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Pilot situation awareness and its implications for single pilot operations: Analysis of a human-in-the-loop study

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Abstract

In 2012, NASA began exploring the feasibility of single pilot/reduced crew operations in the context of scheduled air carrier operations. The current study examined how important it was for ground-based personnel providing support to single piloted aircraft (ground operators) to have opportunities to acquire situation awareness (SA) prior to being called on to assist an aircraft. We looked at two distinct concepts of operation, which varied in how much information was available to ground operators prior to being called on to assist a critical event (no vs. some Situation Preview). Thirty-five commercial pilots participated in the current study. Results suggested that a ground operators' lack of initial SA when called on for dedicated assistance is not an issue, at least when the ground operator station displays environmental and systems data which are important to gaining overall SA of the specified aircraft. With appropriate displays, ground operators were able to provide immediate assistance, even if they had minimal SA prior to getting a request.

Keywords: Single pilot operations (SPO); Reduced crew operations (RCO); Remote pilot support; Ground station; Situation awareness (SA)

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1. Introduction

1.1. Why single pilot operations (SPO)?

Over the last sixty years, the minimum crew complement for air carrier operations has fallen from five (Captain, First Officer, Navigator, Flight Engineer, and Radio Operator) in the 1950s to two (Captain and First Officer) today. Improvements in cockpit automation and the increased use of remote piloting in the context of unmanned aircraft systems (UAS), coupled with a pilot shortage in the United States [1,2] have raised the possibility of a further reduction from two to one. In 2012, NASA began exploring the feasibility of single pilot and reduced crew operations (SPO/RCO) [3]. This paper presents data from a simulation that examined issues with having a person on the ground perform some or all of the work currently done by the First Officer (FO). Specifically, we examined the ability of a ground operator who has limited situation awareness (SA) to come to the aid of a single airborne pilot in an off-nominal or high workload situation.

1.2. Concept of operation

Our research has focused on the feasibility of having a person on the ground (a “ground operator”) aid single piloted aircraft in high workload or off-nominal situations, using technology developed for UAS. This study looks at a tension between two principles of our developing concept of operation. First, as noted above, a ground operator must assist aircraft in high workload or off-nominal situations. Second, in order for SPO/RCO to be cost effective, the ground operator must handle more than one aircraft and switch between planes. Under nominal conditions, this seems unlikely to pose a problem. For example, if a pilot needs help handling a high workload approach phase of flight, the ground operator could anticipate this need and step in prior to the start of the approach to assist the pilot. However, in off-nominal situations, such as an engine out, the ground operator may be hard pressed to quickly acquire the SA needed to assist the airborne pilot. In our preliminary work on SPO/RCO, we found that this issue, how much prior SA is necessary to assume the FO role, was a major concern. To address this concern, we could develop a concept of operation that increased the opportunities for ground personal to gain SA by requiring him/her to perform a dispatcher role and track many flights before transitioning into the role of ground-based FO when needed. However, this concept could be costly because it would require dual training (pilot and dispatcher) of ground personnel. The primary objective of this simulation was to determine how important it was that a ground operator has opportunities to acquire SA prior to being called on to assist an aircraft (note that we have no way to assure that participants in this study actually acquired the necessary SA). However, in two of our conditions, the operator was given the opportunity to acquire it. We will refer to such opportunities to acquire SA as Situation Preview. To vary the level of Situation Preview conditions, we contrasted two distinct concepts of operation we had developed for SPO/RCO:

- *Specialist* – a ground dispatcher performs normal dispatch functions and hands the aircraft to a separate person (Specialist) who provides assistance to the aircraft when one-on-one piloting assistance is needed (we refer to such situations as “dedicated assistance” - DA). Specialists would be called upon to provide DA to an aircraft without having previously seen the aircraft or the airspace in which it is flying (*No Situation Preview*).
- *Hybrid* – a ground operator, who can perform both dispatcher and pilot functions, keeps the aircraft, provides DA as needed, and hands off all other aircraft to another operator. Hybrid operators would be assumed to have previously observed (*Low Situation Preview*) and possibly interacted with aircraft needing DA (*High Situation Preview*) as part of their dispatch role.

In both concepts, the ground operator assumes the role of FO when entering DA. The ground operator station (GS) is assumed to have low latency broadband access to the aircraft state, and to be able to make inputs to the autopilot and flight management system. Thus, under DA, the ground operator can perform all duties of the FO short of hand flying the aircraft.

