Effects of Automation in the Aircraft Cockpit Environment: Skill Degradation, Situation Awareness, Workload

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Abstract

Commercial aviation has progressed quite a bit from the early days of the 1900’s to the present-day period. This progression we refer to is in relation to technological advancements, namely, automated systems. Today we use automation for marketable safety and economic benefits such as fuel savings, enhanced reliability, ease in maintenance support, reduction in crew complement, reduced crew training time, and increased cross-crew qualification among similar aircraft types. However, despite the many benefits of using automated systems in the cockpits of commercial aircraft, there are many existing issues that need to be resolved.

After more than a decade of experience with these advanced automated systems, operators and researchers are realizing that the benefits that it initially promised have not been fully fulfilled yet. Some aviation researchers have discovered that increased automation may actually be creating new hazards. Amongst those disturbing trends are the ways in which flight crew workload is affected. It was expected that automation would reduce workload, freeing the crew to be able to perform more complex tasks, but contrarily they are finding that most workload reductions occur when work levels are already low. Also, the reduced workload seems to create a trend toward lack of vigilance and even boredom among the crews of highly automated aircrafts. Automated systems can actually increase crew activity during higher workload phases of the flight, such as departure and arrival, distracting the pilots from critical vigilance for outside traffic and awareness of position, terrain, and the general ATC situation.

The automation issues which impact safety include, but are not limited to, flight crew workload, reduced situation awareness, degradation of basic piloting skills, and incompatibilities of cockpit systems with the Air Traffic Control system. This paper has focused on three of these existing human factors issues based on their importance as cited in previous literatures. After establishment of the theoretical framework for the mechanisms by which automation impacts these three salient human factors issues, empirical evidence is provided to back up the theoretical observations. Based on the research conducted, we feel strongly on the existence and criticality of human factor issues attributed to imperfect automation. The consideration of these human factors issues in the early design phase of automation will foster the full realization of the benefits to be derived from automation.
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1. Introduction

The commercial aviation industry has come a far way in terms of technological advancements. These advances are clearly visible if we were to look at a traditional aircraft cockpit and compare it to today’s modern flight deck, say a Boeing 787 or Airbus A380. What you would notice is an array of “glass” technologies and a complicated array of buttons. For the novice observer, this may just “wow” them and not mean much, but for trained eyes like ours - certified pilots - this means that more automation is present. But what exactly is automation? Automation is essentially any component that removes the necessity for direct human control of certain processes (Sherman, 1997). However, to better understand the topic of automation as applied to commercial aviation, we need to move beyond the basics, and this is what our paper aims at doing.

1.1 Developments of Cockpit Automation

During the early days of aviation, there was no such thing as automation. Pilots controlled the aircraft by manual inputs, and these inputs were determined based on feedback from elementary cockpit instruments, e.g. magnetic compass and engine gauge. The first noticeable signs of aircraft automation were in 1914, and it began with systems that stabilized the aircraft’s attitude via mechanical manipulations of the aircraft control surfaces. One example of such a system was Sperry’s autopilot, named after its inventor, Lawrence Sperry (Landry, 2009). It revolved around the same concept governing the gyroscope compass. More specifically, the Sperry detected deviations in orientations from the neutral position of the aircraft. The detections by the Sperry were then translated to drive the control surfaces of the aircraft based on specific control laws. Sperry’s autopilot was the first invention to fall into the class of control automation, whose purpose was to replace human control of the aircraft with machine control.

In the 1960’s warnings and alerts, which are another form of automation were being developed. The first signs of warnings and alerts originated with the development of the instrument ‘off” flag, which indicated a malfunction. Eventually, in the 1970s, engine fire warning systems were installed in the Boeing 707, Boeing 747, and Boeing 777. The purpose of warnings and alerts is to basically replace the need for the pilot to manually monitor hazardous conditions. For instance, airspeed indicators were developed to help pilots track and maintain a
sufficient airspeed to prevent an aerodynamic stall. Now, in modern aircraft, the airspeed monitoring function is replaced by a stall warning device, which alerts the pilot to an impending stall without the pilot having to monitor airspeed and compare it with the memorized stall speed (Landry, 2009).

Finally, information automation became visible with the introduction of the flight director. The flight director reduced mental calculations required by pilots. It did this by providing intercept angle guidance to pilots for a desired course and glideslope to a runway. Essentially, the purpose of information automation was to provide the pilot with access to information they would otherwise have to manually retrieve or calculate. For instance pilots will follow written checklist for portions of the flight, and have procedures to ensure that checklist items are completed. In some aircraft, checklists are presented in electronic format, with the system ensuring that checklist items are completed (Landry, 2009).

To put things in perspective, automated systems were first developed and are continuously being improved in aviation because of the potential benefits they offer. In fact, researchers have documented a variety of automation success stories in aviation: Amalberti, 1998. These success stories sum up to marketable safety and economic benefits, e.g. fuel saving, enhanced reliability, ease in maintenance support, reduction in crew complement, reduced crew training time, and increased cross-crew qualification among similar aircraft types.

1.2 Human Factors Issues Related to Cockpit Automation

There are probably many cases where automated systems, as a result of being introduced to the aircraft flight deck, have provided desired benefits (as mentioned before) and extended system functionality well beyond the existing capabilities of the human. However, with those advantages came a price. This price is paid as a variety of human factor issues, which include but are not limited to, flight crew workload, reduced situation awareness, degradation of basic piloting skills, and incompatibilities of cockpit systems with the Air Traffic Control system.

