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Flight crew and aircraft performance during RNAV approaches: studying the effects of throwing new technology at an old problem

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Abstract

Non-precision approaches (without vertical guidance) are known to expose aircraft to greater risk of CFIT (controlled flight into terrain). One solution consists of RNAV (area navigation) approaches with a computer-generated lateral and vertical path, which use the aircraft's flight management computer to fly an approach without any conventional ground-based radio facilities. We studied 22 pilots who flew 66 real RNAV approaches. Of special interest to us were the human factors and safety implications of using this new technology for an old problem. The high level of automation used for RNAV approaches brings with it a new potential for automation surprise (e.g. unexpected level-offs at go-around altitude) and extra monitoring requirements, especially for the pilot-not-flying. There is also an effect of low temperature that makes for shallower approaches as compared to ILS (instrument landing system). Pilot acceptance of RNAV approaches as measured in this study is high, and perceived mental workload for both pilot flying and pilot not-flying is low. This can be explained in large part by the shift from double-checking height against distance in traditional non-precision approaches, to pattern matching (aircraft symbol/reference) during RNAV approaches.

Introduction

Airlines are increasingly seeking ways to improve operational reliability, even at airports without conventional ground-based navigation aids. A promising technological possibility today consists of area navigation (RNAV) approaches, where the aircraft follows a lateral and vertical track towards the runway that is computed and flown by on-board flight management and guidance systems. Non-precision approaches (i.e. towards runways not equipped with vertical descent guidance such as or instrument landing systems (ILS), carry a higher CFIT (controlled flight into terrain) accident risk than precision approaches (Russell, 1994), which means that RNAV approaches to non-ILS equipped runways could carry safety benefits as well. Using new technology for an old aerospace problem however, always has reverberations for pilot roles, responsibilities, tasks, workload distribution and co-ordination requirements (Billings, 1997; Dekker and Hollnagel, 1999). The study reported here not only set out to validate RNAV approaches as accurate (and safe), but to investigate the human factors implications, especially in terms of workload effects and procedural requirements.

RNAV stands for area navigation. The method was developed during the 1980s and permits aircraft operation on any desired flight path irrespective of ground based radio navigation facilities. Modern flight management systems (FMS) are now used for RNAV operations. The FMS is a very capable aircraft navigational computer and the FMS in some aircraft is also capable of generating a vertical path between waypoints that can mimic the ILS vertical beam (this is called a Baro-VNAV or vertical path). The vertical path is constructed through barometric altitude constraints over the waypoints in the FMS navigation database. Thus a Baro-VNAV vertical path differs from an ILS glidepath because cold ambient air temperature will make the Baro-VNAV approach vertical path shallower. The reverse is also true: high ambient air temperature will make the Baro-VNAV approach vertical path steeper, but this is not critical for obstacle clearance in the approach sector.

RNAV approaches have been tried almost since the advent of FMS equipment. Alaska Airlines pioneered RNAV operations in Juneau, Alaska and other US operators have used the LNAV and VNAV Automatic Flight System modes to fly conventional non-precision approaches since the introduction of B757 and B767 (Boeing, 1982). Lufthansa used GPS to fly approaches with the A320 family (Airbus, 1996). However, the vertical path for approaches did not address the temperature effects on the vertical path with these types of approach. The Brazilian operator VARIG conducted trials for approaches and missed approaches, using curved paths into the domestic airport of Rio de Janeiro (de Abreu, 2000). Some Flight Management Systems are also capable of guaranteeing a maximum lateral error. These are capable of so-called required navigation performance (RNP) RNAV operations. Using RNP RNAV, the obstacle clearance surfaces can be narrower than for existing surfaces associated

with ground based VOR or NDB procedures. Narrower obstacle clearance surfaces may lead to lower minimum descent heights for RNAV approaches, making them still more attractive for airlines aiming for higher regularity into smaller airfields. Thus, there is a considerable pressure to develop and fly RNAV approaches for both flight safety and commercial reasons.

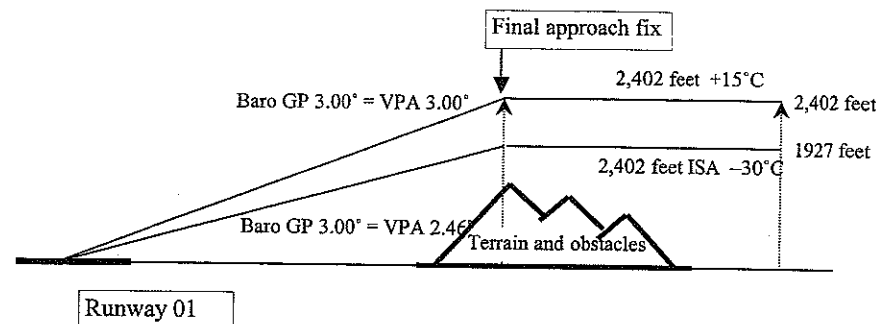


Figure 1 Example of how low ambient temperature effects the Baro-VNAV Final Approach surface to runway 01L at Stockholm-Arlanda. With an ambient temperature of 30°C the pressure altimeter would show 2,402 feet above the threshold elevation. The aircraft is only 1,927 feet above threshold elevation. The aircraft would fly a 2.46° vertical path instead of a nominal 3.00° vertical path

