Pilots are very careful about making clear which pilot "has the airplane", and usually communicate efficiently about their
intentions. In interaction with sophisticated automation, however, it is sometimes not clear to the crew who (or what) has what part of the airplane and what the automated systems' intentions are. Glass cockpit crews occasionally ask aloud, "Why's it doing that?", "What's it doing, now?", "Is it supposed to do that?" (Wiener, 1989). When unexpected mode behavior occurs, there is little support in the modern cockpit for determining the cause or communicating about the state of the system.

Most (but, alas, not all) mode selections are made by taking action on the MCP. The language of execution is button presses and switch throws on the MCP. And on the MCP, there is feedback for the flight crew about the actions they have taken. Flow-bars in the switches on the MCP indicate that a selection has been made. For some, but not all, of the switches an illuminated light means that the mode can be disengaged by selecting the switch again. The proper evaluation of the consequences of mode selection actions taken on the MCP cannot be made on the MCP. Instead, evaluation takes place in a different language, the language of flight mode annunciation and in another place, on the FMA panel (Douglas) or on the PFD (Boeing).

3.2.1 Failure of integration: the flightdeck tower of babel

The introduction of several waves of automation over the years has made the modern flightdeck a tower of babel. Flight path information is expressed in at least ten different identifiable languages: 1. Spoken ATC, 2. Written IFR shorthand, 3. Primary flight control positions, 4. MCP selections, 5. FMA indications, 6. Primary flight display indications, 7. FMCS/CDU character strings, 8. Navigation Displays, 9. Published navigation charts and plates, and 10. The behavior of the aircraft itself. Some pilots have observed that this list is too short, since the FMS/CDU, the navigation displays, and navigation charts may each contain a number of languages themselves. In a typical approach to landing, the crew will interpret, manipulate, and translate expressions in and among all of these languages (except perhaps 2).

In some cases, the multi-voicedness of the flightdeck is useful. The costs of computing some result in a representation that is not well suited to the computation may be greater than the costs of translating the problem into another representation and solving the problem there. For example, weather avoidance planning can be done on the basis of printed descriptions of the locations of weather fronts, but it is so much easier to do the planning on a chart that it may be worth plotting the locations of the fronts on a chart before attempting to formulate a plan for avoiding the weather.

The descriptions of flight path that are supplied to the autoflight systems always ultimately decompose to heading, altitude, airspeed, and implicitly, time. The bottom region of Figure 1 shows the basic control loops of the modern aircraft. These are unlikely to change much in the foreseeable future. The upper region shows, from the bottom up, the layering of
increasingly complex specifications of flight path that have been introduced over the years. This corresponds to the discussion above of the history of flightdeck automation. The right hand column of the upper section of figure 1 lists the media in which the constraints to be satisfied are represented at each level.

Given the state of the art in technology, there is no need to have this many representations. What we see now is a consequence of a particular history of innovation. A considerable reduction in complexity is possible through an integration of these languages into a smaller number of ways to represent and evaluate flight path information. There is probably no need to eliminate specific functions nor should the ability to revert to simpler descriptions when they are needed be sacrificed in the interest of simplification. The issue concerns the representational media in which the descriptions are composed and in which the adequacy of the descriptions is evaluated.
IMMI

Waypt list Waypt Alts, winds Perf Spec

LNAV PATH VNAV PATH VNAV SPD

TOGA (ground track) TOGA (+2000 fpm, CMD +10)

APP

VOR & LOC GLIDE SLOPE

FLCH

VERT SPD

HDG SEL ALT CAP SPD SEL

HDG HOLD ALT HOLD

Heading Altitude Airspeed

Descriptions of Flight Path

Autopilot Flight Director

Pilot

Controls (Yoke, Rudders Throttles, Trim)

Autopilot Servos

Control Surfaces

FMCS/MCDU pages

FMCS computed

FMCS fixed function

Track nav signal

MCP Target Set

Hutchins
Figure 1. (Previous page) showing how descriptions of flight path are linked to the flight controls.

Descriptions of flight path can be linked to the flight controls either by way of the autopilot servos, or via the flight director and pilot inputs to the controls. The modes concerning lateral navigation of the airplane are called roll modes because they achieve their goals primarily through the control of the roll attitudes of the airplane. The modes concerning the vertical navigation of the airplane are called pitch modes because they achieve their goals primarily through control of the pitch attitudes of the airplane. The modes concerning the thrust of the engines are called autothrottle modes because they primarily act through the autothrottle system to control engine thrust.

In the 747-400, there are 7 roll modes, 9 pitch modes, and 5 autothrottle modes. Logically 315 mode combinations are possible! Fortunately only about 60 of these logical possibilities actually occur. That is still a large space of modes to think about. Is there any way to simplify the conception of the space of modes and the problems of mode management?

3.3. Operational incidents

The following selection of incidents (most observed from the jumpseat on actual revenue flights) will serve to illustrate a number of categories of operational problems with autoflight mode management. Many of these incidents represent instances of problems that have been identified in other contexts, training, simulator flights, and in other studies of aviation automation. Each incident will be analyzed as a small case study. A theoretical interpretation of the cognitive sources of the incident will be given. The theoretical interpretations of the problems lead to design goals for a system in which the observed problems can be expected to occur less frequently. Furthermore, the theoretical interpretations should support design goals that will not only fix the observed problem, but other potential problems as well. (e.g. what are called "metabutton" effects observed in some lateral navigation events argue for the elimination of metabutton effects in all contexts of the interface.)

In section 5, actual design decisions based on the design goals are described. One can then come back to the described incident and ask how the system with the new design would operate in the circumstances described in the incident.

These incidents and their theoretical interpretations were also used in the design of the flight scenarios used in the evaluation of the IMMI described in section 6 below.

It is widely acknowledged that vertical navigation presents more difficulties for flight crews than horizontal navigation. (Vakal, et.al., 1996).
Horizontal or lateral navigation is simpler than vertical navigation because it is governed by a single roll axis, roll, and because it is supported by the lateral navigation display (moving map). There are, however, still some observed mode management problems in the domain of lateral navigation. We will begin with a few of these.

3.3.1. *Modify RTE, execute, and then...*

Climbing out the airplane was given a vector to intercept a published SID routing. The airplane was then given a vector for traffic that was not a vector to intercept. Finally the aircraft was cleared to resume the departure. At that point, the captain set up the intercept by modifying the RTE-LEGS page of the CDU, but did not press the NAV button to arm the lateral navigation function. As a result, the aircraft flew, in heading select mode, through the departure route by about 2 miles. The captain noticed the deviation of the airplane symbol from the magenta track on the navigation display, ND, and brought the airplane around with heading select. He then selected NAV, which engaged. No mention of a deviation from course was made by ATC. The captain subsequently complained that the automatics had failed to capture the route.

This a classic case of Polson calls an “and then” problem (Polson: cognitive walkthroughs). The modification to the route is made on the MCDU, (and in Boeing airplanes, is executed there). If a mode that uses the modification is not already engaged, it is then necessary to arm that mode on the MCP. This additional action is difficult to remember because it is carried out in a different place from the route modification actions and because the execution of the modification has the feel of a completion to the route modification plan. **Design goal:** Route modification and mode selection should take place in the same location as a single course of action. The IMMI does not address the problem of route creation and modification. A second design goal is to make the distinctions among modes more perceptually salient and conceptually meaningful on the NAV display. This can easily be done.

3.3.2. *Engage LNAV with active waypoint on wingtip*

Just prior to top of descent, the aircraft was given a vector for traffic. When the captain attempted to re-engage NAV, the aircraft made an unexpected turn to the right. The captain engaged heading select and spun the heading bug to the left to reintercept the FMC route as displayed on the ND. After the airplane was again established on a heading to intercept the route, the captain selected
NAV and the plane made another unexpected turn. He went back to heading select. Finally, he was able to get NAV to engage and continue on course as he wanted it to.

The cause of this unexpected behavior by the autoflight system is that while being vectored the airplane had almost, but not quite, passed the active waypoint. With the active waypoint having a relative bearing of less than 90 degrees, it will not transition. The airplane was trying to fly to a waypoint that was nearly abeam of the plane, thus entering an unexpected steep turn.

This problem has been observed in actual and simulated flights in many glass cockpit airplanes. It is possible that some crew members consult neither the ND nor the ACT F-PLN or RTE-LEGS pages of the FMS before re-selecting NAV. For those who do consult the ND, the active waypoint is not saliently marked on the ND. Down-course waypoints are white, the active waypoint is magenta. That makes sense because the active route is displayed in magenta, and for the sake of consistency, all items depicted in magenta are elements of the active route. Unfortunately, there is a conflict here between consistency and discriminability. That is, the inactive waypoints are perceptually easier to find on the display than the active waypoints. This is because the white symbology contrasts with the magenta route line while the magenta symbology blends into it. The white symbology also has a better contrast with the display background. **Design goal:** Make the active waypoint perceptually more salient on the lateral navigation display.

The deeper problem here is that the NAV button on the GCP (or LNAV button on the MCP) is what Ev Palmer (Palmer, personal communication) has called a "meta-button." The structure of the button itself contains no information about the content of the mode that it selects. The meaning of the button is "fly the lateral route described in that active legs page beginning with the active waypoint." The route description is available on the RTE-LEGS page of the CDU (which might not be visible when mode selections is made, and on which the information is in text form), and in graphical form on the NAV display (but as noted above, the active waypoint is not salient), but this information is not represented in any way on the glareshield where the mode selection is made. The act of selecting the mode can proceed to conclusion without the pilot processing any representation of the content that will be evoked by the engaged mode. This is what makes unintended outcomes possible. **Design goal:** Require the operator to process the content of the mode in the act of selecting any mode. A simple way to do this is to have NAV mode selected by touching the active waypoint icon on the NAV display. This requires a bit more work than pressing the NAV button on the GCP because the pilot must first find the active waypoint in order to touch it. This search and touch activity make the spatial relation of the active waypoint to the airplane apparent to the pilot. This extra work is part of the work the pilot should always do before engaging the mode in any case. The wider design implication is that for all modes, the action taken to
select or engage the mode should somehow bring the operator into contact with easy to process representations of the specific consequences of engaging that mode.

3.3.3. Heading bug behind the airplane

This one was observed in a simulator flight rather than in revenue service.

The departure SID contains a turn of nearly 180° early in the procedure. The heading bug is lined up with the runway for takeoff. LNAV is engaged after liftoff and the procedure is flown as depicted. After turning more than 90°, ATC calls traffic and asks for a turn. The crew engages heading select, but now finds that the heading bug is behind the airplane and not visible on the nav display. The airplane continues its uncontrolled turn until the crew can spin the bug around in front of the airplane.

The root of the problem here is that the button press that engages Heading Select mode is a meta-button. Its meaning is roll to capture the heading indicated by the current position of the heading bug (wherever that may be). The current position of the heading bug is indicated as a number of degrees in the window above the heading select knob. This representation does provide some information, but it is not in a form that is easy to process. Suppose ATC said turn left 15° for traffic. One would have to read one’s current heading, and then subtract 15° to get the desired heading. Now, suppose the desired heading is 320 and the heading window reads 130. which way should one spin the bug to get it to the desired heading? The act that engages the mode does not require the crew to process any aspect of the heading that will be selected. The crew may use the heading window to determine the current location of the heading bug, but this representation is not easy to process. Furthermore, the heading bug itself is only visible when it is ahead of the airplane symbol on the navigation display. When the heading bug is on a heading that is behind the airplane, the bug itself is hidden. Many instructors and line pilots emphasize the importance of establishing a habit of keeping the heading bug in front of the airplane in order to eliminate this problem.

Design goal: Like the problem with wingtip LNAV, the solution to the meta-button problem here is to require the crew to process the content of the mode that will be selected in the act of selecting the mode. In this case, that can be accomplished by having heading select mode be selected by touching the heading bug on the NAV display. This implies another design goal, having the heading bug always be visible on the NAV display. A further goal is to have the display itself change in some way to indicate that the heading bug is going behind the airplane.
We now turn to the more complex, and less well supported, task of vertical mode management.

3.3.4. Unexpected leveloff at crossing restriction

The Peble One departure out of San Diego includes an at-or-below altitude restriction early in the SID. This restriction protects airspace used by fighters operating out of Mirimar Naval Air Station. I have observed this departure from the jumpseat many times. Out of 5 departures I observed in 757s, three crews were surprised by an unexpected leveloff at this altitude restriction. Other researchers (Palmer, Degani) flying this leg in 757 have also observed this problem. The following two incidents are typical.

Peble incident 1: The Peble one departure was selected to go with the company route. The departure clearance was to 14 thousand. The crew briefed the departure and put 8000 in the altitude window "just to be safe." After TOGA, the climb was commenced in FLCH and LNAV. Out of 4,000, the aircraft was cleared unrestricted to 14,000. The crew put 14,000 in the window, and engaged VNAV. Approaching 8,000', the aircraft began to leveloff. The Captain said, "Oh, I know what it's doing" and selected FLCH. He then deleted the restriction from the RTE-LEGS page and reengaged VNAV.

Peble incident 2: The crew carefully briefed the departure, and talked about the restriction. They put the company route with the Peble 1 departure in the CDU. After takeoff the aircraft was cleared unrestricted to 9000'. The airplane leveled at 8000'. It took quite a while for the crew to figure out why it leveled off. The FO finally pushed FLCH to resume the climb. By the time they began to remove the restriction, the waypoint had transitioned.

In these two cases, the MCP window altitude seems to be the most salient representation of anticipated flight path. The restriction to pass a waypoint at or below 8000' is visible as text on the RTE LEGS page of the CDU, but is not obvious even if that page is displayed. In each case, the clearance to climb unrestricted should lead the crew to delete the restriction from the FMS.

In a third case involving this departure (reported by Palmer, personal communication b), the crew were required to meet the altitude restriction. They did so successfully, but while trying to confirm that they had done so, they failed to continue the climb after the waypoint as expected.

The problem here is that the relevant system state - the representations of the altitude restriction - are weak and possibly hidden. Sherry and Polson (1995) discuss this sort of unexpected level-off as an example of the weakness
of current mode annunciation systems. Design goal: provide a graphical representation of the future vertical trajectory of the airplane. Just as the lateral navigation display makes the lateral path visible, a vertical navigation display could represent the vertical path. It should be noted that there are many problems with constructing vertical situation displays.