Note that as most automation has been piece-meal, covering certain functions but not others, humans have remained in the system as integrators – monitoring the automation for some functions and performing others themselves (Ensley, 1996). Furthermore, Wickens (1992) and
Wiener (1985) noted that because the complexity of the automated systems that are to be monitored continues to increase, when things go wrong, they go wrong in a big way.

To aid in assessing the effects of automation in the aircraft cockpit environment, this paper focuses on three areas: skill degradation, situation awareness and workload. The main sections that follow outline the impacts of automation on the latter three areas and give recommendations on how to address them.
2. Skill Degradation

Automation has many advantages (e.g. reduced workload), but by definition, it removes the necessity for direct human control of certain processes (Sherman, 1997). This removal of the pilot from the manual control process of flying the aircraft brings with it the inherent disadvantage of skill degradation through complacency and non-practice. This is particularly true because if the automation constantly performs a decision making task once assigned to the human, eventually there will come a time where the human operator will not be as skilled in performing that same task (Parasuraman, Sheridan, & Wickens, 2000). To clarify, when we refer to skill degradation in this paper, it is in relation to the manual flying skills of the pilot.

This section on skill degradation is divided into four main subsections. Section 2.1 aims at defining manual flying skills in terms of two components: psychomotor and cognitive. Section 2.2 then illustrates how each of the two components can be negatively affected as a result of automation. Upon highlighting potential skill degradation issues, section 3.3 gives supporting evidence to show that skill degradation actually exists and has been sighted in the literature. General evidence of skill degradation being an issue is first provided. Next, supporting evidence from empirical studies are given. After which, accident analysis data supporting skill degradation is presented. Finally, case studies correlating skill degradation to automation are presented. Section 2.4 finishes by talking about how skill degradation can be addressed and possible challenges in doing so.

2.1 Definition of Manual Flying Skills

Manual flying skills are essentially those which are displaced by the automation present in the aviation flight deck (Ebbatson, 2009). As briefly mentioned before, skill degradation can manifest itself in the reduction of the two manual flying skills: (1) psychomotor skills and (2) cognitive skills. The psychomotor aspect is observable, e.g. the physical act performed by the pilot on the controls to orient the aircraft in space or change its flight trajectory. The cognitive aspect is hidden, e.g. the necessary actions performed by the pilot to respectively monitor, plan and predict current and future aircraft states and trajectories to satisfy required navigation objectives. Degradation in psychomotor skills and cognitive skills are issues most critical following a failure of the automation. For instance, if the pilot operator’s skill has degraded
overtime and a critical task which is automated fails, the operator may take over the once automated task in an incorrect, inappropriate, or inefficient manner and this could potentially lead to the occurrence of a near miss event, an incident, or a catastrophic accident.

There are different phases of flight, and as a result, the demands placed on the manual flying skills of the pilots vary drastically in relation to those phases. Figure 1 illustrates the phases of flight through which aircraft have to transition during any given flight. Generally, during the phases of flight where the aircraft is in a steady state, the demand placed on the pilot’s manual flying skill is reduced. On the other hand, if the aircraft is in a transitory state, the opposite is true.

![Figure 1: Aircraft state transitions over a typical flight profile (Ebbatson, 2009)](image)

Starting with the taxi and takeoff phases, the aircraft goes through a few dynamic states. While taxiing, the pilot constantly has to adjust the power setting and apply breaks as necessary to safely maneuver the aircraft to the active runway. Once on the active runway, the takeoff procedure begins and the pilot adjusts the power once again and has to constantly ensure that the aircraft’s path is along the centerline of the runways by adjusting rudder (left/right) inputs to the aircraft. Once the aircraft actually takes off the runway, its configuration changes (e.g. gear and flaps are retracted).
In the initial climb phase, the aircraft is in a relatively steady state. During this phase of flight, the pilot rarely adjusts the thrust settings or aircraft configuration. Occasionally, the pilot may be required to stop climbing and level off due to operational procedures or airspace requirements, however, the high level goal of this phase is to climb at a constant speed and therefore aircraft settings are usually fixed. Considering a situation where no automation is present, the burden on the pilot’s flying skills is directed toward laterally navigating the aircraft. To achieve the latter, the pilot must monitor and synthesize the flight and navigational data to develop a mental model for the aircraft’s current and future horizontal position, and how it correlates to the horizontal restrictions and goals, and necessary path corrections for achieving those goals.

Note that the cruise phase of flight is expected to be similar to the initial climb phase in terms of demand on manual flying skills. During the cruise phase, steady aircraft settings and configurations can be expected, with minimal changes to altitude and course. As a result, the amount of psychomotor effort and cognitive input required to, respectively, control the aircraft and monitor the health and status of the aircraft is minimal.

The descent, approach, landing, and missed approach (if necessary) phases of flight are quite different in the demand they place on a pilot’s manual flying skills. For one, these four phases of flight are quite dynamic and transient. During these phases of flight, there is a lot of lateral maneuvering required by the pilot to achieve safe operational goals, while taking into consideration airspace restrictions. As a result, the pilot is required to make many changes to the aircraft thrust setting and configuration to achieve favorable or required descent profiles. Summing up the responsibilities of the pilots during these phases, it can be determined that their mental models for assessing current and future states of the aircraft, and planning future trajectories will be very dynamic and prone to greater probabilities of cognitive failures. The demanding nature of theses phases of flight support statistics correlating these areas to greatest percentage of aircraft accidents.