Redistribution and transformation of work with new approach technologies

The change from flying a non-precision approach without a reference glidepath, to flying an RNAV approach using a FMS computer-generated path produces shifts in flight crew work. With a reference glidepath, a previous task (matching altitude and distance to runway) is changed into a perceptual task (matching the aircraft own symbol to the reference glidepath on the primary flight display). This change should, in principle, produce lower pilot mental workload (cf. Hutchins, 1995). But there are other changes too. The computer-generated reference glidepath of an RNAV approach presents a linear deviation of feet above or below the reference glidepath. The conventional ILS glidepath presents angular deviations in degrees above or below the reference glidepath. The flight instrument symbology during both RNAV and ILS approach is similar to the pilot, but s/he has to make different corrections to a similar deviation indication, depending if s/he is flying an RNAV or an ILS approach. The RNAV trials in the study reported here were flown with the autopilot engaged, which may have mitigated the effects of the degree-to-feet

deviation indication change. On the other hand, high levels of automation produce greater monitoring requirements (Parasuraman, 1996); they can lower process observability, increase the risk for surprising system behaviour (Billings, 1997) and drive up crew co-ordination requirements (Dekker and Hollnagel, 1999).

To date, the literature has not reported any systematic assessment of the human factors implications of using RNAV technology for an old problem (flying non-precision approaches as if they were precision approaches), neither with respect to the effects on flight crew workload or co-ordination, nor with respect to formulating safe and useful cockpit procedures. For this purpose, we were particularly interested in the flight crew's perceived mental workload, and ways in which both flight deck procedures and approach procedures can be designed to generate maximum operational and safety leverage with RNAV approaches. While one purpose of this study was to determine whether RNAV approach operations with a Baro-VNAV would produce a highly reliable (i.e. replicable) flight path pattern, the other purpose was to explore appropriate flight deck procedures and to try to locate potential vulnerabilities in RNAV approach procedures.

Method

Studying real aircrews, flying real approaches on normal flights, we set out to study the effects of RNAV approaches, not only in terms of navigational accuracy, but also in terms of their implications for flight crew work. Thirty-seven volunteer pilots (17 captains and 20 first officers) from one airline were selected from three crew bases and trained for RNAV approach operations. All 37 pilots held a valid type rating and flew as line pilots on the B737-New Generation (600-700-800). They were familiar with the trial airport, Stockholm-Arlanda (ESSA), but had no previous experience of RNAV approach operations. The selected crews were specially trained for RNAV approach operations, using a two-hour theoretical briefing on RNAV operations, RNP concept, RNAV approach procedures, flight deck procedures and conditions to conduct trial approaches. This theoretical briefing was followed by a two hours hands-on session in a fixed base simulator. Trained RNAV flight crews always flew the approaches together.

Our study used the B737-600/700/800 aircraft equipped with a flight management computer system (FMCS). The FMCS uses the global positioning system (GPS) satellites for position update and is capable of complying with a required navigational performance (RNP) of 0.11 Nm. In flight, the FMCS position is continually updated from GPS, ground based radio navigation aids and the aircraft's inertial reference system (IRS). No alteration to the standard line configuration of the aircraft was performed.

The RNAV approach procedure (which is the prescribed lateral and vertical flight path) was constructed as a physical overlay to the existing ILS procedures. RNAV approach procedures with Baro-VNAV vertical path were constructed to runways 01

and 19 using the proposed international construction criteria available at that time.¹ The respective RNAV approach procedure for these two runways were tested for flyability in a B737-700 simulator under both cold and hot temperature conditions.