It is easy to imagine how Situation Preview could help performance. If the ground operator already knows which airports have the best weather or that an aircraft has no holding fuel, when an emergency occurs, he or she can save time by not having to look up this information or acquire it from the onboard Captain. However, it is not certain how much increased SA will help. Once an event occurs, much of the contents of the pilot's SA may no longer be relevant; for example, when you have an engine out, you no longer care about time to the original destination. Instead, he or she needs to know where the engine out checklist is and what the weather at the closest airports looks like. Further, we made an effort to design the GS so that information that pilots need in order to gain SA would be easily available, mitigating the costs of not having good SA at the moment the event occurs.

2. Method

2.1. Participants

Thirty-five CRM-trained commercial pilots (all male) with more than 1,000 flight hours were recruited for the current study. All were active duty except three (two retired less than a year and one retired less than five years).

2.2. Experimental design

The experimental design consisted of a single fixed factor, Situation Preview, and two random factors, Subject and Scenario. There were three levels for Situation Preview: No (Specialist concept), Low (Hybrid concept with no prior contact from the DA aircraft), and High (Hybrid concept with prior contact from the DA aircraft). Each participant was exposed to two scenarios in each condition for a total of six scenarios.

2.3. Simulation environment

Experimental participants managed the GS; all other aspects of the simulated environment (piloting, air traffic management, and company services such as maintenance and weather forecasting) were handled by confederates. Push-to-talk communication was available between all stations. When in DA mode, a hot-mic was enabled between the GS and flight deck. The airspace and aircraft were simulated using the Multi Aircraft Control Systems (MACS) [4]. All aircraft were set to emulate generic Boeing transport aircraft. Performance numbers were based on 737-800 for fuel burn and other flight characteristics. Our prototype GS is only briefly described in this paper. It consisted of two conceptually separate areas. The right-side displays provided dispatch and company level tools, which allowed simultaneous monitoring of several aircraft at once. The left-side displays provided essential flight deck controls and instrumentation for a specific "focus" aircraft (see Fig. 1).

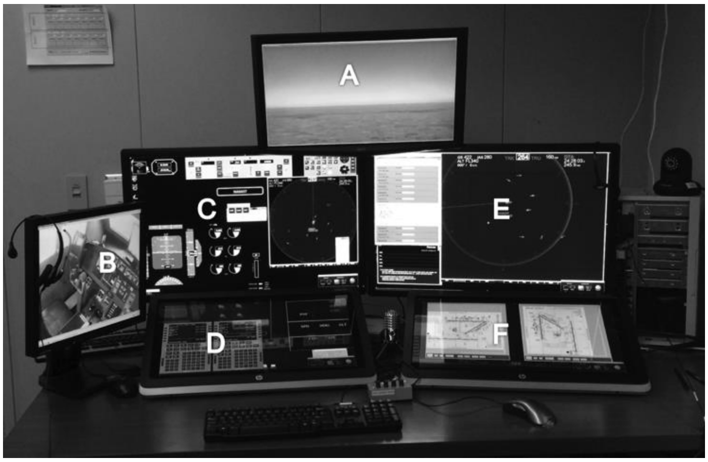

Fig. 1. Participant GS configured for dedicate assistance. A. Out-the-window display of weather. B. Video feed of the flight deck. C. Left-side displays for single focus aircraft. D. CDUs, CRM indicators, real time SA probes. E. Right-side displays for managing multiple aircraft. F. Shared and private charts.

2.3.1. Right-side displays (for managing multiple aircraft)

The right side of the station hosted an *Aircraft Control List* (ACL), the primary tool for managing multiple aircraft and switching the focus between aircraft (see Fig. 1, Display E, upper-left corner). When the ground operator was not providing DA to an aircraft, the ACL was used to switch the operator focus between aircraft. When DA was requested, the ACL allowed the ground operator to switch to a mode where he/she could gain access to the specified aircraft's flight controls. The ACL also provided information crucial for SA about all of the aircraft the ground operator was responsible for such as callsigns, departure and destination city pairs, estimated time of arrivals, flight plans, souls on board and pilot details including the Captain's name and hours on duty. A selectable flight details box provided space for the ground operator to add notes regarding the flight, such as any delays or inoperative equipment. These notes not only served as a memory aid, they provided crucial information to the receiving ground operator when the aircraft were handed off. This was essential in the case where a Hybrid operator needed to enter DA with one aircraft and hand off other aircraft quickly. Aircraft callsigns were also color-coded by flight state (e.g., nominal, off-nominal). These color codes were set by the ground operator, and again served both as a memory aid and a way of alerting an operator to whom the aircraft was handed off about its flight status.