2.2 Impact of Automation on Manual Flying Skills

Now, that we have a clear understanding for the definition of manual flying skills and how it varies with the different phases of flight, the following subsections will emphasize the
negative impacts that automation has on manual flying skills in terms of the psychomotor and cognitive components.

### 2.2.1 Psychomotor Skill Degradation

Flying in today’s technologically advanced and highly automated aircraft cockpit environments has transitioned the human operator from performing more manual flying tasks to performing more monitoring tasks (Puentes, 2011). It doesn’t take long (any time at all) for psychomotor skill performance to start deteriorating as a result of non-practice due to the implementation of automation. In fact, studies have found that flight skill decay is present regardless of the duration of elapsed time without practice (J. M. Childs, Spears, & Prophet, 1983). Moreover, Ammons et al. (1958) found that skill degradation increased as the time of non-practice increased, however, it quickly returned to a proficiency of 75% in as little as five minutes of practice. It should be noted that the type of operation being conducted by the human operator will typically determine how much practice a pilot receives. For instance, Puentes (2011) noted that short trips performed by domestic carriers will offer both pilots a daily opportunity to practice their manual flying skills, whereas, pilots flying internationally may only get the chance to practice their manual flying skills a few times a year. It should be further noted that relief pilots/second officers (which are not always present) on international flights are even worse off in maintaining their manual flying skills since they serve as back up for the main flight crew (captain and first officer).

### 2.2.2 Cognitive Skill Degradation

Flying an aircraft does not exclusively involve psychomotor skills but is also dependent on cognitive processing. In fact, we know that two control behaviors are required by the pilot for manual aircraft control: (1) Open-loop and (2) Closed-loop (Baron, 1988). Open-loop behavior refers to the psychomotor component we spoke about in the earlier section, and is independent of feedback. Closed loop behavior is the cognitive component we are referring to in this section, and is dependent on feedback. The feedback comes from cockpit instrumentation, visual, vestibular, somatic, proprioceptive, and auditory cues. In closed-loop control, the pilot monitors and refines their actions based on feedback to reduce any variations between the observed and the actual desired aircraft state.
Figure 2: The series model of pilot control (adapted from McRuer, 1982)

To make the connection between the importance of cognitive processing and Figure 2, take the following example into consideration: The pilot ultimately wishes to fly the aircraft at an altitude at 10,500ft. The control system limits the pilot to the direct manipulation of the aircraft’s basic six degrees of freedom, i.e. translational movements (heaving, swaying, surging) and rotational movements (pitching, yawing, and rolling). As a result, the pilot must then manipulate lower order parameters (e.g. attitude and airspeed) in order to control higher order goals (e.g. altitude and flight path). The pilot must close several loops synchronously, and in the series model, these control loops are shown nested within each other. The ‘inner’ attitude control loop is closed in order to satisfy the ‘outer’ flight path control loop. The control system employed in large transport aircraft can be a bit challenging because there are significant time lags between the pilot making a control input and the resulting effect in an outer loop parameter (i.e. a control wheel input causing a lateral displacement of the aircraft’s position). Controlling such an aircraft would require the pilot to anticipate the aircraft’s likely and desired flight path, and this required projection consumes a great amount of cognitive resources. Therefore, also considering that making corrections to heading, altitude, or airspeed based on information received from the primary flight instruments constantly occur throughout any given flight, it is clear that cognitive processing is important. Note that mental models, which are simplifications of the real system dynamics, help in the effective control of this cognitive process.
Having understood the importance of cognitive skills, like psychomotor skills, it is safe to say that cognitive processing skills degrade as a result of disuse (Arthur Jr, Bennett Jr, Stanush, & McNelly, 1998; Wright, 1973). Wright (1973) discovered that instrument flying placed significant cognitive demands on pilots and skill related to such tasks were most affected after a period of non-practice. Arthur Jr, Bennett Jr, Stanush, & McNelly (1998) found that cognitive skills learned early in flight training but not used for extended periods of time decrease over time. Research has shown that pilots who had significant experience flying non-glass cockpit aircraft developed robust mental models of performance characteristics during different phases of flight (Ebbatson, 2009). These robust mental models (heuristics) allowed those pilots to reduce their cognitive processing demands imposed by “closed-loop” processing by allowing quick and accurate anticipation and prediction of how the aircraft would perform. The opposite was true for less experienced pilots. With the technological shift toward more automated systems in the aircraft cockpit, the problem of deteriorating cognitive skills exists because over-reliance of the automation inhibits the ability of the pilot to develop the required robust mental models for manually flying an aircraft. To support the hypothesis that non-practice decays cognitive processing, Ebbatson (2009) conducted research on the flight skills of pilots transitioning from light twin engine training aircraft to modern airliners. Pilot performance was tested before and after a 40-hour jet training course. Ebbaston found that pilots who did not have the experience of developing a robust schema for predicting aircraft performance had difficulty in predicting where in space the aircraft would arrive at a given period. Contrarily, when pilot performance was measured after the 40-hour jet training course, an increase in their ability to anticipate the performance of the jet aircraft and make smooth and precise controls for the desired outcome also increased.