3.3.5. Unexpected level-off at cruise altitude

The aircraft was climbing out to the west with VNAV, LNAV and right autopilot engaged. Out of FL240 the aircraft was cleared to FL350. The captain put 35000 in the MCP altitude window. The FMS had been programmed for an initial cruise at FL310. (It is not known why the clearance did not match the programmed cruise altitude). The airplane was handed off to a new sector at about FL300. As the Captain began to check in, the airplane began to capture FL310 so he said, "Callsign 281, leveling at FL310." The controller replied: "I thought you were cleared to FL350, Sir." The captain glanced at the altitude window (he must have immediately figured out what happened), and said: "Yes, I guess we were, but we'd like to stay here if the ride has been okay here."

In this case, it is not clear that the captain had well formed expectation concerning the behavior of the airplane, but he and the FO were surprised that the airplane had leveled off before reaching the altitude in the MCP window. The problem here is that there are multiple descriptions of flight path, these descriptions are not always consistent with one another, and which of the descriptions is actually controlling depends on situational factors. The mismatch between the representation of flight path programmed into the FMC and the representation on the MCP leaves the behavior of the airplane ambiguous. The MCP representation occupies a more central location in the cockpit, but in this case, the less accessible FMC representation is the controlling representation. Again, the difference between what is programmed into the FMS (not immediately accessible - but operative) and what is displayed on the MCP (immediately accessible -but not necessarily operative) led to an altitude awareness problem. These discoordinations are symptoms of the complexity of operation via the two different interfaces located in different parts of the cockpit.

Design goal: To have a single representation in which all descriptions of flight path are displayed in such a way that it is easy to determine which will be controlling in any situation.
3.3.6. Failure to note FMA change

Navigation error on the Border 3 departure. Just before reaching the turn at PGY 19 DME cleared direct PGY. FO programs FMS, Capt goes to heading select. I think he went for a 080° heading (the final inbound course to PGY if the whole SID was flown.) With the FMS programmed, should have gone back to LNAV. I think the FO did not know that the capt had selected heading select. So FO believed LNAV still selected. 080° heading brought us over North Island. Capt noticed then and reselected LNAV.

This should have been easy to see on the annunciators on the PFD, but I have heard many complaints by crew that they do not use the annunciations as much as they should. Autoflight instruction packages always stress: "When you make a change up here (MCP), you've gotta look down here (PFD annunciations) to make sure you really have what you think you have." The problem here is that the annunciations are cryptic and not salient. Also, lateral mode status is not indicated on the map display itself. Design goal: indicate lateral mode status on the map display, and do it in a way that makes the mode annunciation perceptually salient.

3.3.7. Unanticipated automatic mode transitions

VNAV PTH reverts to VNAV SPD mode without warning in overspeed descent. Sherry and Polson (1995) also discuss this automation behavior as a context for crew confusion. Vakil, et.al. (1995) describe three kinds of mode transitions: commanded mode transitions, immediate consequences of crew mode selections; uncommanded transitions, usually invoked by the automation as envelope protection; and automatic/conditional transitions, such as when an armed mode engages. Design goal: Indicate impending uncommanded, and automatic/conditional mode transitions.

3.3.8. Knowing which modes can be engaged when.

On the climb we were given a speed restriction to maintain 250 until further advised. It wasn't until we were out of FL250 that we got econ speed. I was looking at the captain's climb page and could see that econ speed was 309 KIAS or Mach .797. I wasn't exactly sure how to get back to econ speed since we had the speed intervention showing in the window 250. When the captain asked the FO to restore the econ speed, the FO reached up and pressed the VNAV button. VNAV was already engaged though, so this had no effect. (Note: part of the logic of the system is that modes are
normally only dis-engaged by the selection of another mode.) The
captain pointed to the speed select knob, making a pressing motion.
the FO pressed the knob. The window blanked and the command speed
bug jumped up to the econ speed.

Technically, this is not a mode change. It is instead a change in the
target for the engaged mode. Still, it presents a problem for the crew. There
is nothing to tell the pilot that econ speed target will be restored when one
pushes that knob, or even that the knob is pushable. This is a case of more
hidden system state. Design goal: represent engaged, armed, and selectable
modes and their performance targets (speed, path) explicitly.

This raises the more general issue of knowing which modes can be
selected for engagement at any point in time.

3.3.9. Why SPD is not selectable when in FLCH, VNAV or
TOGA.

At the end of a VNAV-PTH descent, the FO wanted to reduce
speed. He reached up and pressed the SPD button on the MCP.
Nothing happened. He pressed it again, and still nothing happened.
He pressed it five times in all before giving up and selecting
vertical speed (which automatically activated SPD mode).

In this example, it is clear that the FO did not know that the SPD mode
is not available for selection when in FLCH, TOGA, or any VNAV mode. A
pilot could memorize this fact, but there are many other facts just like it.
Fortunately, there is a simple conceptual regularity in the system that implies
this constraint. This regularity will be presented below in the discussion of
the conceptual organization of autoflight functions. A better solution would
be to base one's knowledge of this constraint on the underlying regularity.
Unfortunately, the existing interface masks the underlying conceptual
regularities that govern the behavior of the autoflight system. Design goal:
Present for selection, only those modes that can be engaged or armed from the
current operating mode. Design goal: Associate salient perceptual regularities
in the display with the underlying conceptual regularities that govern the
behavior of the autoflight system.

3.3.10. Mode selection in wrong operational context: Killing the
capture

Palmer (1994) reports a case from a simulated flight in which a pilot
intending to soften a level-off maneuver caused a failure to capture the target
altitude. In some automated airplanes, pilots find the level-off maneuver to
be somewhat abrupt. One way to provide more passenger comfort is to select
V-SPD mode prior to the capture and to reduce the vertical rate at which the target altitude is approached. This normally works fine. If however, the selection of V-SPD is made after the altitude capture has begun, the selection of the new mode will “Kill the capture.” In the case observed by Palmer, the new mode selection came less than a second late. Since modes are not annunciated in the same place where mode selections are made, there is a possibility that the operating context could change between the time the pilot decides on an action and when the pilot takes the action. **Design goal:** Put the means of evaluating the current state of the system, making changes to the system, and assessing the consequences of changes all in the same location.

As long as the parameters of flight path are specified through the CDU, the autoflight modes that link those parameters to the controls are selected via actions on the MCP, the consequences of mode selection actions are evaluated on the FMAs and the compliance of the airplane with the specified parameters is monitored on the PFD and ND, there will be problems like those observed in these flights. These flight decks scatter flight path displays and controls all over the instrument panel.

### 3.4 Mode Naming

A lexicon for verbally representing the states and guiding one’s own and the attention of the other pilot is needed. How are pilots going to talk about what they see and what they are doing on this interface? This raises the issues of mode naming. Currently, the mode naming and the representations of the modes are a single system. The mode names appear as text in the mode annunciation. Pilots refer to the modes by their text names or phonetic variants of them. Because of display space constraints, most text representations of mode names are contractions of longer words. Sometimes pilots use the longer words - expanding the contraction. e.g. LvlChg= Level change. Sometimes they coin a new phonetic token based on the contraction. e.g., FLCH = flitch. Even within the current system of mode naming it is possible to make improvements along the lines of the theory presented here. That is, conceptually similar modes could have conceptually similar names. Some of this is present in a partial compositional structure of names. For example, the vertical navigation modes in which performance targets are set by the FMCS all begin with the character string “VNAV”. One can see why engineers would name modes this way. Grouping modes that are controlled by the FMCS reflects both the history of the introduction of modes and the nature of the data flow within the autoflight system. However, there are other ways to group modes. For pilots, the source of the target may not the most important feature of modes. From an operational perspective, VNAV-SPD may be more similar to FLCH (both are pitch to target speed modes) than it is to VNAV-PTH.

The general problem here is that the mode space is multi-dimensional, and text string annunciations tightly constrain the number of independent
features that can be meaningfully distinguished in the representation of modes. The hyphenated mode names convey only two dimensions. The graphical depictions of the IMMI permit simultaneous representation of a wider range of features - up to four dimensions simultaneously. However, regardless of the capabilities of graphic displays, the mode naming issue remains a factor in crew communications and reasoning about modes. Airbus naming conventions may have some advantages because they are more explicitly compositional. For example, the difference between what Boeing calls VNAV-SPD climb and FLCH climb is noted in the Airbus system as the difference between managed speed climb and selected speed climb.

### 3.5 Folk models:

The failure of the current interfaces to provide the crew with the raw materials necessary to construct coherent models of the conceptual organization of autoflight, and the failure of most manufacturer and airline training programs to teach the conceptual structure of autoflight leaves to pilots themselves the job of trying to come up with conceptual models to understand the behavior of the systems they use. Unfortunately, the regularities that are most important are often masked in the current designs.

Sometimes, these folk models are quite good. In some cases they are charmingly naive, and on other cases they are probably quite dangerous. Here is an example of a naive model. Most airlines specify a procedure for autopilot use in which the autopilot that is used to control the airplane should not also be used to drive the flight director of the pilot flying. In airplanes with three autopilots, the center autopilot is usually engaged. In two autopilot airplanes, the autopilot on the side opposite the pilot flying is used. One captain told me that you can't use same autopilot to drive the servos and to generate the f/d command bars. His folk theory to account for this fact was a resource limitation argument. He claimed that "the box can't drive both at once. That's why with 3 autopilots, we normally use center in command." A better reason is that if an autopilot fails active, you don't want it sending bad information to both the f/d command bars and to the servos. If these are on separate boxes, then if the one driving the command bars fails, the airplane will continue flying fine. If the one driving the servos fails, the pilot will be able to use the command bars to recover.

The MCP is not completely lacking in conceptual organization. While explaining to me how the MCP is laid out, one captain seemed to achieve the insight that N1 and SPD are thrust modes and that FLCH and VNAV are pitch modes. N1 and SPD are on the left of the speed select knob while FLCH and VNAV are to the right. Unfortunately, the conceptual organization of the MCP is at best local and inconsistent. Another pilot (B-737-300) told me that "this stuff up here (top row of buttons on MCP has to do with this (the MCP). This stuff down here (bottom row of buttons) has to do with this (FMS)."
This desire on the part of pilots to read conceptual meaning into the spatial layout and the behavior of the MCP and other mode management displays and controls suggests a final design goal: to build an interface in which the physical layout and behavior of the displays and controls maps easily onto the underlying conceptual regularities of the autoflight system.
4. A conceptual analysis of autoflight modes

If the analysis presented above is correct, then making the concepts that underlie autoflight operations more explicit in the behavior of the interface may improve operability and the rate and quality of learning. What are the underlying conceptual regularities and conceptual distinctions? Some of these come from the realm of flight in general (e.g. the distinction between pitching to a speed and pitching to a path) and some are specific to automated airplanes (e.g. is the performance target set by the crew or computed by the flight management computer system.)

4.1. Methods for discovering the conceptual basis.

Over the years cognitive anthropology has developed several methods for discovering conceptual structures. First and foremost among these methods is participant observation in which the researcher participates in the normal activities of the people and thereby learns to speak and act like the people do (Agar, 1980, 1986). Engaging in appropriate talk and action requires at least partial mastery of the conceptual structures that the natives use to organize their own behavior. Over the past 7 years, I have become a pilot. I now hold a commercial pilot’s license with multi-engine and instrument ratings. This, of course, does not mean that I can claim to know the conceptual structures on the basis of introspection, but it has permitted me to engage real line pilots in meaningful discussions concerning the problems they face. I have conducted dozens of interviews with pilots, both in the cockpit and out. Analysis of discourse and interviews is a second major technique of cognitive anthropology (Hutchins, 1980, Holland and Quinn, 1984; D’Andrade, 1995).

To construct a knowledge of autoflight systems in state of the art aircraft, I have completed the ground schools for the Boeing 747-400 and the Airbus A-320. These ground schools do not qualify me to fly these airplanes, but they do permit me to observe pilots in flight in a different way. Before I took the training, I could see what pilots were doing. After the training, I could see not only what they were doing, but what they could have done but chose not to do. These courses enhanced my abilities as an observer. I have logged over 300 hours of jumpseat observations of line operations in domestic and international flights. These observations are the basis of the observed problems section of this paper. Participation in the training also gave me access to training materials, operational manuals, pilots, instructors, and, at Boeing, access to engineers who designed the systems.

A third method for discovering conceptual structure is called componential analysis (Goodenough, 1957; Romney & D’Andrade, 1961; Werner & Schoepfle, 1987). The goal of componential analysis is to isolate a set of underlying distinctions that can account for the system of meanings in a noun domain. In this case, the names of the autoflight modes constitute a
noun domain. A componential analysis of the mode names reveals the underlying conceptual distinctions that account for the differences in meaning among the mode names. A comparative componential analysis contrasting the underlying distinctions for the Boeing and Airbus mode naming conventions has been completed\(^8\). The major results of this analysis will be given below.

### 4.2. Autoflight modes

The following sections present the autoflight modes for the Boeing 747-400. This aircraft was the original target for the IMMI development.

#### 4.2.1. Roll Modes

The roll modes for the 747-400 are given the following names: HDG SEL (heading select), HDG HOLD (heading hold), LNAV (lateral navigation), TOGA (takeoff and go-around), LOC (localizer), ROLLOUT, and ATT (attitude). The conception of roll modes can be simplified considerably by noting that each mode is no more than a method for computing the directional target for the airplane. While there are seven roll modes, the modes fall into two major classes: modes in which the target is the **heading** of the airplane, and modes in which the target is the **ground track** of the airplane. The heading based roll modes are HDG SEL and HDG HOLD. HDG SEL turns to the airplane to a selected heading and keeps it on that heading. HDG HOLD rolls the airplane's wings level and holds the heading that was achieved when the wings came level.

Further distinctions among modes are made on the basis of the sources of track information. In LNAV mode, a ground track is computed by the flight management computer system, based on inputs to the MCDU. This ground track may be used to do the equivalent of VOR radial tracking, although it is the ground track defined by the radial, rather than the VOR signal that is being tracked. LOC and ROLLOUT modes track the localizer signal of an instrument landing system approach facility. TOGA uses the on-board inertial navigation system to determine the ground track of the airplane at the onset of TOGA guided flight and uses that ground track as the target.