The *Traffic Situation Display* (TSD) was a 3D map display of company aircraft (see Fig. 1, Display E, large map). Information such as flight plans, trajectories and data tags were selectable. Color-coding from the ACL was maintained allowing the ground operator to, at a glance, identify which aircraft were in a nominal state and which were off-nominal. NextRad weather and turbulence boxes were graphically displayed as well. Additional features such as the display of terrain and the ability to pan or zoom were available. Within the TSD, the ground operator had access to a Route Assessment Tool (RAT) [5], which facilitated the ground operator in submitting proposed flight plan changes to the onboard Captain. During DA, the ground operator could manage ATC communication and could evaluate and execute route changes with the agreement of the onboard Captain. Lastly, the TSD had an Emergency Landing Planner (ELP) [6,7], which provided a current list of the best runways for emergency landing and automated rerouting advice. In the event an aircraft needed to divert to another airport (which occurred at least once per scenario), the ground operator could uplink suggested routing to the runway. If in DA, the ground operator could then manage ATC communication and gain approval of route changes. Automatic Terminal Information Service (ATIS) and Terminal Area Forecasts (TAF) *weather reports* were provided in a single window directly under the ACL (see Fig. 1, Display E, lower-left corner).

2.3.2. Left-side displays (for single focus aircraft or any aircraft selected in the ACL)

The left side of the GS provided essential *flight deck controls and instruments* that allowed the ground operator access to the simulation flight deck through a GUI Mode Control Panel (MCP) and access to the Flight Management System (FMS) through a GUI Control Display Unit (CDU). Instrumentation and information displays included a Primary Flight Display (PFD), a 3D Cockpit Situation Display (CSD) and some Engine Indication and Crew Alerting System (EICAS) functionality (see Fig. 1, Display C and left-side of Display D).

Manual flight controls and secondary flight displays (aircraft synoptics and controls) were not available/used in this study. Flight path and navigation information was presented on the CSD [5], a display which provided similar information to the TSD, but from an aircraft-centric viewpoint, and without panning or ACL color-coding. When an aircraft was selected on the ACL during non-DA operations, the ground pilot could only view, not manipulate, the flight deck displays and controls.

Earlier studies revealed a number of problems related to the loss of non-verbal communication and designed and evaluated collaboration tools to solve these problems [8,9,10]. These tools, *CRM indicators*, video and shared charts were also provided in this study but with modifications based on results from the previous studies. CRM indicators provided a mechanism for pilots and ground operators to track their respective responsibilities, actions and acknowledgements during DA. A touch panel provided at both the GS and on the flight deck (see Fig. 1, Display D, upper-right corner) indicated who was the pilot flying or pilot monitoring, who was responsible for MCP manipulations (speed, heading, altitude), CDU inputs, and ATC communication. Items were color-coded green when the pilot at that station was responsible for those actions and white when the other pilot had responsibility.

A *video feed* of the flight deck was provided to the ground operators when in DA mode (see Fig. 1, Display B). A cockpit *out-the-window display of weather* was also presented at the GS during DA (see Fig. 1, Display A). When in DA mode, both crewmembers had access to a *shared chart* display on a touchscreen, which allowed them to refer to the charts and checklists as the other person manipulated them (see Fig. 1, Display F). The touchscreen included a drawing feature that allowed one pilot to highlight and check off items and for these marks to be seen by the other pilot. In addition, the ground operators always had access to a second set of private (unshared) charts and checklists for use at any time.

2.4. Procedure

Each day consisted of approximately 3.5 hours of training, six 15-30 minute experimental scenarios, and a 75-minute debrief session in which additional feedback was gathered. Scenarios were developed to maximize crew interaction and decision-making under difficult circumstances. Seven scenarios (six experimental and one training) were constructed, all containing weather and systems challenges requiring the crews to divert to an airport other than their scheduled destination. The six experimental scenarios were counterbalanced so that each participant saw each scenario only once, but across every three participants, each scenario was run under all three conditions.

