Concept of Operations for RCO/SPO

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EXECUTIVE SUMMARY
Reduced crew operations (RCO) refers to the reduction of crew members flying long-haul or military operations with more than one pilot onboard. Single pilot operations (SPO) refers to flying a commercial transport aircraft with only one pilot on board the aircraft, assisted by advanced onboard automation and/or ground operators providing piloting support services. Properly implemented, RCO/SPO could provide operating cost savings while maintaining a level of safety no less than conventional two-pilot commercial operations. A concept of operations (ConOps) for any paradigm describes the characteristics of its various components and their integration in a multi-dimensional design space. This paper presents key options for human/automation function allocation being considered by NASA in its ongoing development of RCO/SPO ConOps.

1. INTRODUCTION

Many aircraft, such as small private airplanes or military fighters, are operated with a single pilot in the cockpit. Although commercial aircraft can be operated by a single pilot from either of the two-pilot seats, U.S. federal aviation regulations (FAR 121.385) currently requires a cockpit crew of at least two pilots for most commercial air carriers[1]. The cost associated with crews (salaries, benefits, training, etc.) is a significant fraction of the aircraft operating cost, especially for regional/commuter operators that typically fly smaller aircraft with fewer seats than major airline operators that fly narrow/wide-body aircraft. Additionally, current trends indicate a possible shortage of available pilots in the future (USA Today, 2013). Crew cost and availability issues provide the motivation to explore the feasibility of safely operating long-haul and military operations with a reduced crew, and commercial aircraft with a single pilot in the cockpit assisted by advanced onboard automation and ground operators providing flight support services well beyond those currently delivered by aircraft dispatchers.

These paradigms are termed Reduced Crew Operations (RCO) and Single Pilot Operations (SPO), respectively. A key requirement of RCO/SPO is to maintain safety at a level no less than current two-pilot operations by the introduction of advanced cockpit automation and possibly new ground operator positions using support tools and air-ground communication links. The major emphasis is placed on SPO in this ConOps paper because SPO poses more unique challenges than RCO, making its analysis more critical. SPO, in particular, will yield economic benefits if the costs of new ground operators and advanced automation are surpassed by the savings from a ~50% reduction in cockpit crew costs. In addition to the primary cost savings arising from eliminating the first officer position, there will likely

[1] FAR Sec. 121.385 (c) The minimum pilot crew is two pilots and the certificate holder shall designate one pilot as pilot in command and the other second in command.

be secondary savings for SPO due to better crew connection integrity and smaller/lighter cockpits in next-generation commercial aircraft designed for single-pilot operations.

NASA is conducting research on SPO feasibility under its Airspace Systems Program (Warwick, 2013). Some aspects of SPO are also being researched in Europe under the Advanced Cockpit for Reduction Of Stress and Workload (ACROSS) program (ACROSS, 2014). An important element of NASA's SPO research is the development of a concept of operations (ConOps) that covers the roles and responsibilities of the principal human operators, the automation tools used by the humans, and the operating procedures for human-human and human-automation interactions. This ConOps is being constructed using insights gained from a variety of sources including subject matter experts, human-in-the-loop experiments examining key aspects of the ConOps, and cost-benefit analyses.

This paper presents key options for human/automation function allocation being considered by NASA in its ongoing development of a SPO ConOps. It is beyond the scope of this paper to explore all options in the ConOps design space. The options presented here were selected by the research team based on insights drawn from subject matter experts participating in an SPO technical exchange meeting (Comerford et al., 2013) and knowledge gained from initial human-in-the loop experiments studying specific aspects of SPO (Lachter, Battiste, et al., 2014; Lachter, Brandt, et al., 2014). Section 2 provides a brief history of the evolution from a five-person cockpit to the current two-person cockpit, and outlines some implications of one-person cockpit operations. Section 3 presents a taxonomy of operating conditions for SPO, to establish high level requirements for operator functions and equipment. Section 4 presents key options for function allocation among various types of human operators, while Section 5 describes considerations for human-automation function allocation. Some concluding remarks are presented in Section 6.

2. COCKPIT CREW COMPLEMENT

SPO may be regarded as the next phase of a decades-long downward trend in the minimum number of cockpit crew required for safe operations. In the 1950s, commercial aircraft typically had five cockpit crewmembers: captain, first officer (co-pilot), flight engineer, navigator, and radio operator. Advances in voice communication equipment removed the need for a dedicated radio operator position. Next, advances in navigation equipment (e.g., inertial navigation systems) removed the need for a dedicated navigator position. Finally, advances in r engines, aircraft systems and improved tools for monitoring have removed the need for a dedicated flight engineer position.

Over the past 25 years or so, commercial aircraft have operated with a two-person cockpit (captain and first officer). It is important to note that the functions associated with the radio operator, navigator, and flight engineer positions did not simply disappear – they are now performed by the captain and/or first officer, assisted by cockpit equipment that has greatly reduced the human workload originally required to perform those functions. This new equipment along with new flight deck procedures have preserved or increased flight safety, even with a reduced crew. Economic benefits have been realized because the savings from reduced cockpit crew expenses have exceeded the costs of equipage.

The transition from a two-pilot cockpit to a single-pilot cockpit will be significantly more challenging than the transitions from a five-person cockpit to a two-person cockpit. Unlike the previous transitions, it may not be possible to assure safety of SPO simply by adding new automation to the cockpit. There will likely be situations where the single pilot in the cockpit needs to collaborate with a person on the ground to solve a complex problem. There is also the issue of single-pilot incapacitation, which could be addressed by a ground operator directing advanced cockpit automation.

Implementation of SPO involves a transition from the current paradigm of a Captain, First Officer, and Dispatcher team using conventional automation tools, to a new paradigm of a Captain and Ground Operator team interacting with advanced human-centered automation tools (see Fig. 2). Although many of the functions currently performed by the first officer could be performed by some combination of ground operators and advanced automation under SPO, there is an opportunity for a "clean-slate" allocation of functions for Captain, Ground Operator, and Automation. This clean-slate approach to SPO would result in a new/different model for crew resource management (CRM).