Ground track can thus be defined by geographic coordinates (LNAV), by signals from ground based navigation aids (LOC and ROLLOUT), or by a momentary sensation of the inertial reference system (TOGA).

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\(^8\) The details of this method and its results will be reported in detail elsewhere.
The one remaining roll mode, ATT (attitude) is an infrequently used reversion mode. It engages only when a flight director is turned on in flight after a period in which neither flight director and none of the autopilots have been engaged and the bank angle exceeds 5°. Its main function is to provide a flight director guidance mode that keeps doing what ever the airplane was doing before the flight director was turned on.

4.2.2. Pitch Modes

The pitch modes are: TO/GA (takeoff and go-around), ALT (altitude), V/S (vertical speed), VNAV PTH (path), VNAV SPD (speed), VNAV ALT (altitude), G/S (glide slope), FLARE, and FLCH SPD (flight level change, speed).

4.2.3. Autothrottle Modes

The autothrottle modes are: THR-REF, THR, HOLD, IDLE, and SPD. These come in two flavors: speed modes and thrust modes.

4.3. Mode Interactions

Fortunately, the Roll modes are essentially independent of the Pitch and Autothrottle modes. The exceptions are that the toga and rollout roll modes only occur with certain pitch and autothrottle modes. Unfortunately, this independence is conceptually masked by the fact that the flight mode annunciator formats of both Boeing and Douglas aircraft display roll mode between the pitch and autothrottle mode displays. This is probably an attempt to maintain consistency with the layout of the primary flight displays in which the ADI and the HI (primary roll instruments) lie between the ASI (thrust instrument in level flight) and the Altimeter (a pitch instrument in level flight).

Treating roll modes independently and knowing that there are few interactions between roll modes and other modes simplifies the mode management problem considerably.

There are, however, significant interactions between pitch and autothrottle modes, and it is here that most of the conceptual problems seem to arise. Segregating the modes into classes and showing a simple set of relations among the classes may help to simplify the conceptual space.

The rule is that whenever the pitch mode is controlling to a speed target, the autothrottle mode will be controlling to a thrust target. Whenever the pitch mode is controlling to a path target, the autothrottle mode will be
controlling to a speed target. Figure 3 shows the interactions between the pitch modes and autothrottle modes.

4.3.1. What every pilot knows

![Figure 3. The general rule of interaction between pitch and autothrottle modes.](image)

This should make sense to all instrument rated pilots, since it reflects the changes in the primacy of instruments in standard maneuvers. That is, in a normal climb, thrust is set, and speed is controlled by pitch. If the airspeed is too high, raise the nose; if the airspeed is low, lower the nose. When approaching cruise altitude, the nose is pushed down and the airplane accelerates to cruise speed. Pitch is now controlling flight path and thrust is controlling speed, which will increase if thrust is not reduced. A similar transition occurs at top of descent where thrust is typically brought to flight idle (or other descent value), and speed is controlled by pitch.

4.3.2. 747-400 vertical mode interactions

Note that speed should always be controlled by a pitch mode or an autothrottle mode. This regularity considerably reduces the complexity of

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9 One exception exists. On an autoland, the pitch mode FLARE engages at about 50' AGL and the autothrottle mode IDLE engages at about 25' AGL. For that last 25' of descent, speed bleeds off and neither pitch nor thrust controls to a speed target.
the space of mode combinations. Figure 4 shows the space of possible combinations of pitch and autothrottle modes. In this table, the distinctions among modes are made on the basis of the mode type (pitch or autothrottle), the controlled parameter (speed or path for pitch modes, speed or thrust for autothrottle modes), and the source of the target (Mode Control Panel, Flight Management Computer, or Ground Signal).

10 There is a hidden danger here. It is possible to fly a visual approach in the 747-400 with the autopilot, flight directors, and autothrottles off. If a go around is required, pushing the go-around buttons will provide go around thrust. The upward pitching moment caused by the below-wing mounting of the engines can feel like the TOGA pitch mode acting through the autopilot, even though the autopilot and pitch modes have not engaged. In this case, the autothrottle mode controls thrust, but only pilot action with the control column can control speed. It is possible for a distracted pilot in such a situation to inadvertently approach a stall condition.
Figure 4. The logically possible mode combinations.

Figure 5 shows the space of actually occurring mode combinations. The cross-hatched area indicates combinations that do not occur.
In training a lot of emphasis is placed on monitoring and calling out mode transitions whether they are crew selected or automatic. The purpose of making mode transition callouts must be to bring the conceptual implications of the current mode to the attention of the pilots. These conceptual implications concern what is being controlled and how. This is precisely what the figures above attempt to capture. Unfortunately, these relationships do not appear explicitly anywhere in the training materials.

One reason that crews in training have so much trouble learning to attend to and call out mode transitions is that such callouts are only perceived as useful to the extent they bring to mind operational implications. When crew members are unclear on the meanings of the modes, they have little motivation to note mode transitions.

What can be done about the seemingly arbitrary rules governing the availability of modes?

In the automatic flight section of the 747-400 airplane operations manual the description of the speed switch on the mode control panel states that the speed switch is "inactive if in FLCH, VNAV, or TOGA" (07.10.2A). A pilot in training may choose to memorize this bit of information. If he
does not, he is at risk (as reported in section 3.3.9 above) of pushing this button while on one of these modes and finding that it does not respond. "What's going on?", he might ask. "Why can't I get speed mode?"

The answer is difficult to see in the current system for two reasons, one having to do with the design of the mode control panel, the other having to do with the training. The answer to the question is that the speed switch engages an autothrottle speed mode. FLCH, TO/GA, and VNAV-SPD (pitch modes) are speed controlling modes. Speed is already being controlled by pitch in these modes, so it cannot also be controlled by the autothrottle. All the VNAV modes include an automatic speed control function, so SPD mode is not appropriate. But this is hard to see because 1) the layout of the MCP provides only implicit hints that the speed switch controls an autothrottle mode rather than a pitch mode (after all, either sort of mode could control speed) and 2) the training does not make it clear that autothrottle and pitch modes have a mutually exclusive relationships with respect to the control of speed. If these relationships had been made clear, it would be easy for a pilot reading the manual to know immediately why this switch will be inactive when the pitch mode is FLCH, VNAV, or TO/GA. The need to memorize the fact that SPD is inactive in these modes is eliminated. The behavior of the airplane autoflight system becomes meaningful rather than mysterious.

In the description of the IAS/MACH selector, the pilot is told that when the IAS/MACH selector is pushed, the "IAS/MACH window does not blank if SPD, FLCH, or TO/GA mode is active" (07.10.02B). Again, to avoid surprises in flight, the pilot could either memorize these facts, or understand the reasons behind them. But the underlying conceptions are masked by the organization of the presentation of information. In this case, no effort has been made to distinguish the autothrottle mode, SPD, from the pitch modes, FLCH and TO/GA. If this had been done, it would be easy to see from the diagrams above that these three modes share in common the properties that they are modes that control the speed parameter on the basis of a speed target that is set on the MCP. The existing instruction and design of the flight deck give absolutely no explicit representations of the dimensions on which these three modes are members of a single conceptual category. If these dimensions were to be represented to the pilots, it would be obvious why the IAS/MACH window does not blank when the selector knob is pushed while these modes are engaged. These are just the modes in which a speed target is already being set on the MCP. A simple conceptual regularity replaces the need to memorize what otherwise seem to be unrelated facts.

Similar problems exist in the relationship between the autothrottle mode engaged with the speed switch and the speed modes engaged by "speed intervention" when the IAS/MACH selector is pushed. The former is exclusively an autothrottle mode. The latter is a "hidden" pitch mode. I say hidden because when speed intervention is selected on a descent, all the outward indications are that pitch is controlling path. However, "During descent, when speed intervention is used, the guidance mode essentially
changes to speed on elevator...." FCTM, p. 3-7. Path is no longer controlled by
the pitch of the airplane. Deviations from path must be controlled with speed
brakes or throttle.

4.4. The conceptual distinctions for vertical navigation.

The componential analysis reveals that the following dimensions and
dimension values are required to make all the distinctions made in vertical
modes for either of the mode naming schemes:

<table>
<thead>
<tr>
<th>Pitch target type:</th>
<th>speed, path, vertical speed, attitude</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thrust target type:</td>
<td>idle, limit, speed</td>
</tr>
<tr>
<td>Target source:</td>
<td>MCP/FCU window, FMC, Nav aid, Autopilot</td>
</tr>
<tr>
<td>Respect FMC constraints:</td>
<td>Yes, No</td>
</tr>
<tr>
<td>Profile shape:</td>
<td>Airbus: Level, Up, Down. Boeing: Constant altitude, Changing Altitude</td>
</tr>
</tbody>
</table>

Table 4.1. Conceptual distinctions needed to distinguish all modes in
Boeing and Airbus mode naming schemes.

Additional distinctions are needed to actually operate the system.
These include:

| Autopilot engagement status: | engaged, not engaged |
| Mode status                  | engaged, armed, selectable |
| Target priority              | When there are two targets of the
                              | same type, which one will affect the
                              | flight path? e.g. when window alt and
                              | FMC alt targets disagree |

Table 4.2. Additional conceptual distinctions.
5. The current design

An overview of the IMMI is shown in figure 6. The display consists of two main areas: a vertical mode manager at the top, and a lateral mode manager at the bottom.

Figure 6. Overview of the IMMI display. Ready for takeoff. TOGA pitch and roll engaged, LNAV and VNAV armed.

The lateral mode manager looks and behaves much like the current generation of lateral navigation displays. However, in accordance with the design goal to put the means of evaluating the current state of the system, making changes to the system, and assessing the consequences of changes all in the same location, the lateral mode manager has been enhanced to combine the earlier functions of route, data, and weather display with the new functions of mode annunciation and selection. The lateral mode manager hardware consists of a lateral situation indicator display and a heading select knob. Icons on the lateral mode manager show aircraft roll
guidance for heading and lateral path. Icon display state, color, and size indicate mode availability, and mode status (engaged, armed, selectable).

Targets values are set by manipulating the hardware select knobs. The mappings of functions from the mode control panel of a Boeing 747-400 to the IMMI are shown in appendix 1. The appropriate mode icons appear according to the situation of the airplane and the settings of the select knobs. Modes are selected by touching the icons that represent the desired mode. A complete description of the controls and indicators on the IMMI display is given in appendix 2.

The vertical mode manager is an all new display which combines altitude and speed tapes with a vertical situation display that depicts the vertical path of the airplane. Mode engagement status is depicted by the positioning, shape and color of graphical icons. Modes are armed and selected for engagement by touching the icon depicting a selectable mode. The vertical mode manager hardware consists of a vertical navigation display, a speed select knob, an altitude select knob, and a vertical speed select wheel. The vertical navigation display contains an airspeed tape, a vertical profile display, an altitude tape, four columns for the display of mode icons. Icons on the vertical mode manager show relationships of aircraft pitch and thrust to airspeed/mach and vertical flight path. Target source (FMCS or crew input) and target value are indicated by the location of the icon with respect to airspeed/mach and altitude tapes.

Autoflight systems' state display and mode selection actions are co-located. In both mode managers, autoflight modes are depicted by icons on a conceptually meaningful graphical display rather than by strings of characters. Target values are set by manipulating hardware knobs.

Although the IMMI includes an airspeed and altitude tapes, it is not intended as a primary flight instrument. Part of the mode management task is setting targets (speed and path) with respect to other targets, the current operating envelope limits, and the current operating parameters. These tapes are provided to make this possible.

5.1. The lateral mode manager

There were three related design goals relating to the lateral mode management.

1. Make the distinctions among modes more perceptually salient and conceptually meaningful on the NAV display.

2. Make the active waypoint perceptually more salient on the lateral navigation display.

3. For all modes, the action taken to select or engage the mode should somehow bring the operator into contact with easy to process representations of the specific consequences of engaging that mode.
Figure 6 shows the IMMI display with the aircraft ready for takeoff. The active waypoint icon is the white circle in front of the airplane labeled SFO01. It has been increased in size to make it perceptually more salient. It also always is shown in a color that contrasts with the magenta color of the FMC computed track line. The active waypoint icon is now a mode annunciator and mode selector. The color of the waypoint icon indicates the engagement status of the mode. In this case, the white color indicates that LNAV mode is armed for engagement. When the conditions for engagement are met (50’ of radar altitude) the mode will automatically engage, and the icon will turn green. Figure 7 shows LNAV engaged with Porte the active waypoint. When LNAV is selectable, but neither armed or engaged, the icon appears blue (Figure 12, a&b). In order to engage or arm the mode, the pilot must find the active waypoint icon and touch it. This makes the spatial relationships between the airplane, its current course, and the location of the active waypoint apparent to the pilot before the mode is engaged. This solves the “meta-button” problem observed in some engagements of LNAV mode in the current generation of aircraft.

Figure 7. LNAV engaged, heading bug behind airplane and compass rose wrapped to keep heading bug visible.
A similar solution has been adopted for the heading select mode. The heading select mode is selected by touching the heading bug on the NAV display. Just as was the case for LNAV selection, this makes the spatial relationship between the airplane's current heading and the selected heading apparent to the pilot before mode engagement. For this to work in all conditions, the heading bug must always be visible on the NAV display. As the heading bug moves away from the nose of the airplane, the compass rose on the lateral navigation display expands to always include a wide enough arc to include the heading bug. Figure 7 shows the display with the heading bug nearly behind the airplane. This expansion and contraction of the compass rose satisfies another goal of having the display itself change to indicate that the heading bug is going behind the airplane. This additional bit of structure in the display's behavior provides the crew with an additional cue about the location of the heading bug.

5.2. The vertical mode manager

Our most general design goal was to build an interface in which the physical layout and behavior of the displays and controls maps easily onto the underlying conceptual regularities of the autoflight system. The table below shows the correspondence of conceptual distinctions underlying the operation of the vertical component of the autoflight system to perceptual distinctions in the interface.