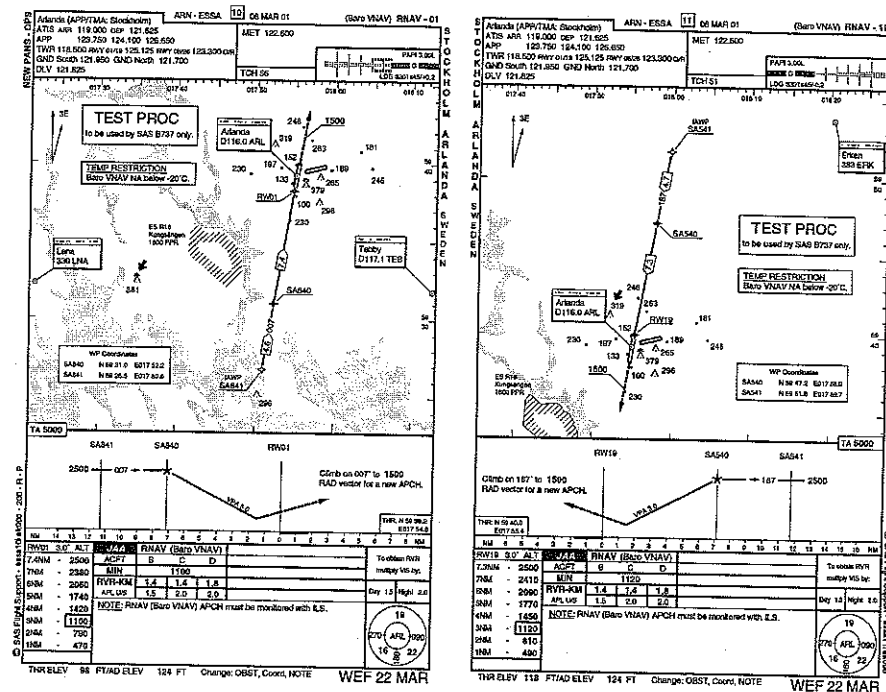


Figure 2 Instrument Approach Charts of the procedures used in RNAV approach trials

Maximum certified airframe crosswind and tailwind limits were tested in the simulator and the effects on the flight path found to be acceptable. After the simulator tests the Swedish CAA validated the RNAV approach procedures for runways 01 and 19 and added a missed approach procedure, assuring obstacle clearance. The validated procedures were check-flown in aircraft in visual weather conditions before start of the trials. The trial target was to gather data from 30 approaches to each runway. We were interested in gathering data from both summer and winter operations.

¹ ICAO document 8168 part II (PANS OPS) describes construction criteria for instrument approaches that will guarantee obstacle clearance. At the time of the trials Baro-VNAV criteria was in a draft state.

The approach trials were conducted in 5 km or better visibility and with a ceiling of 1,000 ft or better. The participating pilots were instructed to request a 'Baro-VNAV, RNAV approach' to RWY 01 or 19 whenever they were paired together with another RNAV-trained pilot. The flight crew co-ordinated their cockpit work using provisional flight deck procedures for RNAV approaches designed by the B737 fleet office of the trial airline.

We measured lateral track accuracy using radar plots from the returns of the approach surveillance radar. The plotted aircraft track deviations from final approach track were measured by a ruler on paper plots and maximum deviation at any point between final approach waypoint (FAWP) and runway threshold THR was noted. Due to the printout quality, the radar plots did not allow for detection of deviations of less than 0.3 mm (0.039 Nm in this scale) from the final approach track. A higher level of measurement accuracy was not operationally necessary, as stricter requirements are not foreseen in the immediate future. But, in order to not produce an overly high navigation accuracy value, a conservatively high deviation value of between 0.039 Nm and 0.055 Nm (which equals to a measured deviation of 0.3 mm) was assigned to all radar plots where no deviation from final approach track could be detected.

For pilot mental workload we used the Bedford Rating Scale, which is a modified Cooper-Harper scale where the pilots rated their subjective mental workload on a unidimensional tree ranging from 1 to 10 (Roscoe, 1987; Berggren, 2000). Pilots rated their mental workload immediately after the approach. Airbus Industrie used a similar method with a seven-unit rating scale during the certification process of the A310 aircraft (Speyer et al, 1987). All in all, during the trials we gathered the following data:

- Radar plots of actual aircraft tracks.
- Vertical path deviations as reported by the pilot.
- Reported ground wind during the approach.
- Pilots' subjective ratings of the suitability of RNAV approaches using a visual analogue scale.
- Pilots' subjective ratings of mental workload intensity and distribution during RNAV approaches, filled in immediately after each approach.
- Autopilot disconnect height (as a measure of pilot confidence in the accuracy of the RNAV approach flown by the automation) from pilot reports.
- Any open comments and feedback from the pilots.
- Number of RNAV approaches performed by each pilot.

Results

We were able to obtain results during the following times and conditions: From January 2001 to December 2002, 21 pilots flew 66 RNAV approaches as pilot

flying (PF). The approaches were distributed as 28 approaches to RWY 01 and 38 approaches to RWY 19 at Stockholm-Arlanda, ESSA with an approach success rate of 95.5% (three approaches were reported as unsuccessfully completed, but the pilot could revert to manual manoeuvring of the aircraft and successfully land the aircraft). Maximum wind velocity measured on the ground during the trials was 18 knots. Maximum ground wind crosswind component was 14 knots. Maximum headwind component was 16 knots. No tailwind component was measured on ground during the approach trials. However, tailwinds were encountered aloft with shifting winds during the approach. Maximum tailwind encountered during approach was with wind at 2,500 feet measuring 320/35 knots, equalling to a tailwind component of 23 knots and a crosswind component of 26 knots. The wind shifted heavily with altitude and ground wind during this approach was 270/15.