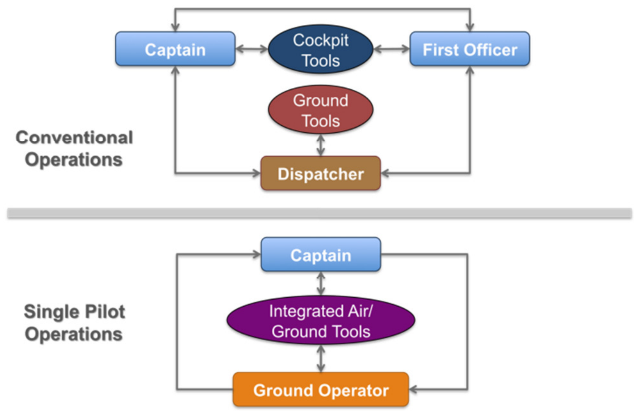


Figure 2. Conventional vs. single-pilot operations

3. TAXONOMY OF OPERATING CONDITIONS FOR SPO

The characteristics (e.g., roles/responsibilities, tools, procedures) of an SPO ConOps will depend in part on the nature of the operating condition. A basic taxonomy is presented in Fig. 3, based on the pilot's physiological and behavioral condition (normal vs. incapacitated) and flight condition (nominal vs. off-nominal). It is noted that the term "flight condition" refers to the myriad factors affecting the flight other than the pilot's condition, such as the status of aircraft systems, weather conditions, and airport availability.

As the taxonomy condition (TC) progresses from 1 to 4, the operating conditions become more challenging, and the requirements for safe implementation of SPO become more complex. For example, in TC–1, there may not be much need for ground operator assistance; the cockpit automation could provide most of the assistance needed by the captain. In TC–2, the captain would likely request the assistance of a ground operator, especially in complex off-nominal conditions with high cognitive workload. TC–3 would require a ground operator to assume the role of captain and interact with cockpit automation to land the aircraft. In TC–4 the ground operator acting as captain may need assistance from other ground operators to land the aircraft.

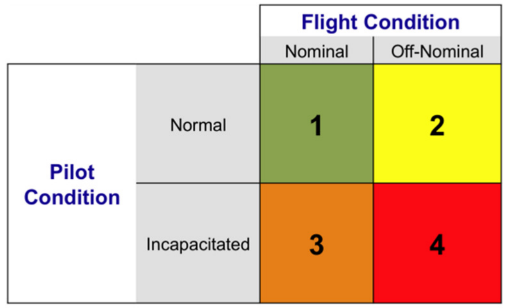


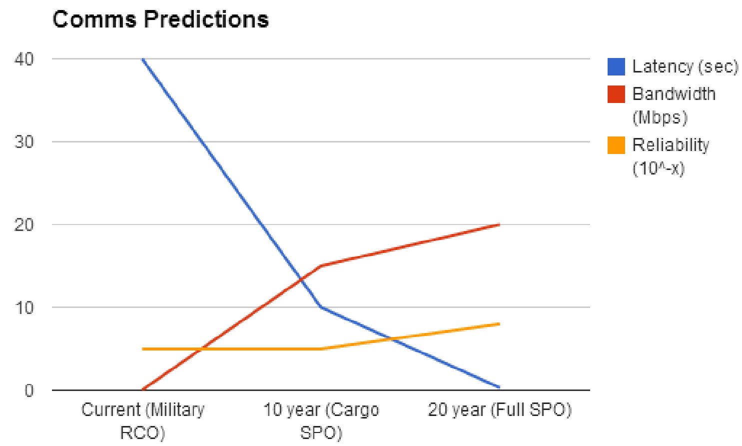
Figure 3. A taxonomy of operating conditions for SPO

Under SPO, it is assumed that an incapacitated pilot condition would be handled as a declared emergency with air traffic control (ATC) providing special handling to the flight which would be directed to land by a ground operator interacting with advanced cockpit automation. A study (DeJohn et al., 2004) conducted by the FAA Aeromedical Institute for U.S. flights over the six-year period 1993–1998 found 39 instances of in-flight medical incapacitation, defined as a condition in which a flight crewmember was unable to perform any flight duties; the in-flight event rate was 0.045 per 100,000 flying hours. This corresponds, on average, to one incapacitation event per 1.85 months or per 2.2 million flying hours. Although these statistics may be somewhat different in the SPO implementation timeframe, the incapacitation rates would likely be low enough that declaring a pilot-incapacitation emergency would not unduly disrupt ATC operations.

The necessity for safely landing an SPO aircraft with an incapacitated pilot will be a key driver of technology requirements for cockpit automation, remote flight-control tools for the ground operator, and air/ground data links. The implementation of these technologies with sufficient reliability/redundancy will likely represent a significant part of the costs of implementing SPO. It is noted that some components of the technologies required for safe landing in an incapacitated-pilot scenario, such as autoland systems, are already available and in current use.

4. FUNCTION ALLOCATION FOR HUMAN OPERATORS

This section presents considerations for function allocation among the human operators on the aircraft and ground. Characteristics of functions performed by the captain and ground operators are described; this includes options for organization structures for ground operators. The material presented in this section is not intended to be an all-encompassing treatment of RSO/SPO options for function allocation among human operators; its scope is limited to the options being considered by NASA in its ongoing development of a ConOps for SPO. Function allocation between human operators and automation is discussed in Section 5.



Year	Latency (sec)	Bandwidth (Mbps)	Reliability (10^-x)
Current (Military RCO)	40	0.03	5
10 year (Cargo SPO)	10	15	5
20 year (Full SPO)	0.3	20	8

Currently, communications to the flight deck have a high latency and low bandwidth compared to technology that is available in other sectors. This is driven by cost considerations of upgrading and the high level of safety that the current system enables. Improvement in latency and bandwidth are being seen for passengers, and this is being enabled by the business case of passengers paying for internet connection. Future improvements to flight deck communications will be able to take advantage of technology developed for passengers and other sectors, but will require infrastructure, including security, that may need to be financed through savings resulting from RCO or SPO.

With ATN mandates being delayed to 2020 and new FANS CPDLC systems being installed at faster rate to more platforms, it is likely that ACARS in support of ATC/CPDLC will be used for 20 to 30 more years. ACARS is not currently protected with a message assurance security system. Pilots can be tricked into accepting a counterfeit ATC clearance because there is no authentication or encryption on Data Link messages. Security measures such as Protected ACARS (Storck, 2013) will be a necessary part of an RCO/SPO solution.

Given the infrastructure financing, there do not appear to be major technological barriers to high-bandwidth, low-latency support to the flight deck in the twenty-year time frame of SPO. One example of a part of this infrastructure is OneWeb, which is building a constellation of more than 600 satellites that, when launched, will provide approximately 10 terabits per second of low-latency, high-speed broadband for aviation (Rockwell Collins, 2015).