<table>
<thead>
<tr>
<th>Conceptual distinction</th>
<th>Perceptual distinction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Target source: FMS/MCP</td>
<td>Icon location: Between tapes/Outboard of tapes</td>
</tr>
<tr>
<td>Target type: Speed/Path</td>
<td>Icon location: Adjacent speed tape/Adjacent altitude tape</td>
</tr>
<tr>
<td>Control axis: Pitch/Thrust</td>
<td>Icon shape: Airplane/Engine</td>
</tr>
<tr>
<td>Mode status: Engaged/Armed/Selectable/Envelope limit</td>
<td>Icon color and fill: Green(solid)/White(solid)/Blue (outline)/Amber(solid)</td>
</tr>
<tr>
<td>Path source: FMS/MCP</td>
<td>Path line color: Magenta/Green</td>
</tr>
</tbody>
</table>

Table 5.1. Correspondence of conceptual distinctions to perceptual distinctions for vertical mode management.

The vertical path display satisfies the design goals to provide a graphical representation of the future vertical trajectory of the airplane and to have a single representation in which all descriptions of flight path are displayed in such a way that it is easy to determine which will be controlling in any situation. Figure 8 (Climbing to an engaged altitude below cruise altitude. The solid green airplane icon on the inboard side of the speed tape shows that the airplane is climbing in a mode that uses pitch to attain an FMC specified economy speed target (VNAV-SPD). The solid green engine icon on
the inboard side of the altitude tape shows that the path of the airplane is controlled by a FMC specified level of engine thrust. The blue outline airplane icon outside the speed tape shows that a mode in which the airplane will pitch to an MCP specified speed (FLCH) is available for engagement. The blue outline airplane icon outside the altitude tape shows that a mode that will pitch to an MCP specified path (V-SPD) is also available for engagement. The green horizontal line at FL230 shows that unless a higher altitude is selected before reaching this altitude, the airplane will level off at this altitude even though the magenta FMC computed climb path continues up to the cruise altitude of FL330.

Figure 8. Climbing to an engaged altitude target by pitching to FMC specified Econ speed target.

The extent of the vertical path that is shown depends on the scale selected on the lateral navigation manager. The vertical path display shows the same path component as is shown on the lateral navigation manager. The enroute waypoints are shown along the bottom of the vertical path display. The “goal-posts” show altitude restrictions specified for the waypoints. This makes it easy to see if the airplane will meet or violate
altitude restrictions. If the autoflight system predicts that an altitude restriction will not be met, the goalpost will turn amber.

All and only those modes that can be engaged or armed from the current operating mode are presented for selection. The display of icons is context sensitive so that icons for modes that are not selectable from the present context are not displayed. Thus, when the airplane levels off at an intermediate altitude in a climb, no pitch modes are selectable until a new altitude has been selected. Figure 9 shows the leveloff condition before the selection of a new target altitude. Figure 7 shows the leveloff after the selection of a new altitude target, and figure 8 shows the situation after a climb method has been selected. On the systems currently in use, all mode select switches are continuously present (as hardware) even though they may not be selectable. In the IMMI it is easy to see that no vertical modes other than the currently engaged modes are available for selection.

Figure 9. Level at 10,000'. No other vertical mode icons will appear until a new altitude target has been set.

Engaged, armed, and selectable modes and their performance targets (speed, path) are represented explicitly in the color and placement of the icons. When speed intervention has been selected in any VNAV mode, an icon indicating return to the FMC computed speed target appears as selectable. This solves the problem of knowing how to restore the econ-speed target for VNAV from the speed intervention condition.
Impending uncommanded mode changes are indicated by the engaged icon turning from solid green to solid amber color before the mode transition. The most frequently encountered such uncommanded change in normal operations is the transition from VNAV-PTH descent to VNAV-SPD when maintaining the path would lead to an overspeed. Figure 10 shows the VNAV-PTH icon turning amber as the speed approaches Vmax.

Figure 10. Impending uncommanded mode change for envelope protection. The VNAV-PTH icon turns amber to indicate impending change.

Figure 11. After the uncommanded transition to VNAV-SPD descent. Notice that the pitch icon has moved from the altitude tape (path) to the speed tape.

Figure 11 shows the state after the uncommanded change has taken place. Automatic/conditional mode transitions are not explicitly represented, but it is always easy to see which mode is coming next. On the vertical path display, the automatic transition from any climb mode to altitude keeping mode is shown by the position of the green line. The transition from
localizer armed to engaged on the lateral mode manager (figure 12a and b), and the transition from glideslope armed to engaged on the vertical are also easy to anticipate.

![Figures 12a & b. The localizer is armed (12a) by touching the localizer icon. The localizer engages automatically upon localizer capture (12b) and the icon turns green.]

5.3. The airspeed tape

The design goal of associating salient perceptual regularities in the display with the underlying conceptual regularities extends to the design of individual components of the displays. The airspeed tape presents an especially good example. The traditional round-dial airspeed indicator has some nice cognitive properties (Hutchins, 1995b). The mapping of the abstract quantity speed onto a fixed extent of space permits pilots to use fast, robust perceptual processes to do conceptual tasks. Speed bugs partition the space of speeds into meaningful regions. One of the most important properties of the airspeed indicator is that its gross physical appearance changes with speed. This is not true of the current generation of “glass” airspeed instruments. On these, the gross physical appearance of the display is the same at all speeds. Pilots often complain that they must read the number in the box in order to determine their speed. Some have advocated
giving up on airspeed tapes\textsuperscript{11}. The problem does not lie in the technology, but in the way it is used. It is possible to build a "glass" tape that has the cognitive properties found in the round-dial instruments. The speed tape in the IMMI is an example. The airspeed tape on the IMMI always displays the entire current operating speed envelope for the airplane. Stall speed is at the bottom of the tape and Vmo or Mmo is at the top. This speed range is sensitive to airplane configuration and atmospheric conditions. Contrast this to the current practice in the 747-400, the A-320, and the MD-11 of showing a constant 120 knot window around present airspeed.

\begin{figure}
\centering
\includegraphics[width=\textwidth]{figures/airspeed_tape.png}
\caption{Figures 13a &b. The airspeed tape showing a slow speed during approach (13a), and a fast speed in descent (13b).}
\end{figure}

\textsuperscript{11} Lovesey, 1992. claims that "tape displays have been introduced into cockpits at regular intervals (for example: 1925, 1938, 1960s, 1970s). Each time they are introduced, they are soon found to be inferior to round dials and are rejected."
While the present airspeed always appears in the center of the tape in the current generation tapes, on the IMMI airspeed tape, the present airspeed box moves to the position on the tape corresponding to the present speed. This means that when the airplane is operating in the slow end of its current operating envelope, for example, the airspeed box will be at the bottom of the tape. This movement of the box is a perceptually salient cue for airspeed. It permits pilots to judge the speed of the aircraft in functional terms of fast and slow even with the instrument in peripheral vision. Figure 13a and b show the airspeed tape indicating a low speed on approach and a near overspeed condition in descent, respectively. Notice that the range of the airspeed scale depends on the airplane configuration and the atmospheric conditions.

5.4. Conceptual validation:

To ensure that the IMMI could represent all autoflight related actions and display changes we conducted a careful analysis of a simulated flight. We identified 102 autoflight related representations and actions in the simulated flight from PHX-LAX. For each event, we mapped out the corresponding IMMI action or display state.

5.5 New problems introduced by the design.

A small number of new problems are introduced by the IMMI design. These became most apparent when the IMMI was installed in the Advanced Concepts Flight Simulator of the CVSRF at NASA Ames. All proposed new instruments face the problem of cockpit real estate. Where can the device be placed in the already crowded cockpit? The design of the ACFS includes 5 display screens arrayed in a row across the instrument panel. The IMMI was installed on the center screen. The hardware knobs used to set target values were installed around the perimeter of the center display screen.

A potentially more serious problem arises from the requirement to have a touch-screen interface. While it is possible to use touch screens in aircraft, the designs are limited by two factors. First, the technology of touch screens is such that there appears to be just enough resolution in the current generation of technology to allow the discrimination of adjacent icons in the display. It is expected that this limitation will be relaxed as the technology matures. A second limitation concerns the pointing accuracy of an operator, especially when the airplane may be bouncing in turbulence. The touch accuracy at arm’s length in bumpy conditions is not good, and there is some concern that a touch interface would become unreliable in turbulence. It is not known how serious this problem might actually be. By placing other fingers on the display frame, it is possible to improve touch accuracy considerably, even in bumpy conditions.
6. Evaluation

The plan for the evaluation of the IMMI has three parts. First, a comparative cognitive walkthrough for the 747-400 and the IMMI was performed. Appendix 3 shows sample pages from the analysis. This analysis led to the production of a set of predictions about the effects of replacing the current interface with an IMMI. Second, the IMMI was installed in the Advanced Concepts Flight Simulator of the CVSRF at NASA Ames research center. This required a large software engineering effort because the variables used by the simulators in the CVSRF are poorly documented and because the IMMI needed to interface with proprietary code supplied to CVSRF by airframe manufacturers. Third, a simulated flight scenario was designed to test the effects of the IMMI compared with the 747-400. Preliminary testing of the IMMI in the designed scenario was commenced in the summer of 1995. A comparative study was planned using 747-400 line pilots flying the scenario in both simulators at the CVSRF. The simulators were taken off-line in the fall of 1995, and unfortunately, the grant ended before the simulators became available again.

6.1. IMMI predictions

It is possible to make some predictions regarding the elimination or reduction of operational errors and the reduction of training time. Here are five different kinds of predictions about the IMMI.

1. Some errors that have been observed with the current system will be entirely eliminated because they are made impossible by the new design. For example, it is not possible with the IMMI to attempt to select a mode that is not available from the current state of the system. The suppression of icons depicting modes that cannot be selected in the current context should simplify the decision rules pilots employ in operating the autoflight system and should eliminate the now common instances of failed attempts to engage modes that are not available. This may be operationally important, but it is not interesting from a theoretical point of view because the prediction does not make much use of the theory. Perhaps a more interesting case is that one cannot choose heading select mode without being aware of the current location of the heading bug. This leads to the prediction that the error of entering heading select mode while the heading bug is behind the airplane (producing an undesired turn) will be eliminated.

   Note the role of observations of current practices as a baseline against which we characterize the performance on the new interface.

2. Other classes of error are also expected to occur less frequently. The unexpected leveloff (e.g. in the Peble 1 departure described in section 3 above) and other vertical awareness problems should be remedied by the presence of the vertical path display. Conflicts between performance targets set by crew
IMMI Hutchins

and FMCS are explicitly depicted in the graphics of the vertical profile display. This should reduce the frequency of errors due to the autoflight system tracking a target that the crew is not attending to. This is a bit more interesting from the theoretical perspective than the suppression of unselectable modes, but not very much. In this case the presence of representations of the right kind makes the construction of a situation model easier for the pilot. The consequence of the actions are easy to see as long as one can interpret the graphical notation.

3. The frequency of unexpected steep turns to the active waypoint when rejoining a LNAV route should decrease. This is because the IMMI requires the pilot to know the position of the active waypoint relative to the airplane before engaging LNAV mode. Putting meaningful content in the action that engages the mode should help fix this problem.

This is the embodiment of a general principle. In the current system the internal structure of the actions that select modes have only arbitrary relations to the consequences of mode selection. In the IMMI, the content of the consequences is built into the selection action. For example, touch the active waypoint to engage LNAV or touch the heading bug to engage heading select.

4. The situation with vertical modes is more complex and more interesting. With the vertical modes the IMMI employs a theoretical principle that the underlying conceptual regularities in the behavior of the system should be reflected in the behavior of the interface itself. This goes back to the Hutchins, Hollan, and Norman (1986) work on direct manipulation interfaces. The basic notion is that the user must create a bridge from the structure of a representation to its meaning. We can make it easy for the user to construct this bridge by providing structure in the representation that can be seen as similar to the conceptual structure of the thing the representation refers to.

In the IMMI, the conceptually meaningful representation of modes mirrors the underlying regularities of the autoflight system. This should reduce the apparent complexity of the autoflight system, thereby promoting safer, more efficient use of the autoflight system. It should also reduce the amount of training required to prepare pilots to fly the airplane, and improve the quality of actual flight experience as a context for learning. This representation also permits flight crews to link perceptual routines for parsing the display to the underlying conceptual regularities.

This problem exists at all levels of organization of the system. Thus the static shapes of the icons should suggest the things they are intended to represent. But also, the behaviors of the icons should suggest the behaviors of the things they represent. The IMMI uses space and color to encode conceptual features of autoflight that are masked in the current interface. For example, icons depicting FMC targets are inside the tapes - adjacent to the FMC computed path. Icons depicting pilot specified targets are outside the
tapes. The icons are of only two types: pitch and thrust (distinguished by meaningful shapes) and they are associated with only two kinds of targets (speed and vertical path). The association of performance target with a control axis is indicated by the spatial adjacency of the icon (control axis) with one tape or another (performance target).

The prediction from this is that it will be easier for pilots to 1) see and understand what the system is doing, 2) operate the system, 3) learn to use the system.

5. Another class of predictions concerns the distribution of places where pilots must attend. MCP, FMA, MCDU, PFD in order to do the job. Co-location of mode state depiction and mode selection apparatus provides for the composition, execution and evaluation of mode management actions all in the same place. This should reduce the frequency of mode selection errors due to crew failure to note flight mode annunciator changes. See (Palmer, 1994) for a case in which an altitude capture was killed by a mode selection in a recently changed mode configuration.

All of these predictions have the character of noticing a problem in the current interface, characterizing the situations in terms of a cognitive theory (is it a memory problem, a reasoning problem, an activation error, etc.) and then exploring design alternatives that, when characterized in terms of the theory, do not generate the earlier observed errors.

6.2. Flight test scenario

A simulated flight from SFO to LAX was designed to test the IMMI. The simulated flight includes operational contexts which have been observed in line operations to lead to various classes of mode management problems. The ATC script for the scenario is shown in Appendix 4. A description of the flight, the interventions, and the expected consequences in terms of mode management are given in Appendix 5.
7. Conclusions

The Integrated Mode Management Interface is a graphical user interface to the autoflight mode management functions of state-of-the-art airline cockpits. It is based on the design principle that the perceptual distinctions available in the appearance and behavior of the interface itself should mirror the conceptual distinctions made in the structure and function of the underlying autoflight system.