2.3 Evidence Supporting Skill Degradation as a result of Automation

Mentioning that skill degradation of a pilot’s manual flying skills as a result of automation is probably not convincing enough to elicit the seriousness of the issue. Hence, what follows in these subsections are supporting evidence to add credibility to the latter claim.
2.3.1 General Evidence

To start off with general proof that skill degradation of manual flying skills as a result of flight deck automation is an issue, let’s take a look at Figure 3. The graph in Figure 3 was adapted from a database aimed at developing a comprehensive list of flight deck automation human factors issues and compiling a large body of data and other evidence related to those issues.

![Figure 3: General evidence supporting skill degradation (Research Integrations, Inc, 1997-2007)](image)

Specifically, Figure 3 shows on the x-axis, the strength for the supporting evidence, where negative values do not support the issue, and positive values support the issue. Also note that the smaller or larger the number, the weaker or stronger the supporting evidence for that issue, respectively. The y-axis simply shows the number of supporting evidence that falls into each rating strength category. Therefore, looking at Figure 3, it is clear that even though there is refuting evidence against the issue of skill degradation as a result of automation, there is also a fair amount of strong supporting evidence for the issue. The point to take away from this opening section is that evidence exists to support the claim that manual flying skills are negatively impacted as a result of automation in the airline cockpit environment.
2.3.2 Empirical Studies

The majority of commercial pilots today are flying advanced aircraft. These aircraft are advanced in terms of the technology equipped in the cockpit environment. To support this claim, surveys have noted that less than 50% of pilots have ever flown two years or more on aircraft that weren’t equipped with glass cockpits (Gillen 2008 as referenced in Puentes, 2011). New pilots today lack the original stick-and-rudder skills and mental models and schemas of older generation pilots. However, the pilots are not solely to blame for the overuse of automation since airlines promote its use as a result of the high levels of precision the automation brings to the operations, allowing the airline to fly more efficiently, hence saving money (Wiener & Curry, 1980). Simply put, technology is out pacing the human operators and becoming a means to increase output while saving cost. This is resulting in a new pilot generation that can only operate aircraft with the assistance of automation, which in turn, lowers the confidence levels in their manual flying skills (Gillen 2008 as referenced in Puentes, 2011).

There have been many studies on the manual flying skills of current airline pilots who fly highly advanced and automated aircraft. Two examples of such studies are given by Ebbatson, 2009 and Gillen, 2008 as referenced in Puentes, 2011. Both studies used high fidelity simulators to assess pilot performance while performing standardized manual procedures. Certified check airmen were used to evaluate the pilot performance. In the study conducted by Gillen, 2008 flight maneuvers were tested in the flight simulator and the check airman gave performance grades to the pilot based on the FAA standard. A scale of 1-5 was used to assess pilot performance. Excellent performance was reflected by a grade of 5; performance at the highest level of aircraft pilot certification or Airline transport pilot (ATP) level was reflected by a grade of 4; basic instrument certification skill level was reflected by a grade of 3; and major deviations resulting in loss of control or crash of the aircraft were reflected by a grade of 2 and 1, respectively. Gillen discovered that most airline pilots perform close to the basic instrument skill level for the maneuvers they performed despite their high level of experience with the major airlines they work for. However that there was no correlation between total number of flight hours and pilot performance, and all pilots were current and proficient in their assigned aircraft.
In the other study conducted by Ebbatson, 2009, check airmen were also used to evaluate pilot performance on maneuvers performed in the flight simulator. However, in this study, additional data was collected from the simulator to further assess the performance of the pilots. The check airman grading was used for validating the information obtained from the data collected from the flight simulator. The manual flight performances of sixty-six current and proficient pilots were evaluated immediately after they received their annual proficiency checks. The maneuvers that were performed by the pilots in the simulator study were typical of the maneuvers they would have to perform for their annual proficiency check, e.g. ILS approaches, go-arounds, and missed approaches. The findings from the study revealed that the manual flight skills of pilots were near the minimum acceptable range for basic instrument flight competency. Airspeed control on the ILS approach was vulnerable to skill decay. Ebbatson found that the amount of manual flight practice the pilots received prior to the test and during the course of typical airline operations was directly associated with the amount of skill degradation observed across all pilots evaluated during the course of the research study. He concluded that the manual flight skills of pilots flying highly automated aircraft degraded despite previous operational experience accumulated or types of aircraft flown during the pilot’s career.

2.3.3 Accident Analysis Data

70% - 80% of aviation accidents occur as a result of human error (O’Hare, Wiggins, Batt, & Morrison, 1994). However, it is hard to isolate causal factors that contribute to such accidents, and more so, to enumerate the ones that occur as a result of manual skill deficiencies of the pilots. For this reason, frameworks such as the Human Factors Analysis and Classification System (HFACS) have been created, as shown in Figure 4. HFACS is widely accepted and it is based on the Swiss Cheese accident model (Reason, 1990).
It should be noted that when trying to determine the contributory actions of flight crew to accidents, as in the case of trying to determine evidence of manual flight skill deficiencies, the focus should be on ‘Unsafe Acts’ (see Figure 3). Decomposing ‘Unsafe Acts’, manual flight skill deficiencies would fall under ‘Skill-Based Errors’ (see Figure 3). The reason for this was supported by the fact that Shappel & Wiegmann, (2000) cited visual scanning breakdowns, poor technique, and over-controlling the aircraft to be common aviation skill-based errors.