Military Long Haul RCO

Along the path to single pilot operations we will see a number of reduced crew concepts which will aid us (FAA regulators and the flying public) in becoming comfortable with reducing the number of flight deck crew on passenger transport aircraft. The first expected change to crew complement will probably come from the military, which are not subject to full FAA oversight. A USAF research and development contract with Boeing is investigating reduced crew operations for military long haul missions. A concept that is being discussed is to reduce the number of crew members for each mission by at least one. In this concept the captain and at least two first officers will man each flight. The crew will begin and end all flights with all crew members on the flight deck during takeoff and landing. However, during cruise the flight deck will be staffed by only one crew member. The other two will be given crew rest periods. Based on the length of the mission, flight deck staffing periods will be assigned to each crew member. This concept will not require anywhere near the level of automation and procedural changes as will be needed for SPO. However, to support this concept some changes in current flight deck procedures will be required. Currently, flight deck procedures require that when only one flight crew member is on the flight deck that that crew member must don an oxygen mask. To support RCO current flight deck requirements and procedures will have to be reexamined. Additionally, new technology to monitor the single pilot on the flight deck will have to be developed. Although the crew response to flight crew incapacitation will not require the same levels of technology as needed for SPO, this crew state will have to be planned for and mitigated. New crew monitoring and alerting techniques will have to be developed along with new automation to maintain safety of flight while the resting crew member are alerted and return to the cockpit. The development of the technology and procedures needed to support RCO for military flight will move us significantly along the path to SPO. An alternative staffing plan which keeps two crew members on the flight deck at all times would significantly reduce the need to develop pilot monitoring and alerting technology, but also significantly reduce crew rest.

Civil Long Haul Cargo and Passenger Transport RCO

The proof of concept for military RCO will provide a road map to both the airlines and the FAA to support an implementation of RCO for Civil long haul transport flight operations. With a good handle on the crew flight deck procedures, technology requirements and safety standards which will be needed, the time needed to certify civil transport RCO operations should be significantly reduced. The business case for the airlines is very straight forward; for long haul missions where two complete crews are normally required they will be able to reduce the staffing complement by one flight crew member. This reduction will translate into a significant savings of 25% on the cost of pilots for each long haul mission. Of course there will be needed changes in technology and procedures which will, in the short term reduce the benefit, however over the long term this concept will reduce cost while also maintaining current levels of safety.

Civil Cargo SPO

The next step along our path to SPO for civil passenger transport will be to development or transition of UAS technology for ground management of civil transport flight deck. SPO civil cargo operations will have one significant advantage over UAS operations, in that a single pilot will remain with the aircraft, thus reducing the need for detect and avoid technology. However, one significant effort will be the development of human centered flight deck automation which can truly replace the second person on the flight deck. Current research on SPO has provided some of the many questions which must be answered to achieve civil cargo SPO – replacement of non-verbal cues; tools and displays to support effective communication; and a possible architecture which support effective crew interactions. The lessons learned from certification and operation of RCO will aid significantly in the move to civil cargo SPO. Finally, this step is also aided by the fact that no passenger issues need to be resolved to certify SPO for civil cargo operations.

SPO for Passenger Transport

The transition from the current two person cockpit to SPO seems a very daunting task with many technology, personnel, and procedural issues that will need to be resolved. However, following a path from near-term RCO from military and civil long haul, through civil cargo will provide a spiral approach to both technology and procedural development. Additionally, using this approach will allow the FAA, the airlines and the flying public to assess and gain confidence in the deployed technology and the safety of reduced crew and single pilot operations. This engineering, build a little and test a little, approach has been found successful on many of NASA airspace and space development and implementation projects. The following sections will touch on the crew roles for both RCO and SPO and will distinguish between the two only as needed for clarity.

4.1. Captain

The captain (unless incapacitated) serves as the pilot-in-command (PIC), making all decisions pertaining to command of the flight. As such, he/she bears the ultimate responsibility for safe and efficient operation of the flight. The captain is the final decision-maker regarding the flight mission, and (according to procedures) calls on automation and ground operator assets to accomplish this mission. The captain's main tasks are to manage risk and resources (both human and automation). Under SPO, the fundamental command/leadership role of the captain will not change, but the individual tasks and duties of the Captain will change significantly. The captain will likely take on some of the conventional Pilot Flying (PF) and Pilot Monitoring (PM) duties, while other PF and PM duties are allocated to the automation or the ground operators. The characteristics of the resources available to the captain will also be quite different, e.g., no first officer in cockpit, expanded menu of resources available from ground operators, new/advanced automation available in the cockpit. With this change in function allocation, a new CRM model will likely be required under SPO.

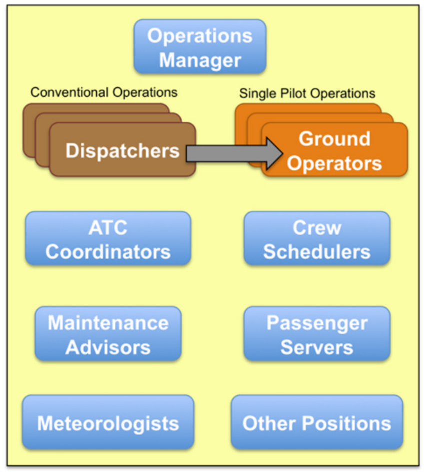


Figure 4. Representative layout of airline operations center

4.2. Ground Operators

In current operations, flights receive ground support services from their airline operations center (AOC). Figure 4 depicts key positions in a typical AOC, which is supervised by an operations manager. There are various AOC teams that provide specialized services, e.g., dispatch, ATC coordination, crew scheduling, maintenance operations, customer service, and weather operations. It is anticipated that SPO would primarily affect the functions of the dispatch operations, with limited impact on other AOC services.

In current operations, each dispatcher serves around 20 aircraft that are in various phases of flight at different locations around the country or even the world. By U.S. regulation, the dispatcher shares responsibility with the captain for safe operation of the flight. To be certified, dispatchers must have the same knowledge of aviation as airline transport pilots; however, they are not required to have equivalent flying skills. A significant part of the dispatcher's duties lies in the pre-flight phase, where the dispatcher consults with the captain and uses various AOC tools to develop a flight plan (e.g., routing, cruise altitude, airspeed), determine fuel loading, meet weight and balance requirements, and ensure compliance with the minimum equipment list (MEL). After the dispatcher and captain sign the flight release, the dispatch functions transition to flight monitoring and serving as a conduit for information between the aircraft and other AOC operations. The dispatcher also plays an active role supporting the cockpit crew during off-nominal conditions such as aircraft equipment malfunctions, diversions to a different destination airport, and large (> 100 nmi) changes in routing. Dispatchers generally serve their flights all the way from pre-flight planning to gate arrival.