More work could surely be done on the design of the icons and the graphics. It may well be that pilots would prefer a different sort of icon set to represent the distinction between pitch and thrust modes, for example. The current design also seems visually busy. A cleaner, simpler design with a lower spatial frequency would probably be an improvement. It may even be the case that a different conceptual model would better capture the underlying distinctions that pilots need to make to reason about and control the autoflight system. Captain Jim Irving has suggested that the display should also represent the energy situation of the airplane\textsuperscript{12}. This would be especially important in an airplane like the High Speed Civil Transport.

Whatever the refinements that are made, I am confident that the principle of building an interface that provides a perceptual basis for conceptual process is correct. The IMMI is an attempt to explore the uses of that principle in the domain of autoflight mode management.

Acknowledgments:

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\textsuperscript{12} Jim Irving, personal communication, August 1994 and May, 1995.
Aircraft (through the help of William Corwin) allowed me to attend MD-80 ground school. I am grateful to American West Airlines (especially, Beth Lyall) for the full A-320 ground school.
8. References


Polson, P. Cognitive Walkthroughs.


Hardware switches, HDG SEL, and HDG HOLD

PFD announcements

Press -> HDG SEL

Press -> HDG HOLD
Available only when in VNAV on G/S. Appears as blue engine icon in the manual speed column.

PFD annunciations when icon is green:
- SPD
- LNAV
- VNAV ALT

Restriction crossed before receiving higher clearance from ATC.
Descent expedited with speed intervention

Press feature removed

PFD annunciations
HOLD | LNAV | VNAV SPD

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Appendix 2
Top Panel - Vertical display

a. Speed Tape.
Displays the appropriate range of speeds for the flight’s current operation envelope. (As determined by weight and altitude.)
b. Vertical profile display.
Displays the vertical component of the FMC entered route. Also displays manual adjustments and overrides.
c. Altitude Tape.
Always displays the complete range of altitudes for the direction of cruise. Includes a sliding virtual window that covers half of the tape in order to provide greater resolution for the 10000 feet surrounding the current altitude. See w for a more complete description.
d. Icon Column for manual speed changes.
All icons for manually adjusted speeds will appear in this column.
e. Icon Column for FMC speed changes.
All icons for either FMC controlled speeds, or FMC speed editing, will appear in this column.
f. Icon Column for FMC altitude changes.
All icons for FMC controlled altitudes will appear in this column. In general, all thrust-to target altitudes will be here, since the FMC controls thrust. (But there are exceptions, such as altitude capture or VNAV-PATH.) Pitch-to targets which are FMC entered altitude restrictions will also be here, even if a different window altitude target exists. Once the altitude target in the altitude window is captured however it will appear in the outside column, g. (see below).
g. Icon Column for manual altitude changes.
All icons for manually commanded altitudes will appear in this column, when captured. Since most altitude targets in the altitude window, although manually selected, are achieved via the FMC, their icons appear on the inside of the tape. At capture however their manual selection is recognized. Vertical speed icons will always go in this column, since they are completely manually determined. Thrust-to icons for A/T HOLD in either TO roll or descent will also go here, since
they indicate that if the pilot manually adjust the throttles the throttles will remain in place at the manual adjustment.

h. Pitch to target icon.
Engaged icons should be LARGER than armed or selectable icons.
Color: white  Condition: armed.
This means that the icon is controlled by some other action, usually via the FMC. When the appropriate conditions are met the icon will automatically engage.
Color: blue  Condition: selectable
This means that the icon represents an option that can be chosen. Touching the icon will engage that option if the conditions for engagement are met (which will usually be the case). Otherwise the icon will go to armed.
(EX. localizer, G/S icons which appear on the lateral and vertical displays respectively.)
Color: green  Condition: engaged
This means that this represents what is currently providing command guidance.
Shown are a selectable pitch-to-manual speed in the far left column, a selectable FMC computed pitch-to-ECON speed in the next column and an engaged pitch-to-path for the captured altitude in the far right column.

i. Thrust to target icon.
Engaged icons should be LARGER than armed or selectable icons. Note definitions of the conditions are the same as in h. above.
Color: white  Condition: armed.
Color: blue  Condition: selectable
Color: green  Condition: engaged
Shown are an engaged thrust-to-speed, selected by speed intervention in the inside left column and an armed thrust-to-path/altitude in the inside right column.

Color: blue  Condition: selectable
This shows the current speed of the aircraft and is associated with the pitch-to-speed icon in the manual column. The selectability is actually of the associated icon.
Color: green Condition: engaged.
Once the appropriate manual icon is selected that icon and this window changes to green to show that this is the engaged option.

k. **FMC edited speed window.**
Color: magenta.
The value in this window is always magenta so that it is clear that this is a target that edits the speed in the FMC. The airplane will follow the magenta path on the vertical profile display at the specified speed if possible.

l. **Altitude window**
Always displays the manually set altitude target, usually the last ATC cleared altitude.
This means that this is the current altitude target being flown to. It is also represented on the vertical display by a green line, n.
Color: blue Condition: selectable
Moving the knob changes the value in the altitude window and moves a line on the vertical display which represents the new altitude target. This line, m, and the number in the window, are both blue. This corresponds to a selectable pitch icon representing choices of how to meet that altitude target. When the desired icon is selected then the icon, the new altitude target in the altitude window, and it's associated line all turn green.

m. **New altitude target.**
Color: blue Condition: selectable
When a new altitude target is selected, if the previous altitude is captured, then a dashed blue line appears on the vertical display. As the altitude knob is adjusted, changing the number in the altitude window, this line moves to the appropriate spot on the display. The new altitude is engaged by touching the appropriate icon corresponding to the desired method of reaching the target altitude. Engaging the icon will change the line to green for engaged. The line for a previously captured altitude will disappear.
n. Captured altitude or engaged altitude target.
   Color: green  Condition: engaged.
   See m.

o. Current FMC route - vertical component.
   Color: magenta.
   Shows the vertical portion of the active route entered in the FMC that the
   auto pilot will fly if A/P engaged and VNAV is the active mode. In this
   case the start of the path in front of the nose of the aircraft indicates the
   top-of-descent.

p. Alternate path
   Color: blue.  Condition: selectable
   Color: green  Condition: engaged.
   Shows the vertical portion of the manual choice for ascent or descent to a
   different altitude when at a captured altitude, IF that path will be
   different from the FMC computed path. In this case the diagram
   assumes that the descent path associated with the manual pitch-to-speed
   icon is different than the FMC computed path. Note that paths
   associated with manual speed targets circumvent the FMC path and
   therefore any FMC known altitude restrictions.
   If the manual pitch-to-speed icon is selected and engaged then this path will
   change to green. The FMC computed path will remain in magenta on
   the display.

Note: behavior of lines representing paths and altitudes
   Magenta paths are always FMC controlled and solid lines.
   Captured altitudes are represented by solid green lines. Engaged altitude
   targets that have not been reached are represented by dashed green lines.
   If this altitude target will cause the aircraft to level off then the portion of
   the line that continues from the path will be solid. Eg. on the diagram if
   line m became the engaged altitude target then the portion of m near the
   letter p would change to a solid line.
   Alternate paths, other than FMC computed paths are solid lines shown in
   blue when selectable and green when engaged.

q. Crossing restriction.
Direction of arrow indicates "cross at or above" versus "cross at or below". If no arrow then it is a "cross at" restriction. Indicated in magenta to show a part of the FMC route. If one changes to amber it is a warning that the current performance of the aircraft may not meet that restriction. The first restriction that may affect the FMC path will have a horizontal dashed magenta line lining up with the altitude tape. For example, the FMC path shown here will easily make both restrictions at CZI, but the restriction to cross ROCKY @ 10000 will force the aircraft to level out, so there is a dashed magenta line.

**r. active waypoint.**
Color: green Condition: engaged.
Color: white Condition: armed.
Color: blue Condition: selectable.
Corresponds to the active waypoint on the lateral display. Green and engaged refers to the engagement of LNAV. If LNAV is not engaged because HDG-SEL is engaged, then the active waypoint is blue. If LNAV is not engaged because LNAV is armed before TO, but not engaged then the active waypoint is white.
Note: Waypoint identifiers are shown below the line delimiting the vertical display. Waypoint identifiers are assumed to be either 3-letter VOR identifiers, 5-letter intersection names, lat-long designators or fix/radial distances (eg. BLH275/075 where BLH is the VOR, 275 is the radial and 075 is the DME distance).

**s. inactive waypoint(s)**
Color: magenta.
Corresponds to the inactive waypoint(s) showing on the lateral display. Regardless of whether LNAV is or is not engaged the inactive waypoints will always show in magenta.

**Note: route mismatches on approach**
If during approach a route in the FMC does not match the displayed glide slope (G/S) for the runway then the waypoint identifiers will appear in amber as a warning that the displayed waypoints and their restrictions are not for the G/S displayed.
t. Speed knob.
To manually adjust speed.
If the aircraft has captured an altitude and a new altitude target is selected, then the current speed will appear in the manual speed window and an associated pitch-to-speed icon will appear in the far left icon column. In this case moving the knob will adjust the speed, as well as moving the appropriate icon in the manual column.
If the aircraft has captured an altitude, but no new altitude target is selected, then touching the speed knob will cause the current speed to appear in blue in the manual speed window. An associated pitch-to-speed icon will appear in the far left icon column. Moving will then change the speed that appears in that window, as well as moving the appropriate icon in the manual column.
Pushing the knob is required for speed intervention. This will cause the current speed to appear in magenta in the FMC speed editing window. An associated pitch-to-speed icon will appear in the FMC speed icon column. Moving will then change the speed that appears in that window, as well as moving the appropriate icon in the FMC column.

u. Altitude knob.
The altitude knob is used to manually adjust the altitude target. The current altitude target always appears until a new altitude target is entered. This knob changes the value in the window, as well as moves the appropriate icon in the FMC or manual column, and the altitude target line on the vertical profile display.

v. Vertical speed wheel
Touching this wheel causes a pitch-to-path icon to appear in the manual altitude icon column at the current rate of vertical change. Note: here, at level flight the appropriate icon would show 0 for no rate of vertical change.
Moving the wheel will change the rate of descent or ascent. The icon will appear next to the altitude target and the value of vertical rate will alter inside the icon as the wheel is moved.

w. Altitude resolution window
The nearest 10000 feet to the aircraft are displayed at a higher resolution than the rest of the altitudes. This virtual window moves with the
aircraft. In the scenarios the window is shifted when the aircraft is in the middle of the range. Ideally in implementation the window shifts continuously.

During approach the resolution shifts from a tick mark every 1000 feet to a tick mark every 500 feet.

x. Aircraft
Color: white. Position on the vertical display indicates the aircraft altitude.

y. Glide Slope
NOT SHOWN-
Glide slope(G/S) symbol as shown on approach plates. When the runway is entered in the FMC the G/S symbol will appear on the appropriate place on the route in blue to show that it is selectable.

When touched, the blue icon changes to white to show that the G/S is armed for capture. When the G/S signal is captured the icon automatically changes to green to show engaged. When engaged this signal controls the vertical guidance of the aircraft, so horizontal lines associated with altitude targets disappear from the display. Note: at G/S capture the altitude window can be reset to show the missed approach altitude.

Bottom Panel - Lateral display

a. Heading bug knob.
Moving the knob moves the position of the heading bug in the direction of movement.

b. Aircraft Indicator.
Color: white. Indicates the aircraft position and direction of flight.

c. FMC route.
Color: white  Condition: armed.
Shows the active route entered in the FMC that the auto pilot will fly if A/P is engaged and LNAV is the engaged roll mode. Waypoints other than the active one are in the same color as the route. The extent of the laterally displayed route corresponds to the extent of the vertically displayed route.
d. **Active waypoint.**
   Color: white Condition: armed.
   Color: green Condition: engaged.
   Color: blue Condition: selectable
   Shows the immediate target waypoint for the FMC. Distinctions between 
   armed, selectable, and engaged correspond to that described for the 
   vertical display.

e. **Heading bug line.**
   Color: white, green
   Dashed line that extends from the nose of the aircraft indicator to the 
   current position of the heading bug.
   If the heading bug is selected then this line will change to green.

f. **Heading bug.**
   Color: blue Condition: selectable
   Color: green Condition: engaged.
   When green the heading bug indicates in HDG-SEL mode. Changing the 
   bug position will result in changes in aircraft position.
   When blue the heading bug shows that HDG-SEL is available and selectable.
   In this mode moving the heading bug does not alter the aircraft's course.

g. **Current heading/track indicator.**
   Color: white.
   Always indicates the current heading or ground track being flown. Which 
   one is determined by the display mode the lateral display is in.

h. **Compass rose**
   Color: white
   Note: this rose is not an accurate 180 degrees. Rose can be displayed in any 
   of the legitimate display modes for the lateral display.

i. **Ground track indicator.**
   NOT SHOWN-
   Straight green line with arrow at the end where meets the compass rose.
   Color: green Appears only during takeoff to indicate the ground track 
   aircraft is flying for roll guidance during TOGA mode.

j. **Localizer**
   NOT SHOWN-
Localizer symbol as shown on approach plates. When the runway is entered in the FMC the localizer symbol will appear on the appropriate place on the route in blue to show that it is selectable. When touched, the blue icon changes to white to show that the localizer is armed for capture. When the localizer signal is captured the icon automatically changes to green to show engaged. When engaged this signal control the lateral guidance of the aircraft so if the aircraft was previously in heading select it is not any longer. Note: at localizer capture the heading bug automatically resets to the localizer inbound course.

**HARDWARE**
Duplicates the necessary hardware switches.

**a. Flight Director toggle switch**
Up is the on position, down is the off position. These switches must be manually flipped on in order to provide FMC generated flight director information to the primary flight displays.

**b. Auto Throttle toggle switch**
Up is the on position, down is the off position. When manually flipped this turns the auto-throttles (A/T) on and off. A/T can also be disconnected from buttons on the throttles themselves. When disconnected the toggle-switch should reset to the off position.