Lateral track accuracy

Radar plots were available from 65 of the total 66 approaches to either runway 01 or 19 at ESSA. Data from one approach to runway19 was lost due to technical inability of retrieving the recorded radar plot. Data was available from 28 approaches to RWY 01L and 37 approaches to RWY 19R.

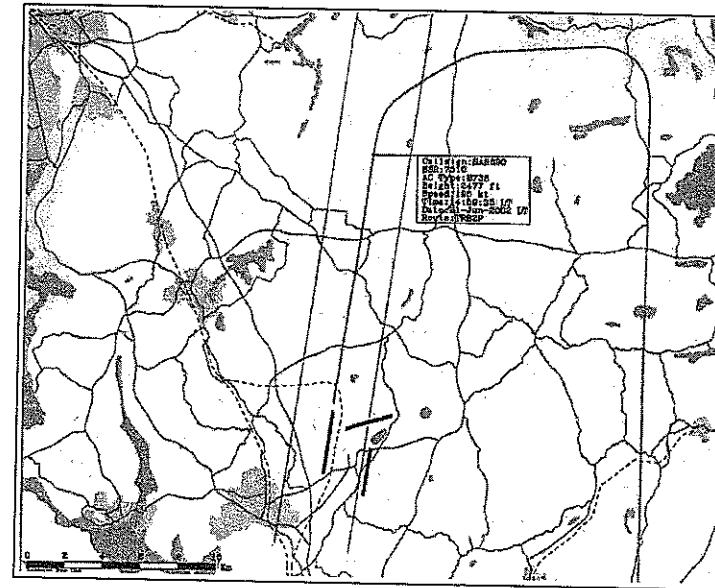


Figure 3 Example of a radar plot of an approach to runway 19. The two lines parallel to the final approach track is the lateral containment limit. The aircraft has to stay inside this area to assure obstacle clearance from FAWP to the runway threshold

Figure 3 depicts a typical radar plot of an approach to RW19. The aircraft was radar vectored by Stockholm Air Traffic control and was then cleared for RNAV approach after a right turn to intercept the final approach track. To give an idea of the required accuracy for RNAV approach operations, the ICAO containment areas of 2 times RNP + 0.5 Nm (1.1) are marked in figure 3 as a parallel line on both sides of the final approach track.

For RWY 19R, the average maximum deviation for the 37 approaches was 0.044 Nm. Based on these results, average maximum lateral deviation from final approach track for a trained flight crew flying this RNAV approach to RWY 19R in B737-NG aircraft can be expected to be less than 0.047 Nm with a 95% probability (0.044 ± 0.003 , $\alpha = 0.05$).

Table 1 Average maximum lateral deviation

Runway	Number of radar plots	Average max deviation (Nm)	Standard deviation (Nm)	95% accuracy confidence interval (Nm)
01L	28	0.069	0.043	0.053 – 0.085
19R	37	0.044	0.008	0.041 – 0.047

For RWY 01L average radar plot maximum deviation for the 28 approaches was 0.069 Nm, corrected for a misalignment of the radar plot system (see the Discussion section about this radar plot system misalignment). With 95% probability the average maximum deviation for RNAV approaches with B737-NG to this runway is within 0.085 Nm from final track.

Vertical track accuracy

Vertical tracking was measured as pilot reported deviation from the ILS glidepath. The pilots noted this deviation on their reply questionnaire. The Baro-VNAV vertical paths were constructed as a 3.00 degrees vertical path, in standard atmospheric conditions corresponding to the ILS glideslope. Deviations above ILS glideslope were reported in 29% of the approaches. There were two reports of deviations below ILS glideslope. All reports of being high on ILS glideslope came from approaches performed during the months from April to August. Average autopilot disconnect height was 344 feet radio altitude, which is approximately the same value above threshold for both runways.

Subjective ratings

The suitability of RNAV as a method to fly non-precision approaches received high ranking on a subjective visual analogue scale by the responding pilots. Data from 63 questionnaires were available for comparison between the RNAV approach procedure and a conventional non-precision approach flown automatically. Data from three questionnaires lacked rating for suitability of either RNAV or a conventional approach and were dropped from the comparison. In 62 of the 63 comparisons, pilots reported a preference for flying the RNAV approach procedure over conventional non-precision approach (NPA).

Data from 50 approaches were available on pilot perceived mental workload. Average mental workload rating was 2.5 units translating into a statement: 'minimal pilot compensation required for desired performance. Enough reserve capacity remaining to allow additional tasks', on the subjective workload reply scheme. Replies varied between 2 and 5 on the modified Cooper-Harper scale which has a maximum of 10 units.