In SPO, certified dispatchers become ground operators (see Fig. 4) who collectively perform conventional dispatch functions as well as piloting support functions, although each ground operator may not necessarily perform both functions. Ground operator teams will collectively perform the following three core functions: (1) *Conventional Dispatch* of multiple aircraft; (2) *Distributed Piloting* support of multiple nominal aircraft; (3) *Dedicated Piloting* support of a single off-nominal aircraft. The Conventional Dispatch function has been described above.

The Distributed Piloting function corresponds to basic/routine piloting support tasks such as reading a checklist, conducting cross-checks, diagnosing an aircraft system caution light, determining the fuel consequences of a holding instruction, etc. It is presumed that a single ground operator can provide such services to multiple aircraft because these non-urgent and relatively brief tasks can be prioritized and executed sequentially, and that little or no specialized training would be required if the distributed piloting function was performed by a dispatcher who has been certified for the aircraft type. This function would be applicable only to nominal aircraft, corresponding to Taxonomy Condition 1 defined in Fig. 3.

The Dedicated Piloting function corresponds to sustained one-on-one piloting support requested by the captain under high-workload or challenging off-nominal operating conditions such as an engine fire, cabin depressurization, or diversion to an alternate airport due to low fuel and/or bad weather, etc. This function is also applicable to situations where the ground operator has to take command of an aircraft whose captain has become incapacitated. The tasks associated with this function may include flying the aircraft, e.g., remote manipulation of the aircraft's flight management system (FMS) for route amendments, or remote manipulation of the aircraft's mode control panel (MCP) for sending speed/altitude/heading commands to the autopilot. The Dedicated Piloting function would be applicable to Taxonomy Conditions 2, 3, and 4 defined in Fig. 3. The skills and training required to perform the dedicated piloting support function are essentially the same as those of a conventional pilot. One possibility is a rotating schedule where a pilot is scheduled for several weeks of airborne (cockpit) assignments followed by a week of ground (AOC) assignments. However, depending on the ground operator unit structure employed (see Figure 5 and sections 4.3.1 and 4.2.2), the pilot may need additional training in dispatch operations.

Ground operators will require tools similar to those on the flight deck for issuing high-level flight control commands such as making route changes in the aircraft FMS, or manipulating airspeed/altitude/heading commands via the MCP. The ground operator tool set may also include next-generation dispatcher tools to reduce workload. Additionally, SPO will require a secure and reliable air-ground link for voice and data communications. These requirements are similar to those currently being considered for unmanned aircraft systems (UAS) operations in the national airspace system.

There are many possible structures for organizing ground operators to perform the three core functions described above. While safe operation is the paramount concern, another key consideration is the operating cost associated with the ground operator team structure. One cost factor is the number of ground operators relative to the number of aircraft they can safely support, as well as the training/qualification requirements for those ground operators. Another cost factor is the number of ground stations that require complex and reliable (and hence expensive) equipment such as that required to remotely control an aircraft's flight-path. Cost/complexity of the ground operator support system can be traded off against cost/complexity of the cockpit automation support system (this will be discussed in Section 5). Two ground operator organization structures of interest, hybrid ground operator unit and specialist ground operator unit, are described below and illustrated in Fig. 5. These ground operator organization structures have been selected by NASA, based on subject matter expert opinion, for evaluation in an upcoming human-in-the-loop evaluation.

4.2.1. Hybrid Ground Operator Unit

In this organizational unit, each hybrid ground operator (HGO) is trained and certified to perform all three core functions: Conventional Dispatch tasks as well as Distributed Piloting and Dedicated Piloting support tasks.

Each HGO generally serves multiple flights from pre-flight planning to gate arrival. However, if/when one of these flights encounters an off-nominal condition that requires dedicated support, the other aircraft are handed off to several other HGOs under the direction of the unit's supervisor. These handoffs will require some briefing given that most dispatch operators monitor and aircraft from preplanning to gate arrival. A more extensive briefing will be required if the involved aircraft needs special handling instructions. The HGO then provides one-on-one support to the off-nominal aircraft, calling upon other AOC positions (e.g., maintenance advisors) as necessary. After the off-nominal situation is satisfactorily resolved, the aircraft previously handed off by this HGO are returned to him/her if they have not already landed.

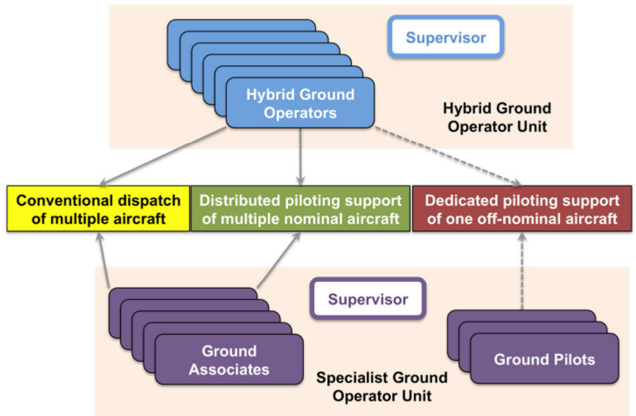


Figure 5. Examples of ground operator unit structures

4.2.2. Specialist Ground Operator Unit

In this organizational unit, there are two types of members. Ground Associates (GAs) are trained and certified to perform tasks associated with Conventional Dispatch and Distributed Piloting support for nominal aircraft. Ground Pilots (GPs) are trained and certified to perform tasks associated with Dedicated Piloting support for off-nominal aircraft. There would be many more GAs than GPs in these units.

Each GA generally serves multiple flights from pre-flight planning to gate arrival. However, if/when one of these flights encounters an off-nominal condition that requires dedicated support that aircraft is handed off to a GP identified by a supervisor. Prior to the handoff, the GP may be on standby or performing collateral duties and would need a handoff briefing from the GA who was serving the off-nominal aircraft. The GP provides one-on-one support to the off-nominal aircraft. The GA maintains general situational awareness of the off-nominal flight in case the GP requires dispatch support or any other AOC support. After the off-nominal situation is satisfactorily resolved, the GP returns the aircraft (if it has not already landed) back to the GA.