When run as a Hybrid (Low or High Situation Preview) concept, the scenario was divided into two parts: first support for multiple (ten) aircraft was provided, then DA was provided for a single aircraft. At the start of the scenario, a confederate ground operator would brief the participant on the area weather and status of individual aircraft. The participant ground operator would then take the station, and one at a time, was contacted by three different flights. Requests included present day dispatch tasks, such as providing weather or turbulence information or logging a note for maintenance and coordinating services, in addition to presumed future NextGen support, such as uplink of suggested re-routes. The fourth aircraft to contact the ground operator requested DA for a more serious issue. The ground operator would transition into DA mode and become the FO for the flight. The remaining aircraft were automatically redistributed to other virtual dispatchers. Once in DA mode, the ground operator would assist the onboard Captain as requested. The run ended at the completion of the approach descent checklist.

Example reasons for DA included weather deteriorating at the destination airport needing to look for an alternate, a critically ill passenger needing medical care, or loss of a hydraulic pump. In all cases, the ground operator would eventually assist in re-routing to a different airport. The role of pilot flying and pilot monitoring would switch back and forth within each scenario based on the task at hand. In the High condition, the ground operator was contacted twice by the aircraft that eventually requested DA: once for minor support or information and later for DA. In the Low condition, no prior contact was made. When run as a Specialist (No Situation Preview condition) concept, the scenario was limited to the DA portion only.

All flights were limited to the Rocky Mountain region: DEN (Denver), COS (Colorado Springs), PUB (Pueblo), CYS (Cheyenne), EGE (Eagle; Vale) and GJT (Grand Junction). This airspace was chosen because of the challenging terrain and the realistic possibility of weather that can shut down many of these airports leaving no other major airports for a considerable distance. This allowed us to constrain the scenarios but keep them realistic. Flight crews in all conditions were expected to fly safely and efficiently manage their flight toward a safe landing. Additionally, we requested that they land with a minimum of 5,000 pounds of fuel.

2.5. Dependent variables

A large quantity of data was gathered on each flight. This paper reports on subjective measures collected both real time and post-trial. Real time SA probes and workload ratings were gathered every 2-4 minutes throughout the scenarios. A Ready prompt would appear on a touch screen panel (see Fig. 1, Display D, lower-right corner) as participants heard a tone in their headset. Once ready, participants were instructed to press the prompt and answer the probe question. All questions were on a five-point scale. If left unanswered, the questions would timeout after 60 seconds, and an additional question would appear giving participants the opportunity to identify why they did not answer the probe question in time. Responses to the questions and response times were collected.

After each scenario, pilots completed a post-trial questionnaire focusing on pilots' perceptions and cognitive processes in relation to that specific trial, such as workload, the transition into DA and decision-making. After all of the flights, the pilots completed an extensive post-simulation questionnaire and debrief in which they were asked to give additional feedback. This included comments and critiques about their experiences of flight safety, workload, communication, crew coordination, and decision-making processes. The debrief discussions typically lasted about half an hour. Ratings and comments on the usefulness and usability of the various tools were also collected.

3. Results

The metrics described above were analyzed using a one-way repeated measures ANVOA. Alpha levels of .05 were used for all analyses, with Sidak adjustments for multiple comparisons. The p-values were adjusted using Greenhouse-Geisser for violations of sphericity where appropriate.

3.1. SA probes

Primary analyses for SA probes were limited to data collected during DA, as that was the only time probes were collected for all conditions. Situation Preview was not found to have a significant effect on response times to the Ready prompt, percent of timeouts or missed probes, or percent of correct responses to probes (Fs < 1) during DA. For further analyses on missed probes, see Cunningham et al. [11]. There was, however, a significant effect of Situation Preview on Probe latency during DA, $F(2,50) = 4.660$, $p = .014$. Response times were shorter for No Situation Preview ($M = 4.97$, $SD = 1.58$) compared to Low Situation Preview ($M = 6.68$, $SD = 2.53$, $p = .011$); High Situation Preview ($M = 5.37$, $SD = .50$,) did not differ from No ($p = .825$) or Low Situation Preview ($p = .201$).

Twice during DA (all conditions) and once prior to DA (Hybrid conditions only), pilots were asked to rate their workload. There was no significant effect of Situation Preview on workload ratings during DA, $F(2,42) = .599$, $p = .554$. However, when workload ratings were compared across all time points, there was a significant effect of Situation Preview, $F(2,50) = 6.547$, $p = .003$. The first workload rating given prior to DA in the Hybrid conditions was lower than workload ratings given during DA for any Situation Preview condition.