Data for peak workload distribution was available from 62 approaches for PF and 59 approaches for PNF. The phase of flight where peak workload occurred was grouped in two comparison groups; either before approach or during approach. There was a significant difference in peak workload distribution between pilot flying and pilot not-flying. Peak workload for the pilot flying occurred just before start of the final approach, whereas pilot non-flying peak workload occurred during the approach. See table 2. A chi-square analysis of the actual distribution yielded a significant difference between PF and PNF ($p < .05$; $df = 1$).

Table 2 Actual and expected values of peak workload distribution for pilot flying (PF) and pilot not flying (PNF)

	Peak workload PF	Peak workload PNF
During final approach	36 (43.0)	48 (41.0)
Before final approach	26 (19.0)	11 (18.0)

Open comments

A total of 44 open comments were received. The most common comment was that the aircraft was high compared to the ILS glideslope (received for 20 approaches). Those comments were received during the months April to August. There were no comments against the use of RNAV as a method for flying non-precision

approaches. Of the remaining 24 comments, 10 were directed at FMS software logic and FMS interfaces with the automatic flight system.

Discussion

Track repeatability

The approach trials were conducted in LNAV with the autopilot engaged, which should result in a good tracking performance. The radar plots confirmed the good tracking capabilities of the FMC system. Indeed, the measuring system (printed radar plots) was sometimes not even accurate enough to measure any deviations, as described in the method section. Halfway through the trials there appeared a constant tendency of a fixed left deviation for approaches to RWY 01L appeared on the radar plots. This deviation was constantly to the left and of a magnitude of 0.15 Nm. The navigation database checks revealed no inconsistencies and no pilot reports of being left of the ILS localiser were received.

It was not probable that all approaches would suddenly deviate to the same side and to a similar amount if there were no systematic faults, so a check flight using an auto-coupled ILS approach to RWY 01L was performed. This check flight showed that the radar plot system was not properly aligned with the final approach track. The misalignment amounted to 0.15 Nm westerly deviation at the final approach waypoint and maximum lateral deviation was consequently corrected.

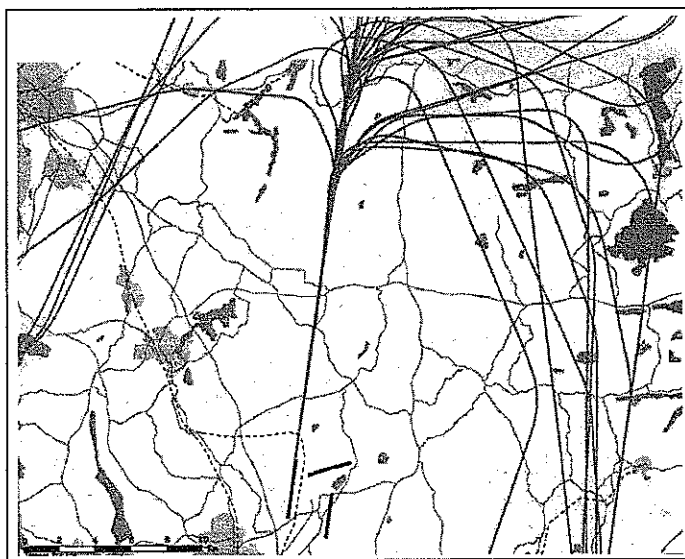


Figure 4 Radar plot of 31 approaches to Runway 19R

In figure 4, tracks of 31 approaches available in September 2002 were plotted from FAWP to runway threshold 19R. With this scale it is barely possible to discern any individual track. This figure of the combined radar plots is shown to illustrate the high repeatability of the lateral tracks flown by the autopilot following FMCS commands in this aircraft.

Vertical tracking

There were only two comments on the aircraft of being low compared to ILS glideslope despite low temperatures encountered during the trials, which is surprisingly few. The lowest reported ground temperature during the trials was 12°. This temperature should make the aircraft fly a vertical path of 2.7° instead of the nominal 3°, leading the ILS G/S pointer to indicate one dot fly up. Reported maximum deviation was 0.5 dot fly up. In contrast to this, pilots reported the aircraft to be high in relation to ILS glideslope in 20 approaches (29%). The 'high' approaches were all performed between April and August, suggesting a possible temperature effect (which increases the true altitude of the aircraft). In addition, there is also an air pressure rounding-down effect. Air traffic control always transmits the actual air pressure for altimeter calibration to the pilots as whole units of HectoPascals (hPa), rounded downwards. This rounding down will cause the aircraft to always be slightly higher than the indicated altitude. One hPa equals about 30 feet in the standard atmosphere. A difference of 0.5 hPa between actual and rounded down hPa is the same as being high by 15 feet. This linear 15 feet deviation will be constant during the whole approach. Consequently, the angular deviation, compared to the ILS angular glideslope, will increase, as the aircraft gets closer to the runway. The theoretically lowest minimum decision height (DH) for RNAV approaches is of 317 feet height above threshold (HAT). A 15 feet deviation will equal an ILS deviation of one dot above ILS glideslope. This was also maximum reported 'high' deviation during the trials. It seems that the QNH rounding-down effect mitigated much of the low temperature effect during the trials and that most vertical deviations during summer months can be expected to be above the ILS glideslope.