4.2.3. Harbor Pilot

A harbor pilot is a type of ground operator serving as a member of a hybrid unit or a specialist unit (or any other type of ground operator unit). The function of a harbor pilot is similar to current practice in maritime operations. For example, there could be a harbor pilot with comprehensive knowledge of the Metroplex airspace around the New York City airports. Each harbor pilot provides distributed piloting support to individual nominal aircraft as they climb and descend through a complex terminal area airspace. This could reduce the workload of other positions in the ground operator units, enabling each position to support more aircraft.

Use Cases

TC1 Normal/Normal Use Case: Normal arrival or departure at high density HUB airport (i.e., a Harbor Pilot ConOp):

This example case describes an arrival flight into Chicago O'hare (ORD) airport with a harbor pilot. The harbor pilot role refers to a ground pilot at a ground control station who can virtually "join" the Captain in the cockpit using advanced tools for communication. At approximately 100nm before the top of descent, the harbor pilot will contact the captain of an arriving aircraft (called SPO1 for this use case), as expected, and will introduce him/herself. Before contacting the Captain of SPO1, the harbor pilot will become familiar with the current status of SPO1 by reviewing the aircraft displays via the ground control station. After the introduction, the captain will brief the harbor pilot on his/her plan for the arrival and assign flight management duties (i.e., pilot flying and pilot monitoring duties typically assigned in current operations). The harbor pilot will then brief the arrival and current ATC operations for ORD. Normal flight duties for the harbor pilot will be to assume pilot monitoring role for the remainder of the flight. Thus, the harbor pilot will manage communications and CDU inputs for the flight while the captain will continue to manage all direct flight inputs - MCP, throttles, etc.). The two person crew will safely and efficiently manage all elements of the arrival and landing including taxiing the aircraft to the gate where the harbor pilot will verify with the captain that his services are no longer needed. After being released the harbor pilot will be "returned" and available to assist other arriving flights.

A second example is provided for this condition using a Departure flight from Chicago O'Hare (ORD).

For departures the harbor pilot will virtually "virtually join" the captain for the dispatcher flight briefing. The captain along with the harbor pilot will receive a dispatch briefing on their flight and any systems issues that are included. After the dispatcher's briefing, the harbor pilot will brief the captain on current airport and taxi operations since her last flight. The captain and the harbor pilot will brief the departure and flight operations through arrival at cruise altitude. The captain will assign flight duties for the departure - normally the harbor pilot will assume the role of pilot monitoring. However this assignment is totally at the captain's discretion. After the briefing the captain, being the only pilot onboard the aircraft, will conduct the walk-around while the harbor pilot enters and verifies information in the flight computers and request push -back and taxi instructions. The captain and harbor pilot will brief the taxi and departure operations. The flight departs normally and after arriving at cruise altitude, the harbor pilot will normally bid the -captain a safe flight and sign off the flight.

TC-2 Normal/ Off-Nominal Use Case: Off-nominal weather event -Airport closed due to weather

Ground dispatcher contacts SPO1 200nm from destination and advises that its current arrival destination is closed due to weather. The captain requests dedicated support from a ground pilot to replan the route to the nearest open destination which can accommodate the flight and passengers. For the Hybrid Ground Operator Unit, the dispatcher is a certified Ground pilot and hands off all other flights to the supervisor who assigns them to other HGOs. The dedicated HGO introduces herself as new ground first officer (GFO) for SPO1. For the Specialist Ground Operator Unit, the Ground Associate hands off SPO1 to a Dedicated Ground Pilot.

The Captain briefs any special needs for the flight and assigns the ground pilot the pilot monitoring task. The GFO consults the ELP for airports in the area which can accommodate their flight and advises the captain of the ELP suggested airport. They both concur on the choice and agree to the change. The GFO calls ATC and request ELP routing to new destination. ATC clears flight as requested and GFO loads routing into FMS. Captain and GRO concur on routing and are now 100nm from new destination and begin arrival briefing. Flight lands at new destination and taxies to the gate. During arrival GFO coordinates new destination with ground dispatch to manage passenger handling and advises the captain who briefs passengers.

Another example is provided for an off-nominal system problem of low fuel pressure light. In this scenario, the captain calls dispatch and reports a fuel system problem. She also requests dedicated support. Dispatch concurs with reported problem, based on information from his ground station which shows the same problem based on downlinked telemetry data. The ground dispatcher, and certified ground pilot, hands off the other flights to another ground dispatcher and introduces himself as new GFO for the flight. The captain briefs current state of the flight and fuel system problem. The captain assigns the pilot flying role to the GFO and also suggest that he handles all flight deck task while he diagnoses the fuel system problem. The captain runs the fuel system checklist, but they are unable to resolve the problem. Captain works with GFO and they agree that the flight needs to land short of their destination. The GFO consults ELP for airports in the area which can accommodate their flight. The GFO advises the captain of ELP suggested airport; they concur on the choice and agree to the change. The GFO calls ATC, declares an emergency and request ELP routing to new destination. ATC clears flight as requested and GFO loads routing into FMS. They concur on routing and are now 100nm from new destination and begin arrival briefing. Flight lands at new destination and taxies to the gate.

TC3 Incapacitated Pilot/Systems Normal Use Case: Incapacitated pilot during enroute flight with all aircraft systems being normal

For this TC3 and TC4, separate scenarios are provided for the RCO and SPO context due to the critical issue of pilot incapacitation.

RCO: Onboard sensors (passive and active) detects possible pilot incapacitation. The active sensor request a response from the pilot which it does not receive. The onboard automation confirms that the aircraft is in a stable flight mode and also alerts (aural horn and flashing lights) the resting crew member(s) to the possible pilot incapacitation. Onboard crew member(s) immediately return to the flight deck and take control of the aircraft. After verifying aircraft state the crew attends to the pilot who is unresponsive to crew input/questions. Since no medical care is available the aircraft is diverted and lands at the nearest suitable airport with medical facilities.