**c. Auto Pilot Push buttons.**
Pushing these buttons engages the auto pilot (A/P). Each button represents one of three available A/Ps. Usually the aircraft is flown with the Center (C) A/P engaged. Engaging the A/P means that the FMC computed commands are being directed to control surfaces to fly the aircraft, depending on the engaged modes. When an autopilot is engaged the button will change to green.
Appendix 3
Outcomes:
AFDS provides guidance to follow target heading.
1. HDG SEL is always available
2. Location of icon is meaningful; Action of selecting HDG-SEL mode

Notes:
bug change to selection
Numbers in heading
Display turns green
HDG target bug on lateral

Pilot
Set another target heading

AFDS
(These actions may occur in either order)

Pilot
Touch label
Target heading bug on lateral

Pilot
Set target heading

Lateral display
Front of the plane on the display

Pilot
Keep target heading bug in

NONE

Pilot
Decide to engage HDG SEL

Table:

<table>
<thead>
<tr>
<th>AFDS Constraints Source</th>
<th>Available Actions</th>
<th>System State Interpretation</th>
<th>Representation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Target heading bug on the lateral display</td>
<td>Turn aircraft to a target heading and maintain target heading</td>
<td>Goal: HDG Select</td>
<td>IM1 System Mode: HDG SEL</td>
</tr>
<tr>
<td>FMC</td>
<td>LNAV engages (Engaged)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>-----</td>
<td>------------------------</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pilot</td>
<td>If not engaging, begin diagnosing constraints are not met</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pilot</td>
<td>Still white, HDG SEL off, TOGA, maybe in white armed (white armed)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>FMC</td>
<td>Wait for engagement</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pilot</td>
<td>Touch waypoint or LNAV route decision to arm LNAV</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pilot</td>
<td>Set NM for LNAV display</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pilot</td>
<td>Route programmed route from CDU</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

---

**AFDS Source**

- **Available Actions**
  - Representation Waypoint and label on lateral display
  - Follow programmed route along lateral (N-S-E-W) headings

---

**Mode State**

- **System State**
  - Goal: LNAV
  - IMC System
  - Previous Mode
  - AFS provides guidance for airplane to follow programmed route.
  - FMA - green LNAV waypoint turn green label and active
  - Engaged

---

**Constraints**

- **AFDS State**
  - HDG hold (white armed)
  - HDG SEL or Toga, white armed (white armed)
  - Available
  - Route visible (white armed)
  - Lateral display not available
  - No route visible (white armed)
  - Lateral display available
  - Route visible and label and active (white armed)
  - Lateral display available
  - Waypoint turn label and active (white armed)
  - Lateral display available
  - Waypoint turn label and active (white armed)
  - Lateral display available
  - Waypoint turn label and active (white armed)
  - Lateral display available
  - Waypoint turn label and active (white armed)
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  - Waypoint turn label and active (white armed)
  - Lateral display available
  - Waypoint turn label and active (white armed)
  - Lateral display available
  - Waypoint turn label and active (white armed)
<table>
<thead>
<tr>
<th>AFS Constraints</th>
<th>Source</th>
<th>Available Actions</th>
<th>Mode State of System State</th>
<th>Interpretation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Runway distance from Approach within 40 miles, localizer course, 120 degrees of receive signal, enough to Aircraft close</td>
<td>Pilot/AFDS</td>
<td>Be within capture range</td>
<td>Arm</td>
<td>localizer icon turns white</td>
</tr>
<tr>
<td>Fly intercept course</td>
<td>Pilot/AFDS</td>
<td>white</td>
<td>localizer icon appears Available</td>
<td></td>
</tr>
<tr>
<td>Airspeed</td>
<td>Pilot</td>
<td>Combined approach mode</td>
<td>Local only or G/S icon to arm</td>
<td>localizer icon appears Available</td>
</tr>
<tr>
<td>Touch either local icon to arm to engage mode</td>
<td>Pilot</td>
<td>Readable scale</td>
<td>localizer icon appears Available</td>
<td></td>
</tr>
<tr>
<td>airport that shows display scale</td>
<td>Pilot</td>
<td>localizer icon appears Available</td>
<td>localizer icon appears Available</td>
<td></td>
</tr>
<tr>
<td>Not required on new radio tuning on the glare shield</td>
<td>Pilot</td>
<td>localizer frequency programmed into CDU</td>
<td>localizer icon appears Available</td>
<td>localizer icon appears Available</td>
</tr>
<tr>
<td>In 757 have to tune</td>
<td>Pilot</td>
<td>localizer icon appears Available</td>
<td>localizer icon appears Available</td>
<td>localizer icon appears Available</td>
</tr>
<tr>
<td>Entered in CDU</td>
<td>Pilot</td>
<td>localizer icon appears Available</td>
<td>localizer icon appears Available</td>
<td>localizer icon appears Available</td>
</tr>
</tbody>
</table>

**IMSI System**

**Goal**: Find and track the localizer

**Mode**: Localizer
<table>
<thead>
<tr>
<th>Signal Strength</th>
<th>AFDs</th>
<th>Localizer Mode</th>
<th>Localizer Icon</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strong Reception</td>
<td>AFDs</td>
<td>Engaged</td>
<td>Green</td>
</tr>
<tr>
<td>Weak Signal</td>
<td>AFDs</td>
<td>Engaged</td>
<td></td>
</tr>
<tr>
<td>Disarmed mode</td>
<td>Pilot</td>
<td>Touch, white icon</td>
<td></td>
</tr>
</tbody>
</table>

Outcome: AFDs provides guidance to steer to localizer heading and to then maintain that heading.
ADF provides guidance to airplane to follow ground track in flight. 
Outcome: 

Select any other roll mode. 

TogA armed. 

ADF (From Flight, G) 

TogA armed. 

ADF (From the ground, J) 

Press TOGA switch.

Pilot: 

3. Capture glide slope in high. 

2. Flaps out of np on the ground. 

1. Turn on F/D while 3 ways to arm: 

Pilot/ADF 

Outcome: 

Disengaged. 

Engaged. 

FMA for arm method J). 

FM appears in green on old system TogA just on lateral display. (In old system there is no centerline turns green. 

Arrow from runway. 

White arrow projected from runway centerline. 

Armed.
### Outcome

AFDS provide guidance to roll airplane wings level, then flys that heading when wings are level.

Level the icon gets a HDG number.

AFDS

1. HDC Hold is always available in flight.
2. Need a heading hold icon on lateral display (IMI) needs a HDG hold bug on compass rose in front of the airplane on the lateral display (icon should stay in front of the airplane on the lateral display when wings roll)

### Notes

Green two handed icon engaged

Engages HDG Hold.

- Turning on the F/D or A/P
- AP and A/P are off,
- Bank angle less than or
equal to 5 degrees and
- Pilot
- Primary method—Press
- Pilot knob
- HDG Select knob
- The head, just know.
- Knowledge pilot has in
- Available

<table>
<thead>
<tr>
<th>AFDS Constraints</th>
<th>AP Source</th>
<th>Available Actions</th>
<th>Interpretation</th>
<th>Representation</th>
<th>Mode System</th>
</tr>
</thead>
<tbody>
<tr>
<td>Goal: Maintain heading aircraft is on after wings are rolled level</td>
<td>(a) Button on Heading selector, and (b) Two handed HDG Hold Icon Holding airplane symbol</td>
<td>Available</td>
<td></td>
<td>Goal: HDG Hold</td>
<td>IMI System</td>
</tr>
<tr>
<td>Source</td>
<td>Available Actions</td>
<td>Interpretation of Mode State</td>
<td>Representation of Attitude Icon</td>
<td>Goal</td>
<td>IMU System</td>
</tr>
<tr>
<td>--------</td>
<td>------------------</td>
<td>-------------------------------</td>
<td>---------------------------------</td>
<td>------</td>
<td>------------</td>
</tr>
<tr>
<td>AFS</td>
<td>None</td>
<td>Tracking attention is required.</td>
<td>Engagement allowed.</td>
<td>None</td>
<td>None</td>
</tr>
<tr>
<td>Pilot</td>
<td>None</td>
<td>AFDs engaged.</td>
<td>AFDs engaged.</td>
<td>None</td>
<td>None</td>
</tr>
<tr>
<td>None</td>
<td>Turn on F/D or A/P</td>
<td>Engagement allowed.</td>
<td>Engagement allowed.</td>
<td>None</td>
<td>None</td>
</tr>
<tr>
<td>None</td>
<td>Engagement is required.</td>
<td>Engagement allowed.</td>
<td>Engagement allowed.</td>
<td>None</td>
<td>None</td>
</tr>
</tbody>
</table>

Outcomes:
- AFDs provides guidance for airplane to maintain current attitude.

ATT Green in FMA Display Icon on Lateral ATTitude Icon
- None
- When IMU is engaged, the F/DP should be left on. When IMU is engaged, the A/P should be left on.

AFDS
- Exceeds 5 degrees Bank Angle
- None
- Turn on F/D or A/P
- None
- Engagement is required.

PILOT
Outcome: AFDs provides guidance so airplane lands on centerline. Passengers clap. Crew welcomes passengers to beautiful San Diego.

Assume runwayHDG

AFDS

5 feet RA
Airplane descent to

Engaged
Locaizer mode

Pilot/AFDS

1500 AGL?
Airplane descent below

Not Available

Available Actions: Rollout icon appears on lateral display (heavy white line in front of airplane)

System State: Maintain airplane on runway centerline till touchdown

Goal: Maintain airplane on runway centerline till touchdown.
Outcome: AFDs provides guidance to follow target heading

Notes:
1. HDG SEL is always available
2. In any mode, at LOC capture HDG bug will go to inbound course for runway.

Set another target heading

AFDS

Iluminated
FM - Green HDG-SEL is engaged

Select switch
Push heading

Target heading window change to Numbers in MCP

Pilot

Always available

NONE

Always available

None

Table:

<table>
<thead>
<tr>
<th>Source</th>
<th>Available Actions</th>
<th>Mode State of System State</th>
<th>Inter inter</th>
<th>Interpretation</th>
</tr>
</thead>
<tbody>
<tr>
<td>AFDs Constraints</td>
<td>Target heading bug on the lateral display (LNAV, TOC, LOC) (iii)</td>
<td>Mode: HDG Select</td>
<td>Goal: Turn aircraft to a target heading and maintain target heading</td>
<td>747-400 System</td>
</tr>
</tbody>
</table>
### AFDS Operational Logic

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<thead>
<tr>
<th>AFDS Source</th>
<th>AFDS Constraints</th>
<th>Available Actions</th>
<th>System State Interpretation of Flight Mode Annunciator - LNAV</th>
<th>Goal: LNAV Mode: LNAV 747-400 System</th>
</tr>
</thead>
<tbody>
<tr>
<td>FM</td>
<td>ALT minimum 50' AGL</td>
<td>Wait for engagement</td>
<td>(while armed) Arm</td>
<td>Amended</td>
</tr>
<tr>
<td>Pilot</td>
<td>If not engaged, begin HDG SEL or TOGA, maybe in HDG HOLD,</td>
<td>FMA white on FMA</td>
<td>LNAV white on FMA</td>
<td>Available</td>
</tr>
<tr>
<td>FMC</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pilot</td>
<td></td>
<td></td>
<td></td>
<td>Available</td>
</tr>
<tr>
<td>Pilot</td>
<td>Route programmed</td>
<td>Route from CDU</td>
<td>No route visible</td>
<td>Not Available</td>
</tr>
<tr>
<td>CDU</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Outcome:**
- AFDS provides guidance for airplane to follow programmed route.
- Previous mode is disengaged.

### Pilot Diagnostics
- Course for active leg
- Airplane on intercept of programmed route
- Airplane within 2.5 NM
- Airplane

### AFDS Engaged
- FMA - green LNAV
- Engaged

### Available Actions
- Push LNAV switch
- Decision to arm LNAV

### System State Interpretation of Flight Mode Annunciator - LNAV
- Goal: Follow programmed route along lateral (N-S-E-W) headings
<table>
<thead>
<tr>
<th>Mode State of System State</th>
<th>Interpretaion</th>
<th>Available Actions</th>
<th>AFDS Constraints</th>
</tr>
</thead>
<tbody>
<tr>
<td>747-400 System</td>
<td>Loc button flowbar or approach button flowbar</td>
<td>- FMA says LOC in armed</td>
<td>- None</td>
</tr>
</tbody>
</table>
| - Loc button for either white 
- Touch either loc button to engage mode | Available | None | - 400 not required on nav radio. Tuning on the glide shield in 757 have to tune frequency programmed into CDU |
| - Pilot entered in CDU | - Pilot | | |
| - Pilot localizer frequency 
- Pilot arrival runway | Available | None | |
| - Aircraft close
- 1 20 degrees of the localizer course, receive signal enough to 
- Pilot/AFDS | Fly intercept course or localizer signal reception range | | |
| - Pilot/AFDS | Be within capture range | | - None |
| - Pilot/AFDS | Approach button and approach button or approach mode | | - None |
| - Pilot/AFDS | Arm button to arm combined 
- Pilot arm-only or approach mode | | - None |
| - Pilot | - FMA says LOC in armed | - None | - None |
| - Pilot | - Loc button for either white 
- Touch either loc button to engage mode | - None | - None |
| - Pilot | - Approach button to arm combined 
- Arm-only or approach mode | - None | - None |
AFDS provides guidance to steer to localizer heading and then to maintain that heading

<table>
<thead>
<tr>
<th>AFDS</th>
<th>Localizer engaged</th>
</tr>
</thead>
<tbody>
<tr>
<td>FMA</td>
<td>Green LOC</td>
</tr>
</tbody>
</table>

- Strong signal
  - Previous mode
  - AFDS
  - FMA engaged

- Reception
  - Weak signal
  - No actions
  - Unreliable signal error
  - AFDS

- APP mode
  - Disarms LOC or
  - Touch loc button
  - Button 1 flows bars go blank
  - FMA

- Pilot
  - Touch loc button
<table>
<thead>
<tr>
<th>AFE Source</th>
<th>Constraints</th>
<th>Available Actions</th>
<th>System State Interpretation of Mode State</th>
<th>Mode Display</th>
<th>Goal</th>
</tr>
</thead>
<tbody>
<tr>
<td>AFE/FEIS</td>
<td></td>
<td></td>
<td></td>
<td>FMA Display</td>
<td></td>
</tr>
</tbody>
</table>

**Outcome:**
- **Disengage**
- **Engaged**

**Pilot Actions**
1. Turn on F/D while 3 ways to arm.
2. Flips out of up on the ground.
3. Capture glide slope in position in flight.

**Press TOGA Switch**
- Only for arm method 1.

**Engaged (for arm methods 2 and 3)**
- None
Outcome: AFS provides guidance to roll airplane wings level, then flys that heading when wings are level.