3.2. Post-trial ratings

At the end of each scenario, pilots were given a questionnaire asking for ratings (9-point scales) on a number of aspects of the scenario. Figure 2 shows the means for the four workload ratings on this questionnaire as a function of the High, Low, or No Situation Preview condition. No significant differences were found (Fs < 1) except for the overall workload while spooling up for DA rating, $F(1.678, 57.064) = 4.683$, $p = .018$.

In addition to the four workload questions, pilots were asked to rate several other aspects of each scenario (see Table 1). None of these ratings were significantly affected by Situation Preview, Fs < 1.5, ps > .22. Thus, the post-trial ratings provide no evidence that Situation Preview improves the performance of ground operators in scenarios such as those presented in this simulation.

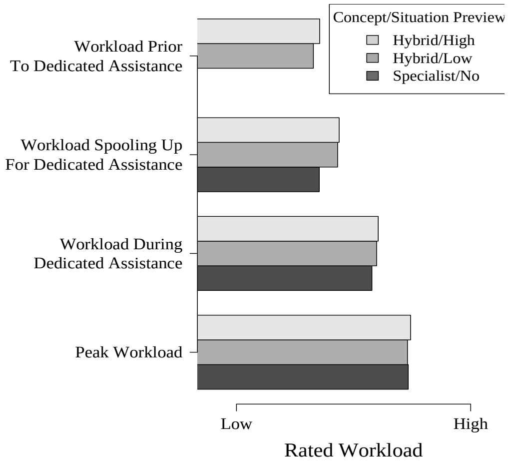

Fig. 2. Workload Ratings by Concept/Situation Preview.

Table 1. Queries presented to pilots about scenario.

- Rate the safety of flight during dedicated assistance.
- How effective were you as a First Officer during dedicated assistance?
- How difficult was it to gather sufficient information to support the onboard Captain?
- During dedicated assistance, it was easy to establish crew roles and responsibilities with the Captain (agree, disagree).
- During dedicated assistance, I knew what the Captain was doing most of the time (agree, disagree).
- During dedicated assistance, how difficult was the divert decision?
- It was easy to discuss position relative to external objects (weather, airports, etc.) with the Captain during dedicated assistance (agree, disagree).
- It was easy to discuss information on the approach plates with the Captain during dedicated assistance (agree, disagree).
- During dedicated assistance, rate your ability to discuss all issues before making decisions.

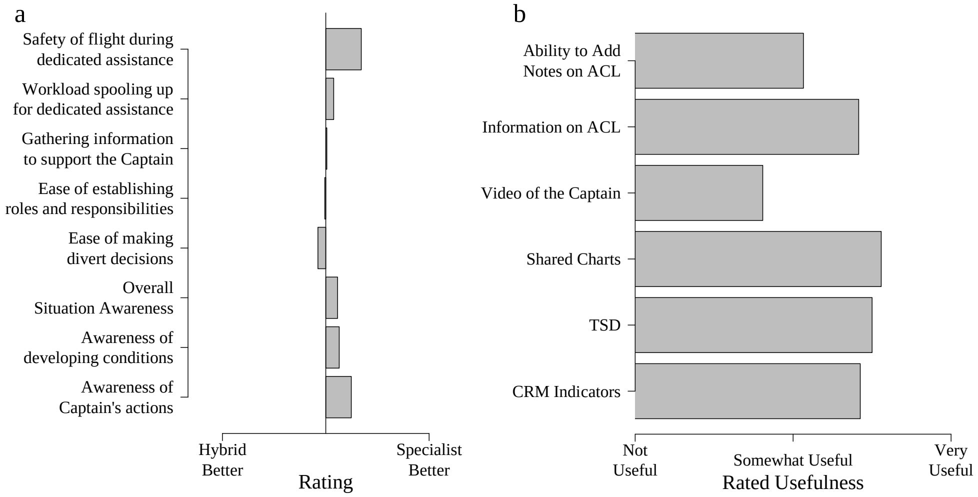

Fig. 3. (a) Post-Simulation Ratings Comparing Hybrid to Specialist Concepts; (b) Post-Simulation Ratings of Usefulness of Tools.