SPO (gradual incapacitation): Ground dispatch receives an alert message on the ACL suggesting that the pilot of SPO1 is not feeling well. Ground dispatch makes verbal contact with the pilot and the pilot indicates that she may have a mild case of food poisoning. Ground dispatch checks and besides report of feeling sick, the physiological readings for the captain (e.g., heart rate, blood pressure) are within normal range. The flight seems to be proceeding normally toward their destination for the next 30 minutes. Then, an alert message appears on the ACL indicating that vomiting was detected from the cameras. Dispatch contacts the captain and receives no answer. Dispatcher contacts the onboard flight steward to determine if the captain has left the cockpit. The steward answered no and indicated that he was unable to make contact with the captain. Then, another alert on the ACL appears indicating that expected pilot inputs at that phase of flight have not been detected. The dispatcher concludes that the pilot is incapacitated. The ground dispatch hands off all other flights and, being a certified ground pilot, assumes role of captain of SPO1. The Ground Pilot asks the flight steward to check up on the pilot. Unable to open the cockpit door from the outside, the flight steward requests the Ground Pilot to open the cockpit doors from the GCS. The flight steward opens the cockpit and finds the captain to be nonresponsive. With assistance of other flight attendants, they help the pilot to the main cabin and contact Ground Pilot to lock the cockpit door. With the onboard pilot now receiving medical attention and all systems being normal, the Ground Pilot of SPO1 decides to continue to their destination airport and advises ATC of the state of the flight but does not declare an emergency and that no special handling will be required. The flight proceeds to destination without further incident and lands and taxis to the gate.

SPO (sudden incapacitation): Ground dispatch receives an alert message on ACL suggesting that the pilot of SOP1 is incapacitated; physiological readings for captain are outside of normal range. Ground dispatch tries to contact captain and is unable to make contact. The flight seems to be proceeding normally toward their destination. Dispatcher contacts onboard flight steward who also was unable to make contact with the captain. Flight steward opens the cockpit and finds the captain to be non-responsive. The ground dispatch hands off all other flights and assumes role of captain of SPO1 given that she is a certified ground pilot. With the captain now receiving medical attention and all systems being normal, the Ground Pilot of SPO1 decides to continue to their destination airport and advises ATC of the state of the flight but does not declare an emergency and that no special handling will be required. The flight proceeds to destination without further incidence and lands and taxis to the gate.

TC4 Incapacitate Pilot/No Radios Use Case: Incapacitated pilot with lost link

RCO: Onboard sensors (passive and active) detect possible pilot incapacitation. The active sensor requests a response from the pilot which it does not receive. The onboard automation confirms that the aircraft is in a stable flight mode and also alerts (aural horn and flashing lights) the resting crew member(s) to the possible pilot incapacitation. Onboard crew member(s) immediately return to the flight deck and take control of the aircraft. After verifying aircraft state the crew attends to the pilot who is unresponsive to crew input/questions. The crew attempts to contact ATC and company but are unable due to problems with the radio. The crew sets transponder to 7600 (no radio) followed by 7700 (emergency). Since no medical care is available the aircraft is diverted to the nearest suitable airport with medical facilities. ATC being aware of the aircraft emergency provides priority service to the aircraft and it lands without incident.

SPO: Ground dispatcher receives an alert that no data is being received from SPO1. All telemetry link with other aircraft are normal at this time. Dispatcher tries all other forms of communication with the aircraft which all fail. During this time he reports possible lost link to ATC, providing standard emergency information - fuel, sob, etc.). Both dispatcher and ATC notice that the aircraft has changed beacon code to squawk 7600 no radio and 7700 emergency. Unknown to both ATC and ground dispatch, the captain has become incapacitated. The status of both the captain and communication link have been detected by onboard automation, which was responsible for the changes in beacon codes. Automation only, is now in charge of the flight. Contingency management software which is installed on all SPO flights, informs the chief Steward on the flight, consults ELP for nearest suitable airport and loads new routing into FMS. The aircraft, still with autoflight systems engaged, proceeds to new destination airport. On the ground the flight dispatcher also consults ELP for emergency routing and based on results is able to correlate aircraft' new track with ELP suggested route. The dispatcher communicates new projected routing to ATC who is managing the emergency flight. The onboard automation combines ELP routing information with autoflight technology to conduct the en route descent and arrival into the selected airport. ATC has advised all participating ATC facilities the aircraft is an emergency and no radio; all provide priority handling of the flight. The aircraft lands and stops on the runway. Now in cell phone contact the chief steward informs dispatch and crew support that the captain has been incapacitated for the last 300nm of the flight. Ground support personnel manage passenger disembarkation and towing of the aircraft. There was a doctor onboard the flight so the captain has been well taken care of and is now conscious.

5. HUMAN-AUTOMATION FUNCTION ALLOCATION

This section presents some considerations for allocating functions between human operators and automation. First, the cost tradeoffs between automation and human operators are conceptualized. Next, some high-level requirements for new cockpit automation are introduced. Finally, some observations are made about desired collaboration between human operators and automation.

5.1. Options Space

In SPO, the captain (in the cockpit) and ground operators (in an operations support center), working as a team, will interact with advanced automation tools (located in the cockpit and at a ground station) to maintain flight safety and efficiency. Some of the simpler functions currently performed by a human pilot in a two-person cockpit, such as reading checklists and conducting cross-checks, are good candidates for automation, although such systems will have to possess some of the same characteristics as the operator they are replacing. Highly complex functions, such as formulating options to address challenging off-nominal flight conditions, are likely best suited to human cognition given the current state of automation sophistication and reliability. Other functions could be performed by humans assisted by various levels of automation; some preliminary recommendations are reported in Johnson et al. (2012). Higher levels of automation will generally require fewer human ground operators to service a given fleet of aircraft. It is likely that there will be a progression, along the SPO implementation timeline, from a larger ground operator complement using lower levels of automation to a smaller ground operator complement using higher levels of automation.

Figure 6 is a notional representation of the relationship between the level of automation and the total number of operators required to support a fleet of aircraft at a given moment. In conventional operations, each aircraft has two pilots, and each dispatcher supports around 20 aircraft, hence a fleet of 100 aircraft needs a total of about 210operators at a given moment. The cost of operations depends on the number and qualifications of the operators as well as the level of automation; therefore the cost of conventional operations is notionally proportional to the distance of the blue dot from the origin of the axes in Fig. 6.