Ebbatson, 2009 noted that Weigmann and Shappell, 2001 illustrated using HFACS on the US National Transport Safety Bureau’s (NTSB) commercial aviation accident record for 1990 – 1996, that 63.6% of aircraft accidents occurring as a result of scheduled airline passenger or cargo operations involved at least one skill-based error. The researchers also went on to note that errors in this category were the most noticeable and remained roughly consistent over the seven
year sampling period. Likewise using HFACS, the Australian Air Transport Safety Bureau analyzed accidents involving Australian registered aircraft occurring during the period of 1993-2002. The board found that 84% of Australian accidents and 77% of US accidents involved at least one skill based error. 80% of the accidents were representative of general aviation operations. Note that assessments using HFACS do not explicitly show the number of accidents related to the degradation of manual flying skills. However, it can be suggested that since a large portion of accidents involving large air transport aircraft involve skill-based errors, manual skill deterioration should represent a significant vulnerability to the safety of flight operations.

An analysis conducted by the UK Civil Aviation Authority (CAA) Accident Analysis Group looked at global fatal accidents occurring during the period of 1997-2006 involving large transport aircraft. Instead of the HFACS, a bespoke taxonomy was used to give more direct evidence about the significant role of flight crews’ manual flying skills in large transport aircraft accidents. The bespoke taxonomy identified primary causal factors, causal factors, causal groups, and circumstantial factors. The results from the CAA analysis showed that 78% of the fatal accidents were attributed to the flight crew as the causal factor. Flight handling accounted for 14% of the primary causal factor and 29% of causal factors. Flight handling was primarily associated with poor speed management and control of aircraft attitude, following an engine failure, resulting in the stalling of the aircraft. When the CAA sorted results by consequence, 17% of events involved loss of aircraft control in flight (following non-technical failure) and 63% of events involved flight handling. Because flight handling is not clearly defined and we are not sure if it also includes actions performed through the automation, we cannot directly attribute the accidents to the degradation of manual flying skills, and caution must be taken in interpreting the results.

A study conducted by Boeing (2008), illustrated the distribution of fatal aircraft accidents by phase of flight (see Figure 4). It should be noted that the approach and landing phases account for 43% of fatal accidents and the takeoff and climb phases account for 31% of the fatal accidents. Interestingly, exposure (in terms of hours) to these phases of flight is the least when compared to the cruise phase. The approach and landing phases are of particular high risk, and if we recall data obtained by the CAA, they are likely to involve loss of aircraft control. Ebbatson (2009) notes that this view is shared by the Flight Safety Foundation, and therefore, to tackle
manual flying skill issues, the approach and landing phases of flight should be the first ones assessed.

**Figure 5:** Distribution of fatal accidents by flight phase for 1998-2007 (Boeing, 2008)

Overall, the results presented from the individual accident reports contribute to the evidence of skill degradation of the manual flying skills of pilots. The *Heinrich ratio*, 1959 as cited by Ebbaston, 2009, points to the fact that for every fatal accident there are 29 less severe accidents and as many as 300 near misses, many of which go unnoticed or not reported. Therefore, considering that accidents are the most severe consequences of errors, and their occurrence is relatively low in frequency, the statistics point to manual handling events may only be representative of a small portion of the larger issue related to manual flight skill degradation.

### 2.3.4 Case Summaries

There are a variety of cases where pilot deviation or loss of aircraft control can be attributed to the degradation of pilot skills in manual aircraft control. Whether or not these cases are documented and given a lot of attention, is another topic. This section discusses a few well known aircraft incident/accident cases where skill degradation of manual flying skills was a main contributing factor.
AirIndia Charters Ltd aircraft, B737-800NG, May 26, 2010 (Sanjay, 2010). This is a case where prolonged use of automation resulted in the pilot being unprepared for the manual override of the aircraft when the automation performed unexpectedly. The aircraft involved in the incident was a Boeing 737 on a routine flight from Dubai to Pune. The first triggering event of the incident was when the aircraft suddenly began an uncontrolled dive toward the ocean. The First Officer was the flying pilot at the time because the Captain had left to use the restroom. The First Officer was trying to comprehend the situation upon occurrence but was immobilized as a result of fear. The Captain rushed back to the cockpit attempting to open the door to try to resolve the problem. Once he got into the cockpit, the Captain was able to recover the aircraft from the nose dive. Simply put, if the First officer was proficient in his manual flying skills, he would have been able to easily disengage the autopilot and recover the aircraft from the nose dive in a timely manner. In summary, the incident was uneventful and no one was injured, as a result of the Captain’s intervening actions.

Colgan Air Flight 3407, February 12, 2009 (NTSB, 2009). In this accident case, the aircraft was approaching an aerodynamic stall and the Captain of the flight exacerbated the problem by manually applying improper control inputs. As a result, the aircraft eventually stalled and crashed, killing everyone on board the flight. Based on the NTSB accident report it was unclear as to why the experienced Captain would apply control inputs to the aircraft opposite to what was taught during his flight training. Note that Captains have to successfully demonstrate bi-annual proficiency in recovering from situations such as those encountered by Colgan Air flight 3407. First Officers on the hand, have to demonstrate this kind of proficiency once a year. The training is directed at ensuring flight crews are proficient in identifying and reacting to emergencies that occur in-flight. In the end, it can only be assumed that the decay of manual flight skills from the time of the last proficiency check was a contributing factor to the Captain’s inappropriate, manual flight control actions.