Notes:

1. HDG Hold is always available in flight.

Engaged

AFDS roll mode
Select a different

Flownbar illuminated

Pilot needs to know mode

Pilot

Press hold button

HDG select knob

Hold button under

Always available

<table>
<thead>
<tr>
<th>NONE</th>
<th>Pilot</th>
<th>Available Actions</th>
<th>Mode State of System State</th>
<th>Interpretation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

AFDS Constraints

Source

Available Actions

Representation

Goal: HDG Hold

Flight plan hold, HDG Hold

Maintenance: HDG Hold is on after wings are rolled level.
<table>
<thead>
<tr>
<th>Outcome: AFDs provides guidance for airplane to maintain current attitude</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Exceeds 5 degrees</strong> Bank Angle AFDs <strong>ATT Green in FMA Engaged</strong></td>
</tr>
<tr>
<td><strong>Exceeds 5 degrees</strong> Bank Angle Pilot Turn on F/D or AP None Available</td>
</tr>
<tr>
<td><strong>None</strong> Pilot angle exceeds 5 degrees F/D and A/P off and bank None Not Available</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Constraints</th>
<th>Source</th>
<th>Available Actions</th>
<th>System State</th>
<th>Interpretation of Mode State</th>
<th>Representation: None</th>
</tr>
</thead>
<tbody>
<tr>
<td>AFDs</td>
<td>Goal: Maintain airplane's current roll attitude</td>
<td>747-400 System</td>
<td>Mode: Attitude</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
passengers to beautiful San Diego.

AFDS provides guidance to airplane lands on centerline. Passengers clap. Crew welcomes

Assume runway HDG

AFDS

5 Feet RA

Airplane descent to

FMA - green "ROLLOUT"

Engaged

Engaged

Localizer mode

Pilot/AFDS

1,500' AGL

Above green "LOCALIZER"

Airplane descent below

White "ROLLOUT" appears on FMA

Arm

Airplane is within 5

Feet RA

None

Not Available

Interpretation of

Available Actions

System State

Mode State

Mode State

Representation

AFDS Constraints

Source

Maintain airplane on runway centerline till touchdown (autoland)
Outcome: FMC provides guidance to follow VNAV route with pitch to path

Change altitude

VNAV Hoverbar

Pitch

Select a different vertical mode

Engaged

FMA "VNAV" transition

None if automatic mode

Armed

If not engaged begin diagnosis

Waiting for engagement

Available

Push VNAV button

FMC

Route programmed in FMC

"Pathable" below current altitude at

distance of current altitude or

above and within capture

Pilot

Pilot

Make next waypoint restriction

Not available

Available

Source AEDS Constraints

Available Actions

System State Interpretation of

Representation: VNAV low bar (any VNAV armed or engaged), while or green FMA "VNAV SPD"

Goal: Follow FMC vertical route (pitching to FMC speed)

Mode: VNAV Path

747-400 System
Outcome: FMC provides guidance to follow window altitude with pitch to path and A/L to FMC speed

Another mode is engaged:
- Affected airplane behavior until change altitude window (does not intervene)
- Change altitude window with speed
- Select a different vertical mode

Pilot

FMC

Route programmed in FMC

FMC

If not engaged begin diagnostics

Pilot

Wait for engagement

FMC

Pilot

Push VNAV button

Available

None

Active

Armed

There is an automatic mode

Pilot

Airplane altitude from airplane

Source APDS

Available

Not Available

Representation: VNAV flow bar (any VNAV armed or engaged), while or green FMA "VNAV ALT" Goal: Pitch to captured altitude with A/L to FMC speed

Mode: VNAV ALT

47-400 System
Outcome: APDS provides guidance to get airplane away from the ground.

**PFD - Green TOGA**
Engage any other pitch mode APDS Toga armed

**FMA - Green TOGA**
Available

For trim methods 2 and
None

Arrow (only for trim)

Press TOGA switch FMA - Green TOGA
Available

Pilot AFDS / Piler 3. Capture glide slope in higher
AFDS / Piler 2. Place out of up position in
Pilot ground
Pilot 1. Turn on F/D while on the
3 ways to arm:

Source AFDS Constraints
Available Actions

Not Available System State: Mode State
Interpretation of Representation: Up angled arrow on the VPD

Goal: Get the airplane away from the ground.
If vertical speed window is set to 0 then mode maintains current altitude.

**Outcome:** AFDs provides guidance to maintain vertical speed.

**Note:** 1. Always available

**Change altitude (before capture)**
- Change vertical speed
- Change airspeed

**Select a different vertical mode**

<table>
<thead>
<tr>
<th>Mode</th>
<th>Source AFDs Constraints</th>
<th>Actions Available</th>
<th>System State</th>
<th>Interpretation of Representation: V/S flow bar (engaged), green VMA &quot;V/=S&quot; is open and 600 KIAS is open if locked</th>
</tr>
</thead>
<tbody>
<tr>
<td>None</td>
<td></td>
<td></td>
<td></td>
<td>V/S lower: engaged, V/S never be in head)</td>
</tr>
<tr>
<td>Pilot</td>
<td></td>
<td></td>
<td></td>
<td>V/S never be in head)</td>
</tr>
</tbody>
</table>

**Target V/S (when V/S window always show numbers in MCR)**

**Always available**

**Mode Vertical Speed**

**Goal:** Achieve and maintain vertical speed in MCP window
Outcome: AFDS provides guidance to keep aircraft on final approach to runway.

Engaged: AFDS engaged until another mode is activated.

Change Mode:
- Change altitude (will not affect pitch or V/S)
- Select a different vertical mode

Pitch or V/S into ALT

Automatic mode transition from None

Available: none

In Pitch or V/S

Approach window altitude while None

Not Available: none

System State

Mode State Interpretation of

Available Actions

AFDS Constraints

Source

Goal: Maintain aircraft altitude at window altitude Model: Alt System 47-400
Outcome: AFDs provides guidance to maintain altitude which was published at (mode engages immediately).

1. Alt Hold is always available in flight.

Notes:

Engaged until another mode is not achievable or performance changes the altitude window (will change the speed of the aircraft) according to the vertical mode.

To change the vertical mode:
- Select a different vertical mode on the FMA.
- Press the HOLD button under Alt.

Available Interpreted:
- Pilot needs to know the current mode and its available vertical modes.
- Indicates that the mode is always available.
- Selecting HOLD while in Alt mode.

System State:
- When HOLD is pressed, the system stops changing the altitude and maintains the current altitude.

Available Actions:
- Pilot needs to press the HOLD button under Alt to engage HOLD mode.

Source: AFDs Constraints

Representation: When the HOLD mode is engaged, the AFDs displays the current altitude and the mode engaged.

Goal: Maintain altitude at altitude switch is pressed at 747-400 System
Outcome: FMC provides guidance to follow VNAV route with pitch to path

Change altitude

"PTF"

Green FMA "VNAV"

Altitude column

Altitude speed with speed

Pilot

Select a different vertical mode

Unengaged

(transition)

If not engaged begin diagonal

Pilot

Wait for engagement

FMC

Altitude column

Touch blue pitch icon in FMC

Available

Route programmed in FMC

FMC

"Pathable"

(below current altitude and
distance of current altitude or
above and within capture

Pilot

Make next waypoint restriction

Source

APDS Constraints

Available Actions

System State

Mode: VNAV system

Representation: Pitch icon in FMC altitude column, while or green FMA "VNAV SPD"

Goal: Follow FMC vertical route (pitching to FMC speed)

IMI System
Outcome: FMC provides guidance to get near next FMC restriction altitude or FMC path (not really MVM) and then calls

<table>
<thead>
<tr>
<th>Action</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Change altitude</td>
<td>Select a different vertical mode</td>
</tr>
<tr>
<td>Change speed with speed intervention</td>
<td></td>
</tr>
<tr>
<td>Pilot</td>
<td>Green FMA &quot;VNAV&quot; speed column</td>
</tr>
<tr>
<td></td>
<td>(none if automatic mode)</td>
</tr>
<tr>
<td></td>
<td>Engaged</td>
</tr>
<tr>
<td></td>
<td>FMC speed column</td>
</tr>
<tr>
<td></td>
<td>wait for engagement</td>
</tr>
<tr>
<td></td>
<td>blue pitch icon in FMC</td>
</tr>
<tr>
<td></td>
<td>available</td>
</tr>
<tr>
<td>Pilot</td>
<td>FMC speed column</td>
</tr>
<tr>
<td></td>
<td>Touch blue pitch icon in FMC</td>
</tr>
<tr>
<td></td>
<td>available</td>
</tr>
<tr>
<td>Route programmed in FMC</td>
<td>FMC speed column</td>
</tr>
<tr>
<td></td>
<td>not able to maintain path</td>
</tr>
<tr>
<td></td>
<td>Or both: (a) below current altitude and</td>
</tr>
<tr>
<td></td>
<td>(b) not within capture distance</td>
</tr>
<tr>
<td></td>
<td>Both: (a) above current altitude and</td>
</tr>
<tr>
<td></td>
<td>(b) not within capture distance</td>
</tr>
<tr>
<td></td>
<td>Make next waypoint restriction be:</td>
</tr>
<tr>
<td></td>
<td>FMC speed column</td>
</tr>
<tr>
<td></td>
<td>Not available no blue pitch icon in</td>
</tr>
<tr>
<td></td>
<td>System busy</td>
</tr>
<tr>
<td></td>
<td>Mode State</td>
</tr>
<tr>
<td></td>
<td>Interpretation of</td>
</tr>
<tr>
<td></td>
<td>Available Actions</td>
</tr>
</tbody>
</table>

**Source**

System State: 

Representation: FMC icon in FMC speed column, while or green FMA "VNAV SPD"

Goal: Follow FMC vertical route (pitch to a speed)

IMI System: "VNAV SPD"
Outcome: ADFs provides guidance to get near window altitude and then it calls ALT mode opens as feedback manual speed column

Green PMA "P/ACH"

manual speed column

Pilot selects a different vertical mode green pitch icon in engaged.

Change altitude (before capture)

Speed window above

Pilot (if window alc is very close to current)

Changes to ALT (second then mode automatically all then P/ACH engages for only a)

Touch blue pitch icon in manual speed column

Available

Not available

System State

Mode: P/CH

Available Actions

Representation: pitch icon in manual speed column, green PMA "P/ACH"

Goal: Reach and maintain window altitude (prior to manual speed)

ADF Constraints
**Outcome:** AFDS provides guidance to get airplane away from the ground.

<table>
<thead>
<tr>
<th>AFDS</th>
<th>TOGA armed</th>
<th>ADI</th>
<th>Engage any other pitch mode</th>
<th>FMA - green TOGA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pilot</td>
<td>Press TOGA switch</td>
<td></td>
<td>Available</td>
<td>Engaged</td>
</tr>
</tbody>
</table>

1. **AFDS Switch**: Engage TOGA armed mode.
2. **Flight**:
   - Press TOGA switch in flight.
3. **Flight**:
   - Engage TOGA armed mode in flight.

---

**Goal**: Get the airplane away from the ground.

**Available Actions**:
- 1. Turn on F/D while on the ground.
- 2. Press TOGA switch in flight.
- 3. Capture glide slope in flight.

**AVFS Constraints**:
- 4. None
- 3. None
- 2. None
- 1. None

**Mode Stake Interpretation of**
- Not available

**AFDS Source**
- Available AFDS

**System Stake**
- Mode: TO/GA - Pitch

**Representation: FMA display**
- 747-400 System
If vertical speed window is set to 0 then mode maintains current altitude.

Outcome: AFDS provides guidance to maintain vertical speed.

Note: 1. Always available (by a two step process)

<table>
<thead>
<tr>
<th>Source</th>
<th>AFDS Constraints</th>
<th>Available Actions</th>
<th>Interpretation of Mode State</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Change altitude (before capture)
Change vertical speed
Change speed
Pilot

Select a different vertical mode
Pilot

Green FMA "V/S"

Green arrow attached in Pitch icon

Choose mode (touched)
Appeared when wheel was touched
(1) Touch V/S while then
(2) Touch blue V/S icon (that
window always show numbers in)

System State
Always Available

Representation: Pitch icon with arrow attached, green FMA "V/S"
Outcome: AFDs provides guidance for airplane to follow window altitude

FMA - Green ALT

Change airplane until another mode is engaged
Change altitude (will not affect manual speed column

Pitch or V/S into ALT
Automatic mode transition from

None

Pitch or V/S
Approach window altitude while

Mode State
Interpretation of

Not Available

Source AFDs Constraints
Available Actions

Goal: Maintain artificial window altitude
Representation: Pitch icon in manual altitude column with engine icon in manual speed column
Outcome: AFDs provides guidance to maintain altitude which was pushed at (mode engages immediately)

Pilot

- Select a different vertical mode
- Change the speed
- Engaged

PMA - Green ALT
- Green altitude knob is in center of PMA
- System state available

Pilot

- Press blue button in center of G/S mode
- Get out of combined LOC and IMI
- System state not available
- Mode: ALT (HOLD)

Available Actions

Source A/PDs Constraints
Appendix 4
IMMI - SFO to LAX

ATC Script

This is a flight starting at the holding short position of runway 01R at the San Francisco International Airport. The crew will enter the flightdeck with engines running. All checklists through the Before Take-off Checklist will have been completed. The only preflight tasks to be performed by the crew will be set up of the MCP and loading the FMC. After obtaining ATC clearance, they will takeoff and proceed to the Los Angeles International Airport via a normal routing. There will be no malfunctions along the way.

**IP 1** SFO RWY 01R
N 37.605
W 122.381666
HDG 130
Altitude 11 ft.

Initial Conditions:
GW - 190,000 lbs. (ACFS) 620,000 lbs (747)
Fuel - 30,000 lbs. (ACFS) 100,000 lbs (747)
Altimeter - 29.92
Wind - 0/0

Weather:
SFO - Clear, 50 nm vis
Enroute - Clear, 50 nm vis., TURB - Level 4, FL280 thru FL360
Level 1 at FL370
LAX - Clear, 50 nm vis. CIG1500 OCST 5 FZ TOPS REPTD 3500

**Airborn IP**

This is a flight starting at approximately 50 nm prior to top of descent for the SADDE 5 arrival for Los Angeles International Airport. The only preflight tasks to be performed by the crew will be set up of the MCP and loading the FMC. After obtaining ATC clearance, they will proceed to the Los Angeles International Airport via a normal routing. There will be no malfunctions along the way.