The green oval represents the domain of various options for human-automation function allocations for SPO. Consider an implementation of SPO, indicated by "A" in Fig. 6, where each first officer is replaced by a ground operator. Hence the total number of operators remains the same, and a higher level of automation/equipage (e.g., air-ground voice/data links, ground pilot stations) is required. This instantiation of SPO has little merit because its implementation cost would likely not provide any savings relative to the baseline of conventional operations. Now consider an implementation of SPO, indicated by "B" in Fig. 6, where each first officer is effectively replaced by highly advanced cockpit automation (electronic pilot associate). The total number of operators is essentially cut in half, relative to the baseline of conventional operations. However, the cost to build such highly sophisticated automation would likely be very high and could result in either a cost advantage or disadvantage over conventional operations (or might simply be a wash as indicated in Fig. 6). A cost-effective solution is indicated by "C" in Fig. 6. Relative to conventional operations, it requires significantly fewer operators and significantly more automation, but much less automation than option "B". Noting that the distance from the axes origin is a proxy for cost, it can be seen that the overall operations cost for option "C" is lower than that of conventional operations (indicated by the arc in Fig. 6).

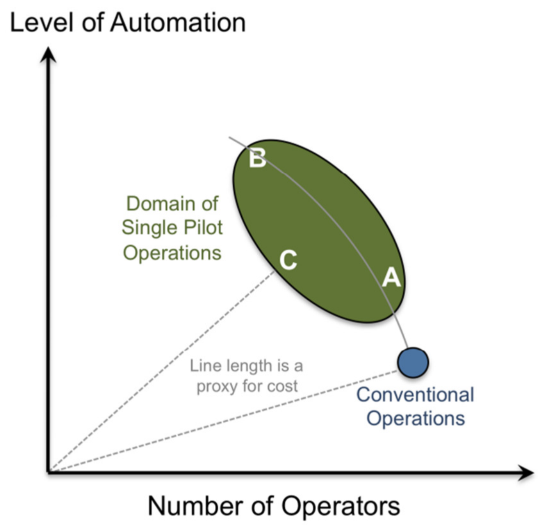


Figure 6. Options space for implementation of SPO

The development of an SPO ConOps requires an exploration of the options space outlined above, with the goal of identifying an SPO implementation that has characteristics similar to option "C" in Fig. 6. For a point of interest in the options space, a key question is: what are the requirements to implement this design of SPO at the same level of safety as conventional operations?

5.2. Cockpit Automation Requirements

A key requirement for SPO implementation is advanced automation (Schutte et al., 2007) that provides onboard support functions at a level well beyond what is currently available in modern commercial aircraft. While it may be tempting to simply automate as many of the current pilot functions as possible, distancing the captain from the flight/mission could erode situation awareness (SA) and cognitive readiness. Over-automation would increase the likelihood of human error and thus handicap the captain. Therefore, there may be functions and tasks that could be automated from a technological standpoint, but should not be automated in order to maintain the captain's SA, engagement, and skill retention.

Some of the cockpit automation capabilities required for SPO already exist, e.g., nearly all modern aircraft can fly a preprogrammed route and land with little or no human aid. However, there are two important automation capabilities that require significant advancement: (i) interaction and task exchange, and, (ii) pilot health monitoring.

5.2.1. Interaction and Task Exchange

The capability development required here is to make the automation more of a team player, rather than a silent and subservient workhorse. This requires changes in the way the automation interacts with the human, rather than what tasks it performs. For example, cockpit automation needs to clearly inform the captain about what it is doing, and to confirm important parameters (e.g., altitude settings). In response to a command from the captain, the automation must repeat the command for error-checking, inform the captain that it is executing the command, and notify the captain when it is done. In short, the automation must follow current best practices for human-to-human CRM.

The automation will be called upon to assist the captain in declarative, retrospective, and prospective memory items. Required tasks of the automation may include checklists, task reminders, challenge-and-response protocols, and recall of information or instructions provided by human actors such as ATC personnel or ground operators. But these tasks cannot be rigidly prescribed. The human brings certain unique capabilities to the cockpit as does the automation. Both types of capabilities are required when performing basic interconnected tasks such as: Aviate, Navigate, and Communicate. It may be detrimental to assign one task (e.g., Aviate) entirely to the captain and leave the others entirely to automation. It is also highly unlikely that the level of automation assistance would remain constant for the entire mission; for example, the level of automation will change in the Aviate task, depending on whether the captain is manually flying or being assisted in some way by the automation.

The unique capabilities of the human and the automation may be required at different times. The captain and the automation have to be able to hand tasks back and forth between each other in a simple, quick, reliable, and well-understood fashion. This reallocation of tasks between them (or between the captain, automation and the ground operator) will likely be required in off-nominal or unique situations. In these times, workload on the human is already high, and if the captain has to "hand off" the aircraft to the automation in order to deal with a navigation or systems problem, he/she must be able to do so quickly and with full confidence. Similarly, if the automation has to hand control back to the captain because it is reaching its limitations, it must inform the pilot ahead of time and provide SA information to the pilot about why the hand off has become necessary (e.g., with what aspects the automation is having difficulty, or is unable to perform.)

5.2.2. Pilot Health Monitoring

The second automation capability that requires development is the monitoring of the captain's physiological and behavioral state. This health monitoring serves two purposes: assessing the capacity of the captain, and catching mistakes made by the captain. In multi-crew flight decks, the crewmembers monitor each other. It is unlikely that automation will advance to the full monitoring capability of a human crewmember in the timeframe of SPO implementation, but there are many important health factors that could be monitored by the automation.

Physiological sensors can assess health factors ranging from simple heart rate variability and pulse oxygen levels to more elaborate measures such as electro-encephalograms (EEG) and functional near-infrared spectroscopy (fNIRS). The challenge here is to make the measurements as non-intrusive and comfortable as possible – the idea of wiring the body with multiple sensors is highly undesirable for human acceptance. Still, technology continues to advance in remote sensing capability so that no physiological measurement should be ruled out at this point. These measurements would provide a primary basis for assessing whether the pilot is healthy and responsive.

Behavioral measures are also important. Monitoring the captain's actions with regard to instrument and inceptor control, communications, and scan patterns is critically important to detect piloting errors and to make assessments of cognitive capability. Prescriptive assessments, where the human's behavior is compared to what he/she should be doing at any particular time or after performing a particular task (e.g., Task A, then Task B, then Task C), are useful but are often overly rigid and not flexible for real-time operations. Another approach is to monitor the human's actions to ensure that he/she does no harm, that is, does not do something that would jeopardize the flight. More than likely, a combination of these two methods will be required.