United Flight 863, June 28, 1998 (Airliners.net, 1999). This case involved a B747-400 aircraft bound for Sydney. The aircraft experience an engine failure and the pilot flying the aircraft at the time failed to immediately employ the correct manual aircraft control inputs. As a result, the situation was exacerbated and the aircraft barely missed (by 100ft) a mountain in the
area. Manual flight skill degradation was attributed to the incident because the pilot flying at the time was actually conducting his first landing within nearly a year from his last one.

2.4 Addressing Skill Degradation in Manual Flying Skills

We have noted before from the Boeing statistics (refer to Figure 1) that the majority of manual flying skills are utilized by pilots during the phases of flight before the initial climb and after cruise, so that includes taxi, takeoff, initial approach, final approach, and landing, respectively. Additionally, if we were to recall the accident statistics presented by Boeing (refer to Figure 5), we would note that the majority of commercial aviation accidents occur during the approach and landing phases combined. This correlation should tell us something: manual flight skills are deficient when needed. So how do we approach the issue? Let pilots hand fly the aircraft more often to improve their recency of manually flying the aircraft, right? This is easier said than done because there are some associated challenges.

The first challenge in having pilots hand fly the aircraft when they want to is that operating/company procedures require them to utilize the automation during specified phases of flight. The company would prefer the automation to fly as much as possible to utilize the maximum economic benefits of the technology; that’s why it’s there in the first place.

The second challenge is that pilots flying internationally are aware of their lack of manual flying skill proficiency. As a result, if you were to give them the option to hand fly the aircraft during certain phases of flight; they would more like choose to use the automation. Reason being, they are not confident in their skills and wouldn’t want to do anything unnecessary to jeopardize the safety of the flight.

Lastly, pilots are mission oriented. This simply means that if you were to tell a pilot to make an approach to landing, he/she would do everything within their capability to make the landing. It doesn’t matter if the approach is “unstablized” (the aircraft is not fully configured for landing) in the beginning, they will continue the approach if they think that from experience, safety won’t be compromised. In such cases you would probably want the autopilot to fly the aircraft within its tolerances and procedural envelopes.
Taking everything into account, we can see that addressing the issue of manual flight skill degradation would be very challenging. We can’t just decide to allow pilots to hand fly the aircraft when they feel like it, but a more structured approach should be taken. Structured in the sense that maybe we can implement schedules for manually flying the aircraft. What schedule should be used? Further research would have to be done to address this, and it would probably vary on a company-by-company basis.
3. Situation Awareness

There is an increase of interest in understanding how pilots maintain high level of awareness of the complex and dynamic events that occur simultaneously during the phases of a flight, and how this information is processed to be used for future actions. The growing interest is due to the large amount of information available in the modern cockpit, combined with the flight crew’s ‘new’ role as a monitor of aircraft automation.

Automatic systems bring advantages to the aircraft cockpit, such as reducing human error, increasing safety, shortening operation time, and reducing cost. However, problems arise from the fact that most of aircraft automation designers put a lot of emphasis on the functional and reliability aspect of automation, ignoring a lot of the human factor issues that take place in the aircraft cockpit (Lee & Moray, 1992). The automated systems coupled with poorly designed cockpit displays, makes it difficult for the pilot to maintain high awareness of the dynamics going on inside the cockpit (Sarter & Woods, 1995). Thus, the term ‘situation(al) awareness’ (SA) was adopted to describe the processes of attention, perception, and decision making that together form a pilot’s mental model of the current situation (Endsley, 1995; Adams, Tenney, and Pew, 1995). Maximizing the advantages of automation while still keeping the pilot adequately “in-the-loop” or aware of actions taken by automated systems, provides a tremendous challenge for researchers in the aviation field.

This section of the paper is focused on the situation awareness aspect of impact the automation brings to the cockpit. Section 3.1 examines on how situation awareness is defined and then expands that to the dynamics in the aircraft cockpit through three hierarchical phases. Section 3.2 looks at the general methods used to measure situation awareness and then section 3.3 illustrates how automation can impact situation awareness in the cockpit. Finally, general evidence will be provided in section 3.4 by case studies correlating to situation awareness, followed by how skill degradation can be addressed and possible challenges in doing so in section 3.5.
3.1 Definition of Situation Awareness

It is important to realize that situation awareness has no absolute or ‘correct’ definition. Many definitions were brought up by researchers to describe the concept of situation awareness, but since situation awareness cannot be assessed or measured directly there still is a debate on which definition ideally explains the concept best. The following definition of situation awareness is one of the most commonly used term by researchers today: “Situation awareness, or SA, is the perception of the elements in the environment within a volume of time and space, the comprehension of their meaning, and the projection of their status in the near future” (Endsley, 1988).