3.3. Post-simulation ratings and debrief

At the end of the simulation, participants were asked to complete a questionnaire which had them rate many aspects of their experience on a 9-point scale. Figure 3a shows ratings for eight items that asked participants for a head to head judgment about whether the Hybrid or Specialist conditions were better (because participants were generally unaware of whether they were in the High or Low Situation Preview conditions, they were asked only to compare Hybrid to Specialist). Participants did not show a significant preference for either concept on any of these criteria except for safety of flight in which the Specialist condition was rated slightly safer, $t(1, 34) = 3.76$, $p = .001$.

We were also interested in how well our tools supported the ground operator in performing the tasks. We asked participants to rate the usefulness of each of six tools. Overall, participants found the simulation tools useful (1-not useful, 5-neutral, 9-very useful; see Fig. 3b). Information on the ACL, shared charts, the TSD, and CRM indicators were all rated, on average, as useful. Of specific interest was the ACL, which was designed to provide additional SA to the ground operators and aid in their support of multiple aircraft. In a separate question, participants agreement that the information on the ACL improved their SA (1-strongly disagree, 5-neutral, 9-strongly agree) was significantly higher than neutral ($M = 7.00$, $SD = 1.5$; $t(1, 34) = 7.91$, $p < .001$). After rating this item a nine, one pilot provided the following comment, “I would like to see a lot more info on the ACL. I really liked the concept.”

The tools that were not rated as highly were the video feed of the Captain and the ability to add notes to the ACL. Many pilots acknowledged that video could be useful in some situations (e.g., pilot incapacitation), but that it was not useful in the scenarios used here. The ability to add notes to the ACL was also rated relatively poorly (only “somewhat useful”). This may have been due to the limited fidelity of the handoffs in this simulation. While entering information for themselves might not have been useful, the information entered by previous ground operators (as simulated by the information already in the box at the start of the scenario) presumably was useful. During debriefing, several pilots complained about the added workload of having to type information into the box, suggesting pull-down menus to insert commonly used items and automated entry based on telemetry.

As part of the debriefing, pilots were also asked to comment on the differences between the Hybrid and Specialist concepts. As reflected in the ratings data, pilots generally did not feel that safety or SA differed significantly between these two concepts. Most pilots agreed that there was some gain in SA from working aircraft prior to DA. However, two factors were brought up that mitigated this advantage in the minds of some pilots. First, in a real world situation, not all the aircraft would be in the Denver airspace. Ground operators would either have aircraft spread out all over the NAS, decreasing their awareness of weather and traffic in any particular region, or would have to only take aircraft in a specific region (handing them off as they entered or exited that region), which would increase their workload (with the handoffs) and lower their awareness of specific aircraft. Second, many pilots seemed to have difficulty compartmentalizing the issues faced by different aircraft. When DA was requested, they felt the lack of a formal handoff of other aircraft and wanted to type more into the comments box on the ACL, or they felt confused about whether the aircraft they were currently handling or the previous call was the one with a given problem. These issues may explain the trend seen in the ratings data for the Specialist concept to be rated more highly than the Hybrid concept. It should be noted, however, that not all pilots had these concerns. Other pilots said that, once they received the call for DA, the previous aircraft disappeared from their minds.

4. Discussion and conclusion

The primary objective of this simulation was to determine how important it was that a ground operator has opportunities to acquire SA prior to being called on to assist an aircraft. Ideally, DA could be provided by the person most qualified to handle the specific issue. However, this is only possible if that person can acquire SA fast enough to perform effectively as a FO. Also, if ground operators are required to maintain SA on all flights, then you need more ground operators and the financial benefit of SPO might not be realized. The present analysis suggests that a ground operators' lack of initial SA when called on for DA is not an issue, at least when the GS displays present the environmental and systems data which are important to gaining overall SA of the specified aircraft. With appropriate displays, ground operators can jump in and provide assistance, even with minimal SA prior to getting this request. This, in turn, suggests either a Hybrid or Specialist concept of operation, with the appropriate tools and displays, may work.

The obvious caveat to this conclusion is that we only ran en route scenarios. The relatively short times our ground operators took to spool up could still be too long in an aborted landing or takeoff scenario. However, landings and takeoffs occur at predictable times and are known to be the most dangerous and highest workload phases of flight. It might make sense, therefore, to schedule DA for all arrivals and departures (a concept we call Harbor Pilot) [3], or indeed for any predictable events when the single pilot might be expected to be overloaded. For these events a ground operator could have the time to gather the important information they need before, or as a part of, jumping into DA.

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