Pilot health monitoring can also be performed by ground operators who can query the captain or watch a video feed of the cockpit to determine the physiological and behavioral state. This assessment, along with health monitoring data provided by the automation, will be the basis for a decision to declare the captain incapacitated and transfer command authority to ground operators and/or cockpit automation to land safely.

A 2004 FAA report on pilot incapacitation, examining a 5-year period between 1993 and 1998, found that the probability that an inflight medical event (i.e., pilot incapacitation) would result in an aircraft accident was .04 (see http://www.faa.gov/data_research/research/med_humanfacs/oamtechreports/2000s/media/0416.pdf). Similarly, an Australian Government report (2007)covering the period of 1975 through March 2006, found very low occurrences of pilot incapacitation that led to a reported accident (N = 16) or incident (N = 82). In 10 occurrences, though, the outcome of the event was a fatal accident, and all of these accidents involved single-pilot operations (see http://www.atsb.gov.au/media/29965/b20060170.pdf). Evans and Ratcliffe (2012) indicated that the incapacitation rate in current operations can provide a basis for quantifying the acceptable risk of single pilot operations in commercial flight.

From both reports, the cause of incapacitation can be grouped into four main categories of: loss of consciousness, cardiac (e.g., heart attacks), neurological (e.g., seizures), and gastrointestinal (e.g. food poisoning). The probability of pilot incapacitation also increases with age (FAA, 2014; Huster, Muller, Prohn, Nowak, & Herbig, 2014).

Research on Pilot incapacitation have examined methods for: Detection of **Inactivity** (Behavior; motion sensors; e.g., Trujillo & Gregory, 2014), Detection on **Alertness** states and **Fatigue** (Face recognition, eye tracking, behaviors, psychophysiological monitoring for signs of loss of consciousness or drowsiness; e.g., Steffin & Wahl, 2003); Detection of **high environmental stress and workload** (psychophysiological monitoring signs of distress; Sledge, 1978). The Table below provides some indicators of inactivity, alertness, and illness that can be measured for the monitoring of pilot incapacitation. In addition, pilot report of signs of illness or physiological and behavioral indicators of potential impairments and incapacitation can be recorded. It should also be noted, that once the pilot is declared incapacitated, the plane should not only be transferred safely to another pilot (RCO) or to the ground (SPO), but that the pilot receive medical help. This is especially important in SPO if the cockpit can only be unlocked from the inside.

	Loss of consciousness	Cardiac	Neuro-logical (seizures)	Gastro-intestinal
Pilot Acknowledgement of not feeling well				
Verbal (headache, stomach pain, chest pain, etc.)	x	x	x	x
Action (press button)	x	x	x	x
Inactivity				
Muscle tone (stiff/limp)			x	
No Response-Actions (e.g., Langley model)	x	x	x	x
No Response-Communication*	x	x	x	x
No Response-Eye tracking (monitoring and cross-checking of flight instruments)	x	x	x	x
Alertness/Fatigue				
Facial Eye (staring, closing, shut)	x			x
Facial Mouth (drooling)			x	
Irregular EEG activity	x		x	
Subjective Report	x			x
Stress and workload				
Heart Rate	Sudden drop	x	x	
Blood Pressure	Sudden drop	x	x	
Sweating			x	x
Irregular breathing		Shortness of breath		
Premature Ventricular Contractions		x		

(predictive of heart attacks)				
Body temperature	**x**			**x**
Other Signs of Illness				
Facial Eye (twitching, blinking, rolling)			**x**	
Face Mouth (lipsmacking, chewing, swallowing)			**x**	
Muscle (jerking or twitching movements)			**x**	
Nausea/vomiting		**x**		**x**
Loss of bladder or bowel control			**x**	**x**
Reduced blood flow	**x**			

*Flight crewmembers should be alert to subtle incapacitation:

- If a crewmember does not respond appropriately to two verbal communications, or
- If a crewmember does not respond to a verbal communication associated with a significant deviation from a standard flight profile

5.3. Collaboration

While it is important to describe the roles of each of the major players in SPO (Captain, Ground Operator(s), Automation), it is also important to remember that none of these players acts independently. In order for SPO to be feasible, each player must be able to shed and take on tasks and responsibilities as/when needed.

Not only is pilot incapacitation a critical concern, but the prospect of automation failure, and/or communications failure must also be addressed. If the automation is malfunctioning (e.g., stuck in a mode, erroneous flight data, software bug) or non-functional (e.g., total failure of autopilot, guidance, secondary systems), the captain and ground operators should be able to safely land the aircraft and perhaps safely complete the mission. Likewise, if the communications network is impaired (e.g., decreased bandwidth) or non-functional, the Captain and automation should be able to safely land or perhaps even complete the flight as planned.

This flexibility is not only important in off-nominal conditions, but in nominal conditions as well. One example is when the captain has to leave the cockpit for a short break. In such cases, the automation will be flying the aircraft; however, the ground operator would be called upon to closely monitor the flight (and perform remote piloting functions as necessary) and update the captain on the flight's status when he/she returns to the cockpit. Similarly, the captain may sometimes need to manually fly the aircraft; in such cases, some communications, navigation, or systems tasks that the captain might normally have performed (e.g., normal checklists) may be temporarily assigned to the automation and/or the ground operator.

6. CONCLUSION

A framework has been presented for the development of an RCO/SPO ConOps by outlining options for key dimensions of the ConOps design space. First, a taxonomy of operating conditions was defined, spanning the dimensions of pilot condition and flight condition. Next, function allocation among various types of human operators was discussed, as well some candidate structures for ground operator units and the nature of services their operator positions would provide to the captain. Then, an options space was examined, with dimensions spanning the number of air-ground operators and the level of automation; minimizing the total number of operators does not necessarily provide the most cost-effective solution. Finally, requirements of advanced cockpit automation were outlined. Taken together, the above material sheds light on the roles/responsibilities of the various air and ground operator positions as well as the tools required to perform their tasks and collaborate with each other.

The RCO/SPO ConOps framework presented in this work is being used to guide the design of NASA's human-in-the-loop simulation studies; a recently completed study is reported in Lachter, Brandt, et al. (2014) and follow-on studies are in various stages of planning/execution. The results of these operational studies, along with cost-benefit analyses, will be used to develop an RCO/SPO ConOps meeting the requirements that it be technologically feasible, yield economic benefits, and provide a level of safety no less than conventional two-pilot operations.

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