To expand upon the general definition of situation awareness and relate the term to the dynamics in the aircraft cockpit, three hierarchical phases (perception, comprehension, and projection) were suggested. (Endsley et al., 1998)

Figure 6: Endsley’s Model of SA in dynamic decision making (adapted from Endsley, 2000)
3.1.1 Level 1 SA: Perception of the elements in the environment

The perception stage deals with events that take place real time, tying them to tasks that need to be processed right away. So in this initial stage, a well-developed skill of monitoring and an effective scanning technique are required. Crew members with lack of experience and overloaded tasks often only operate in this SA Level. This is mostly due to the fact that they haven’t acquired the skills and techniques that are required of them to maintain the high level of awareness or they are just too overwhelmed with the present task at hand to be able to progress to the higher SA Levels. This first level of SA is commonly the stage where most mistakes and errors occur. In general, the cockpit crew needs to understand the given situation and correctly respond to tasks that are assigned to them in the cockpit. The cockpit crew has to be actively involved in all aspects of the current operation.

3.1.2 Level 2 SA: Comprehension of the current situation

In this second stage which can also be referred to as the understanding stage, you will need to interpret and evaluate what goes around you inside the cockpit. This stage, like the first one, occurs in the present time. A large number of crew will have difficulties proceeding beyond this Level of SA due to high workload, poor CRM or a lack of communication skills. If the crew is able to operate in this area of Level 2 SA, this is an evidence of them being reactive to their present situation. The aircrew has to be equipped with the technical and operational knowledge as well as acquire the necessary airmanship features to fully understand the inter-relationship and implications to operate at this SA Level.

3.1.3 Level 3 SA: Projection of future status

In this last level of SA the aircrew is able to project the elements and dynamics that they have obtained in the earlier stages, thus enabling them to forecast the future status of their aircraft. The aircrew will have anticipated or considered multiple methods to achieving their goal for the mission, so that if one option becomes unavailable they can flexibly change to the next suitable option. A so called “good captain” or a “good crew” is defined by their ability to have contingency plans throughout the entire flight which starts at the pre-flight phase. If the crew is able to operate in this area of Level 3 SA, they are being proactive to their present situation.
The question still remains on how an individual or a pilot in the cockpit acquires and maintains the appropriate level of SA. Endsley’s (1995) model of SA utilizes a feedback mechanism to direct behavior in order to reach a desired level of SA. Also, Endsley (2000) makes it clear that a person’s perception of the relevant elements in the environment forms the basis of SA, whereas action and behavior are treated as separate stage that proceed directly from SA.

Dominguez (1994) brought up a point that SA involves the extraction of information from the environment and integrating this information with relevant internal knowledge creates a mental picture of the current situation. Thus, Dominguez’s defines SA as a process of acquisition and maintenance that is active and cyclical. Like stated earlier, the definition of situation awareness (SA) that can be agreed upon by the vast majority of researchers is still in debate.

3.2 Situation Awareness Measurement Tools

3.2.1 Subjective measure of SA

A subjective measure, such as Situation Awareness Rating Technique (SART; Taylor, 1990) asks operators like pilots and air traffic controllers to scale their own level of SA. SART is a straightforward and easy way to measure individual situation awareness. But, since the individuals are making assessments based upon subjective measure they could be unaware of the information that they do not actually know of.

3.2.2 Objective measures of SA

The objective method typically involves asking the operator comprehensive questions and SA would be measured based upon the answers they gave out by comparing their answers to the actual situation. The most popular amongst the objective method is the Situation Awareness Global Assessment Technique (Endsley, 1995), which asks the questions after the situation has been removed or blanked. Situation Present Assessment Method (SPAM; Durso, Hackworth, Truitt, Crutchfield, Nikolic, and Manning, 1998); (Durso and Dattel, 2004) is also an objective method, but keeps the situations intact while questions are being asked. The evaluator would measure operator’s SA based upon the time and accuracy of the answer presented by the operator.
3.3 Impact of Automation on Situation Awareness

The aircraft cockpit is an environment where the aircrew needs to keep themselves actively involved in monitoring all the dynamics that is surrounding them, including the automated systems. Just because you’ve engaged the autopilot mode, doesn’t mean you can relax and enjoy what the autopilot features can do for you. Flying an aircraft is a constant repetition of the aircrew actively monitoring the flight instruments and controls. If the aircrew is not proactively involved in monitoring the automated system, their SA will be negatively impacted as the automated systems are frequently designed to put the aircrew out-of-the-loop. When put in the monitoring roll, the aircrews have been found to have a lower level of SA when faced with automation failure compared to when they are manually controlling the aircraft. Even though degradation of manual control skills under automation may be a reason for out-of-the-loop performance, loss of situation awareness is also a critical factor that we cannot overlook leading to many of the current aviation accidents.

However, situation awareness is not always negatively impacted by the forms of automation. In commercial cockpits, Hansman et al. (1992) found that the automated flight management system input was more reliable than the manual data entry, resulting in easier error detection of clearance updates. Also, because automation reduces unnecessary manual work for the cockpit crew, data integration required to achieve situation awareness may provide benefits to both workload and SA. The automation can also be implemented in high workload situations to prevent mental overload, by removing the need for the pilot to control the aircraft. The exact conditions for when situation awareness is positively or negatively affected by automation needs to be determined.

Automation affects situation awareness through three major mechanisms: (1) changes in vigilance and complacency associated with monitoring, (2) assumption of passive role instead of an active role in controlling the system and, (3) changes in the quality or form of feedback provided to the human operator (Endsley, 1996). Each of these factors results in the human component falling out of the flight task loop.
3.3.1 Vigilance, Complacency and Monitoring

Parasurman (1987) stated that “vigilance effects can be found in complex monitoring and that humans may be poor passive monitors of an automated system, irrespective of the complexity of events being monitored.”