Pilot preferences

Pilots' preference for RNAV over conventional non-precision approaches supports the idea that RNAV approaches with a Baro-VNAV vertical path may make the pilots' task easier. These results are consistent with the low mental workload ratings, although the mental workload ratings must be interpreted with some caution as pilots rated their mental workload immediately after the approach, instead of, ideally during the approach. Adding the vertical path to the approach may therefore well increase pilot acceptance and lower their perceived mental workload.

RNAV Flight deck procedures

The accuracy of RNAV waypoints was checked before trials by the airline's B737 fleet office using dedicated software. This routine relieved the flight crew the task of checking the correctness of the data. Nevertheless, the flight deck procedures used during the trials required checking THR co-ordinates as well as final approach track and distance against the value on the instrument approach charts (IAL). The purpose of this airborne check was to assure that the correct RNAV approach procedure had been loaded from the navigation database into the FMCS, not to check the co-ordinates of the waypoints. During the trials, the pilots asked for allowable tolerances, as the magnetic track of the final approach increased one magnetic degree due to changes in magnetic variation and the distance calculation algorithms in the FMCS. For the actual RNAV approach procedure this meant that the value of the final approach track differed one degree magnetic between the FMCS and the official instrument chart.

As with other kinds of approaches, pilots expect to get clearly stated limits for when to accept an RNAV procedure; when it is safe to fly. The effect of a wrongly accepted difference of 2 degrees for an approach with a final segment length of 7.4 Nm deviation would be an offset of 0.53 Nm at a decision height of 317 ft. The ICAO containment area of 1.1 Nm is not compromised with a track tolerance of two degrees in the flight deck procedures under those circumstances. Thus a two degree difference between chart track and FMCS track was accepted. For along-track differences a limit of 0.2 Nm was decided on based on the error budget of 1.1 Nm for a 0.3 RNP RNAV approach.

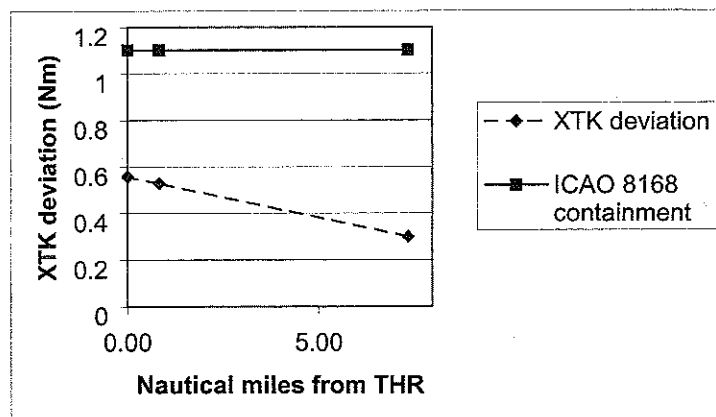


Figure 5 The effect of a two degree deviation from final approach track starting at 7.37 Nm from THR

Using the plan mode of the MAP display the pilots could visually compare the intended procedure on the instrument chart and RNAV procedure loaded in the FMCS that the aircraft would actually fly. The intention was for flight deck procedures to capitalise on pattern matching rather than relying on reading co-ordinates to check for selecting the correct approach procedure (see Hutchins, 1995).

Flying the approach as an auto-coupled approach down to minima meant that the role of the pilot flying changed from controlling the flight path to monitoring the flightpath. Interestingly, this did not result in higher perceived workload ratings. While other possible effect of having the pilots flying the approach in a higher level of automation than usual is discussed in the next section, flying the approach as an auto-coupled approach down to minima meant that the pilot flying could be the one looking out when approaching minima and the pilot not flying could stay on instruments. The transition from instrument to visual cues should be easier if the pilot is already focusing outside the aircraft, but this effect could not be studied during the trials. An unanticipated transition effect reported during the trials was that one pilot reported that transition from head down to head up flying was facilitated when using the head-up display (HUD) for the visual part of the manoeuvring. However, no comparison between HUD and non-HUD was performed in this study, as this was not one of the study objectives.

Weak areas in the RNAV approach concept identified by the study

Three of the RNAV approaches were unsuccessful, that is the pilot had to intervene with the targets of the FMCS/autopilot to complete the approach. Although the overall success rate was 95%, which is what is required in aviation, the three unsuccessful approaches are interesting in themselves as they indicate areas of potential weaknesses in the RNAV approach concept.