**IP 2** APPROX 50 nm prior T/D
N 35.750
W 120.016666
HDG 130
Altitude FL330
Speed/Mach 0.82

Initial Conditions:
GW - 190,000 lbs.
Fuel - 30,000 lbs.
Altimeter - 29.92
Wind - CALM
ATC PHRAESEOLOGY

(After crew calls for clearance)

SFO CLR: NASA8001 is cleared to the LAX airport via the Porte 9 departure, Ave transition, flightplan route. Maintain FL230, expect FL330 10 minutes after departure. Departure frequency will be 135.1, squawk 3724. Do not exceed 250 knots until advised.

(After the crew calls for takeoff)

SFO TWR: NASA8001, amend your clearance, cross Porte above 9000 and below 11000 feet. Taxi into position and hold, RWY 1R.

(Give the crew time to enter the alt and take position)

SFO TWR: NASA8001, wind calm, cleared for takeoff

(When the cab leaves 500)

SFO TWR: NASA8001, contact Bay Departure

(After crew calls)

BAY DEP: NASA8001 Bay Departure, Radar contact. Maintain 6,000

(When cab's heading is 200)

BAY DEP: NASA8001, turn right to 230, left to 180 for spacing

(After 30 seconds)

BAY DEP: NASA8001, turn left right to xxx, intercept and resume the Porte 9 departure

(As cab approaches 6,000 3,500)

BAY DEP: NASA8001, cross Porte at or below 11,000, climb unrestricted and maintain 15,000

(As cab approaches 10,000)

BAY DEP: NASA8001, contact Oak Center on 125.45

(After crew calls)
OAK 12L: NASA8001 OAK CENTER, ROGER

(As cab approaches 15,000)

OAK 12L: NASA8001, CLIMB AND MAINTAIN FL240, RESUME NORMAL SPEED

(As cab approaches 20,000)

OAK 12L: NASA8001, CONTACT OAK CENTER ON 133.7

(After crew calls)

OAK 15H: NASA8001, CLIMB AND MAINTAIN FL290, EXPEDITE THROUGH FL240 FL250

(At 25,000)

OAK 15H: NASA8001, CLIMB AND MAINTAIN FL370 - TURBULENCE

(At OAK/LAX border)

OAK 15H: NASA8001, CONTACT LAX CENTER ON 124.15

(After crew calls)

LAX 26H: NASA8001 LAX CENTER FL370 ROGER

(At .84)

Note for the researchers: the ACFS is unable to attain a speed in excess of Mach .85

LAX 26H: NASA8001, CLEARED FOR THE SADDE 5 ARRIVAL. DESCEND AT PILOT'S DISCRETION, CROSS SIMON AT AND MAINTAIN 12,000. BEGIN YOUR DESCENT AT THE FIM 64 DME, AT 280 KNOTS, LAX ALTIMETER 29.92

-OR-

(Between .82 and .84)

LAX 26H: NASA8001, CLEARED FOR THE SADDE 5 ARRIVAL. CROSS SIMON AT AND MAINTAIN 12,000. BEGIN YOUR DESCENT AT THE FIM 58 DME, AT 280 KNOTS, LAX ALTIMETER 29.92
LAX 26H: NASA8001, CLEARED FOR THE SADDE 5 ARRIVAL. CROSS SIMON AT AND MAINTAIN 12,000. BEGIN YOUR DESCENT AT THE FIM 50 DME, AT 280 KNOTS, LAX ALTIMETER 30.01

(When cab approaches 24,000)

LAX26H: NASA8001, CONTACT LAX CENTER ON 132.6

(After crew calls)

LAX14L: NASA8001 FLxxx, ROGER

(When cab passes 13,000)

LAX14L: NASA8001 CONTACT SOCAL APPROACH ON 124.5

(After crew calls)

SOCAL APP: NASA8001 SOCAL APPROACH ROGER, CROSS SADDE AT 250 KNOTS AND BAYST AT 10,000

(When cab passes SADDE)

*Note for the researcher: If the crew loads and executes the ILS 24R, they will be unable to change to an ILS 25L.*

SOCAL APP: NASA8001, DEPART SMO HEADING 070 FOR VECTORS TO THE FINAL APPROACH COURSE. BE ADVISED, EXPECT ILS 24L-R APPROACH. IF 25L BECOMES AVAILABLE, I WILL CHANGE YOUR RUNWAY.

(When cab passes BAYST)

SOCAL APP: NASA8001, REDUCE SPEED TO 200

(When cab passes SMO)

SOCAL APP: NASA8001, DESCEND AND MAINTAIN 5,000

(When cab passes 6,000)

SOCAL APP: NASA8001 REDUCE SPEED TO 180
(When cab approaches FANGY is 1 mi east of SAPPI)

SOCAL APP: NASA8001, TURN RIGHT HEADING 160, FOR VECTORS TO THE FINAL APPROACH ILS 25L, 24R. DESCEND AND MAINTAIN 4,000

(As cab passes 4,500)

SOCAL APP: NASA8001 REDUCE SPEED TO 170

(When cab approaches final)

SOCAL APP: NASA8001, xx MILES FROM LIMMA ROMEN, TURN RIGHT HEADING 220, MAINTAIN 3,000 4000 UNTIL ESTABLISHED ON THE LOCALIZER, CLEARED FOR ILS25L ILS24R APPROACH

(When LOC and G/S have engaged)

SOCAL APP: NASA8001, xxx MILES FROM LIMMA, TURN LEFT HEADING 220 VECTOR FOR THE ILS25L LOCALIZER, MAINTAIN 3000 UNTIL ESTABLISHED, CLEARED FOR THE ILS25L APPROACH.

(When cab is on final)

SOCAL APP: NASA8001, MAINTAIN 170 KNOTS TO LIMMA, CONTACT LAX TOWER ON 120.95

After crew calls)

LAX TWR: NASA8001 LAX TOWER, WIND CALM, CLEARED TO LAND 25L

(When cab approaches taxi speed)

LAX TWR: NASA8001 JUST STOP ON THE RUNWAY
Appendix 5
SCENARIO

SFO - LAX

SFO..PORTE9.AVE.FIM.FIM6..LAX
FL 330 (note this FL is lower than the final ATC clearance. We are looking for a problem here.)

Departure Clearance

CLDR:
"NASA eight hundred is cleared to the Los Angeles International Airport as filed, on departure fly heading 281 to the Porte 9 departure cross Porte above niner thousand and at or below one one thousand, climb and maintain six thousand, expect higher one zero minutes after departure, do not exceed two hundred fifty knots until advised, departure frequency will be one twenty one point three, squawk 3654."

or, if Departure Clearance by ACARS:

**DPTR CLRNC**
FLT 800 SFO - LAX
NASA800 KSFO /B757/ P1815 RQ330
XPDR 3654
MAINT 6000 CROSS PORTE ABOVE 9000 AND BELOW 11000 EXP REQ ALT 10 MIN
AFT T/O
GND CTL FREQ 121.8
/DPTR CTL SEE SID
DO NOT EXCEED 250 KTS UNTIL ADVISED
EXPECT RWY 28L DEPT KSFO.PORTE9.AVE.FIM.
FIM6..LAX

A/C Call for push back clearance

Ground:
"NASA eight hundred, clear to push"

A/C Call for taxi clearance

Ground:
"NASA eight hundred, taxi to runway 28L via the inner and Foxtrot." [Note: 747-400s are restricted from using taxiway E to or from taxiway B]

Normal takeoff clearance.

After Takeoff and prior to 1000':
"NASA 800 contact departure"
NASA 800 checks in with departure "......"

"NASA 800 Bay departure radar contact"

Radio chatter from other pilots in area ......

We expect the crews to be flying in LNAV and VNAV with A/P engaged before reaching the first turn point.

The SID calls for a 101 degree left turn.

Upon rolling out on the 180 degree heading

"NASA eight hundred, turn left 10 degrees for traffic."

30 seconds later

"NASA eight hundred, resume the Porte 9 departure."

What we expect to see:

MCP: Possible engagement of heading select with the heading bug behind the airplane.

IMMI: Pilot has to find the heading bug in order to engage the mode. Can't make this mistake on our interface.

Rationale: It's been observed in training and from the jumpseat. It will be important to keep the crew busy looking for traffic while the airplane is making the turn in LNAV.

(set up an unexpected VNAV level-off)

Out of 5000'

"NASA 800 climb unrestricted to one five thousand;"

What we expect to see:

MCP: We have now set up the analog of the Pebble departure from SAN. They will put 15000 in the window, but an at-or-below altitude restriction remains at PESCA. May see an unexpected level off. It will be essential to have the performance characteristics worked out so that the airplane will reach 10000 prior to Porte. Since Porte normally required at-or-above 9000, this should be assured in a light 747-400.

IMMI: The vertical path display should make the level-off apparent.

(hand off to Center)

Out of 11000'

"NASA 800 contact Oakland Center on 125.45"

(clearance higher)

Let them level at FL150

When level at FL150

"NASA 800 climb and maintain FL290"

(set up wingtip LNAV)

after crossing Porte

"NASA 800 turn left 20 degrees for traffic" (to 115)

This has the effect of cutting the Pesca waypoint corner of the route

(wingtip LNAV)

When almost abeam of Pesca

"NASA 800, traffic no factor, resume the Porte 9 departure, thanks for
your help."

What we expect to see:

MCP: Possible engagement of LNAV with active waypoint abeam. This produces a steep right turn toward Pesca when pilots expect a shallow left turn to line up with Wages waypoint in front of them.

IMMI: Pilots have to find the active waypoint to engage the mode. It should be obvious that it's off the end of the wing. So, they go to CDU and make the next wpt active, then engage it.

Rationale: MCP LNAV is a "meta-button." It has no content. IMMI's engagement operation requires the pilot to interact with the spatial meaning of the operation.

==================== (hand off to Center 2)
Out of FL210
"NASA 800 contact Oakland Center on XXXXX" (<- need freq)

A/C "Oakland Center NASA 800, out of 220 for 290."

==================== (Center 2 pick up and expedite climb)
"NASA 800 roger, expedite your climb through FL240."

Features: Speed intervention is not shown as available on either interface. The (someday) blue speed select button on the IMMI gives a clue that something is available there. Two problems here. 1) Getting a mode or sub-mode that will control speed. 2) What is the 'best rate of climb' speed right now?

What we expect to see:

MCP: "how do I find that? 250 ought to be about right." The right way to do it is to go to the VNAV page in the CDU. Field 6R of the VNAV page shows Vx. And from school you remember that you can get a good approximation of Vy by adding 25 Knots to Vx.

IMMI: If they can get into speed intervention, setting the icon next to the Vy bug should be easy.

==================== (resume normal speed, final alt clearance)
out of FL250
"NASA 800
------
resume normal speed, (if pilots forgot to resume on own)
------ (or)
climb and maintain FL370
thanks for your help."

==================== (possible unexpected level off at cruise)
Final clearance is higher than initial clearance entered into CDU as cruise altitude. This is a hidden state in the MCP system.

What we expect to see:

MCP:
Expect that the pilots may not edit the cruise page in the CDU to reflect the final ATC clearance, and will be surprised when the airplane levels prior to the altitude in the MCP window.

IMMI:
Expect that the pilots will notice the magenta line levels prior to the window altitude line and they will edit the CDU to change cruise altitude to reflect the final ATC clearance.
(Descent Clearance:

"NASA 800 cleared for the Runway 24/25 Profile descent"

(Over Speed lose path)
During descent a tail wind forces the airplane to use higher and higher speeds to stay on the path. As the airspeed approaches the top of the operating envelope, the FMC abandons pitching to the path with VNAV PATH and instead pitches to a speed with VNAV SPD.

What we expect to see:

MCP:
(a) scratch pad message "drag required", (b) overspeed warning boxes on PFD airspeed tape move toward the current airspeed marker, (c) FMA's change from VNAV PTH to VNAV SPD. The pilots may not notice these changes and the mode transition.

IMMI:
(a) VPD predicted path will diverge from the FMC path at the 4D point of the expected mode transition, (b) the IMMI current airspeed window will climb up on the speed tape toward the overspeed warning area, (c) the pitch to path icon will turn amber, (d) the pitch and engine icons will swap sides of the IMMI when VNAV PTH changes to VNAV SPD, (e) all the changes above for the MCP will also occur. We expect the pilots will notice these changes before the mode transition occurs.

More clearances need to be written here for standard descent.

Los Angeles Airport information Sierra, 1650 zulu. ...

Somewhere in here
"Expect runway 24R."

East of Santa Monica:
"NASA 800 descend and maintain 5000"

Over downtown:
"NASA 800 turn right heading 160 descend and maintain 4000"

Expect to see: use of V/S to make a smoother descent from 5000 to 4000. The IMMI will have the opportunity to show its awkward V/S interface which may be harder to use than the -400.

Turn inbound
"NASA 800 turn right heading 220 vector to the runway 24R localizer, cleared for the runway 24R approach."

The vectors, altitudes, and approach clearance must be given in such a way that LOC and G/S can engage well outside the outer marker. The altitude of the glideslope at Merce is 4783 MSL. Joining the localizer at 4000 will lead to G/S intercept about 6 miles outside of Romen. Once the aircraft is locked in on 24R, ATC calls for a runway change. (This works in the Boeing Datalink study scenario, consult that for details).

"NASA 800, 24R glideslope signal is fluctuating, turn left to heading 220 vector for the Runway 25L localizer, cleared to land, runway 25L."

Expect to see:

BOTH:
Difficulties in disengaging from the LAND configuration

MCP:
No indication that TOGA is the only mode available.

IMMI:
Information available perceptually that no modes - except TOGA - are available (no blue on the screen). This should help crews remember that they have to disengage everything to get another pitch or roll mode.

On 1 mile final, another aircraft moves onto the runway.
"NASA 800 go around fly the published missed approach.
A/C acknowledge
"NASA 800 contact departure on 124.3"
A/C "Departure, NASA 800, missed approach off 25L"
"NASA 800 climb and maintain 3000 proceed to the INISH intersection as published hold west on the SEAL BEACH 251 degree radial, left hand turns."

Release from hold and normal landing on 25L