Unsuccessful approach number 1: context insensitivity of FMCS

The FMCS/autopilot system in the B737-NG does not permit a fly-away from the altitude set in the altitude readout window of the mode control panel (MCP). This was an aircraft manufacturer designed safeguard against altitude deviations, but as many engineered solutions, was it rather insensitive to context. For the trials reported here, the initial approach altitude was 2,500 feet. The missed approach altitude for the RNAV approach procedure was 1,500 feet. That is, an aircraft flying a missed approach would stop climbing at 1,500 feet. This low missed approach altitude forced the pilots to circumnavigate the technical limitation of the aircraft. The aircraft would not leave 2,500 feet in VNAV PATH unless the MCP altitude was set either below, or at least 300 feet above present altitude. With the missed approach altitude of 1,500 feet set in the MCP altitude readout window, the aircraft would make a level-off at this altitude. The decision made by the trial

leader was to have the pilots set the altitude upwards as a safeguard if VNAV disconnect would lead the autopilot to revert to LVL CHG mode. Having the altitude set altitude in the MCP readout would make the aircraft to climb towards the set altitude, instead of diving towards a lower set altitude. This is a typical operational work-around of a technical limitation and as all such is vulnerable to disruptions. One of the unsuccessful approaches happened because the flight crew let the MCP altitude remain at 1500 feet. The aircraft consequently levelled off at this altitude.

Table 3 Unsuccessful RNAV approaches

	Unsuccessful approach 1	Unsuccessful approach 2	Unsuccessful approach 3
Pilot's remarks	Too early selection of missed approach altitude. Aircraft captured 1500 feet and tried to level off.	Radar vectors by ATC resulted in aircraft being high. Pilot used vertical speed mode to intercept vertical path from above.	Right FMC disabled while using right autopilot 2 leading to an autopilot disconnect. (Design specification for fault protection)
Workload rating	2	5	3
Autopilot disconnect height	1300	400	600

Unsuccessful approach number 2: Brittleness in higher levels of automation

The trial procedures had only a straight segment containing three waypoints: IAWP, FAWP and THR. Reason was that ATC required that normal radar vectoring would be performed to position the aircraft on final approach track, similarly to a conventional ILS approach. One of the unsuccessful approaches followed after tight radar vectoring to the final approach track, together with altitude restrictions that kept the aircraft above the vertical descent profile. This left the flight crew with a rather complicated manoeuvre to acquire the vertical descent profile from above using the vertical speed autopilot mode. The workload rating for this approach was 5, the only approach with this high workload value during the trials. The unsuccessful approach despite using the automation indicated that automated flight is not in itself a factor lowering the workload. Rather it is the visualisation of a vertical path that is the main driver. To probe this

distinction further another set of RNAV approach trials flying both with and without autopilot should be tested. The effect of minimising transition from head-down to head-up flying was also not tested with this trial. In further work, this could be tested with the help of a HUD, versus non-HUD trial.

Dual monitoring tasks for the pilot not flying and pattern-matching for the pilot flying

For operational redundancy, the procedure was designed to be possible to fly manually with flight director guidance only. The flight deck procedures stated boundaries for allowable deviations from lateral and vertical track (Flight Technical Error). The allowable deviations were stated as lateral and vertical maximum values in feet and nautical miles. This meant that the pilot-not-flying was tasked with a dual monitoring task during the approach. First the aircraft's navigation accuracy and secondly the aircraft's tracking performance. We expected to see this dual monitoring task reflected in the peak workload distribution, which it did. Pilot not-flying experienced his/her peak workload more often during the final approach phase than the pilot flying did. It is interesting to note that the extent of perceived workload (by the pilot-not-flying) is not so much related to the number of tasks that need to be accomplished. Rather, perceived workload appears linked to the difficulty for the pilot-not-flying to 'make sense' of the data presented to him/her in assessing whether the aircraft is on the right path or not. This observation is in line with what Veltman and Gaillard (1999) reported, that mental workload of the tactical co-ordinator on an anti-submarine helicopter correlated better with effort to build a mental picture of the situation rather than with the number of tasks. The higher level of automation in RNAV approaches, compared to conventional non-precision approaches can also in itself produce higher mental workload from greater monitoring requirements (Parasuraman, 1996) and may lower process observability.

Pilot flying peak mental workload was reported to occur just before start of the final approach. Again, this was expected, as the pilot flying had to manoeuvre the aircraft into a position from where the approach could be flown in higher levels of automation. In a high traffic density area, this could be a rather demanding task, which was illustrated by the unsuccessful approach number 2 above. Earl Wiener (1989) was one of the first to observe and describe this effect of aircraft control automation and coined the term 'clumsy automation' for the human operator's need to adapt the automation to the operational context. In our approach trials this happened when the aircraft reached a point from where the aircraft automation could be engaged in higher levels of automation (LNAV and VNAV modes). From that point it seemed that the task for the pilot flying was to match the lateral and vertical paths of the map against the aircraft instruments and that mental workload was lower again. This effect is operationally important, as it will allow

the pilot flying to concentrate on acquiring outside visual cues for landing during the later stages of final approach.

Navigation database integrity

The co-ordinates for waypoints in the navigation database can probably not be checked by the flight crew with any reliability. In aviation designers are reluctant to set values for human error rates, as the both vary from 10^{-2} to 10^{-4} (Reason, 1990) and vary depending on external factors (Singer, 2002). However, the flight crew can probably reliably check that they have selected the correct procedure from the navigation database by matching the map display against the paper approach plate (see figure 6).

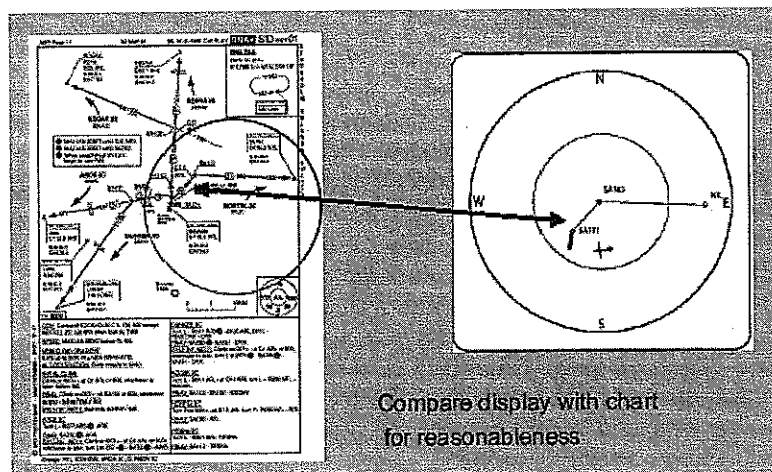


Figure 6 Comparison between aircraft MAP display and approach chart (Source SAS RNAV training material)

The experiences from the trials indicated that both theoretical and practical training was needed. FMCS and flight guidance automation interaction knowledge, and how to effortlessly move between higher and lower levels of automation seemed to be important to increase the robustness of RNAV operations.

Conclusions

Our study has systematically documented and analysed 66 RNAV approaches in real operational settings, with a special focus on human factors and safety

implications. Radar plots and the reply questionnaires indicate that aircraft and flight crews in co-operation are capable of flying RNAV approaches with a Baro-VNAV vertical path with a required lateral navigation containment of 1.1 Nm. Pilot acceptance of RNAV approaches (and the aircraft FMCS/autopilot system) is high, with an average autopilot disconnect height of 344 feet suggesting pilot confidence in the system and its operation. This value also corresponds well with a possible theoretical decision height of 317 feet for RNAV approach procedures. There was no evidence of an increase in mental workload due to monitoring automation. Changing a cognitive task of calculating vertical position into a perceptual task of matching a reference glidepath with the aircraft's position appears to be one important basis for high pilot acceptance of RNAV approaches. For future research, the effect on transitioning from head-down to head-up cues should be investigated. To study this effect aircraft bank angle and vertical speed below decision altitude could be used as a performance measure.

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Response time to reject a takeoff

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Abstract

Rejecting a takeoff at high speed in an airliner is a risky manoeuvre, however, if the decision is not made in a timely manner, at high speeds there is the strong possibility of overrunning the runway. The response times to reject a takeoff were measured in a flight simulator at a variety of speeds using 16 professional pilots. It was observed that as speed on the runway increased, response times decreased, up until a point just before V_1 (the 'go/no-go' decision speed). At this point response times increased dramatically. The results are discussed within the context of the current aircraft certification parameters. Suggestions for further research are made, particularly with respect to extending this work to examine whole crew response times when rejecting a takeoff.

Introduction

Rejecting a takeoff at high speed in a heavy commercial airliner is not a task to be undertaken lightly as the manoeuvre itself fraught with risk. This risk increases as V_1 (the 'go/no go' speed) approaches. In addition to the basic performance of the aircraft V_1 is dependent upon a number of factors, for example its weight, the ambient temperature and runway elevation, but of prime importance in its calculation is the length of the runway available. Although it is expressed as a speed, V_1 actually represents the last point at which it is possible to stop within the confines of the runway, assuming that the aircraft has been accelerating normally. After V_1 the aircraft is committed to taking off. In the decade 1990-99, 51 takeoff accidents were recorded world-wide (Boeing, 2000). Twenty-six of these accidents involved a rejected takeoff. In nine cases the abort was made beyond V_1 . All of these resulted in an overrun.