Complacency and over-reliance on automation, is one major factor that is highly associated with a lack of vigilance in monitoring automation. Significant reductions in situation awareness can be found with automated systems, as the aircraft operators may neglect to monitor the automation and its parameters or operators attempting to monitor them, but failing due to vigilance problems may be another case. Also, Pilots could be aware of problems via system alerts, but not comprehend to the situation due to high false alarm rate (Endsley, 1996).

3.3.2 Active vs. Passive Role

The fact that aircrew can be passive observers of automation instead of active processor of information may add to the problem in detecting the need for manual intervention and in reorienting themselves to the state of the system in order to do so. Endsley and Kris found that subjects’ situation awareness was substantially lower under fully automated and semi-automated conditions than under manual performance in their experiment of automobile navigation task. Even though the test participants were well aware of the low level data, they had little understanding of the data in relation to their operation goals and what the data were actually referring to. Also, out-of-the-loop performance was observed by the participants in automated conditions, which is one of many challenging problems related to automation (Endsley, 1996).

3.3.3 Feedback

Lack of or a complete loss of feedback from automated systems in the cockpit has also been cited as a problem. This is caused by system designers’ belief that certain information are better off not known to the operators to a certain extent. Also, new forms of visual displays are introduced when new forms of feedback are created. The fact that a stack of information is presented to the aircrew in a different format may be challenging for them to process with other information. Kessel and Wickens (1982) found that proprioceptive feedback received during manual control was important to performance and denied in automated tracking tasks in which
information was only presented visually (Endsley, 1996).

Many of the current or newly designed automation systems bring up a considerable amount of challenge to situation awareness due to the elimination of or change in type of feedback provided to aircraft operators regarding the system’s status. Careful attention needs to be paid by the aircrew in the format and content of information presented by the displays; these issues can easily affect situation awareness in a negative way when aircraft operators are working with automated systems (Endsley, 1996).

3.3.4 Lack of Understanding of automation

The lack of understanding of automated systems in aircraft by the pilots who fly with them is another problem associated with automation (Wiener 1989). While the increase of the pilot hours in the aircraft proved some significant importance in understanding the automated system, this also was related to tendency to report that the quality and quantity of information provided was less appropriate and more excessive. These problems again could clearly be attributed to standard human factors short comings in designing the interface of the automation displays. Even though the systems might be operating properly, significant situation awareness problem may occur because; misinterpretation of observed system actions and predicted future system behaviors may confuse the aircraft operators with the way they are presented to them. Providing the information clearly to aircraft operators so that they can fully understand the system state and state transitions becomes a much more challenging task with the increased complexity of the system. There may be cases where the aircraft operators may have never experienced a certain mode or combinations of circumstances that lead to certain behaviors. This leaves the aircraft operators unable to properly interpret the observed system actions and predict future system behavior, thus resulting in a significant situation awareness problem (Endsley, 1996).

3.4 Accident Data and Evidence Illustrating Loss of Situation Awareness in Pilots

3.4.1 General Evidence

According to the UK CAA situation awareness was identified as the most frequent causal factors of all fatal accidents (41 percent) caused in the air.
Table 1: Most frequently identified casual factors in 589 fatal accidents analyzed by the UK CAA (1998)

<table>
<thead>
<tr>
<th>Causal factor</th>
<th>Count</th>
<th>Percent of accidents</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lack of positional awareness in air</td>
<td>244</td>
<td>41.4</td>
</tr>
<tr>
<td>Omission of action or inappropriate action</td>
<td>216</td>
<td>36.7</td>
</tr>
<tr>
<td>Flight handling</td>
<td>177</td>
<td>30.1</td>
</tr>
<tr>
<td>Poor professional judgment or airmanship</td>
<td>134</td>
<td>22.8</td>
</tr>
<tr>
<td>Slow and/or low on approach</td>
<td>113</td>
<td>19.2</td>
</tr>
<tr>
<td>Failure in CRM</td>
<td>101</td>
<td>17.1</td>
</tr>
<tr>
<td>Press-on-it is</td>
<td>97</td>
<td>16.5</td>
</tr>
<tr>
<td>Deliberate non-adherence to procedures</td>
<td>72</td>
<td>12.2</td>
</tr>
<tr>
<td>Design shortcomings</td>
<td>67</td>
<td>(11.4)</td>
</tr>
<tr>
<td>Post crash fire</td>
<td>63</td>
<td>(10.7)</td>
</tr>
</tbody>
</table>

Note: These factors are not mutually exclusive as most accidents involved more than just a single factor

To complement the statistics shown above, the Figure provided below makes it clear that even though there is some evidence against the issue of situation awareness as a result of automation, there is also a fair amount of strong supporting evidence for the issue.

Figure 7: General evidence supporting situation awareness issues (Research Integrations, Inc, 1997-2007)
3.4.2 Accident Analysis Data

Following is the examples of three cases where automation contributed to a loss of situation awareness of the flight crew. In 1983, a Korean airlines flight was shot down over Russia (formerly known as the USSR) leaving no survivors. There was no radio communication and the aircraft was mistaken as a hostile over the airspace, without having authorization. It is assumed that an incorrect data entry was inputted into the flight plan, resulting in the aircraft’s deviation from its intended path (Kuypers, 2001).

In 1987, a Northwest Airlines MD 80 crashed on takeoff at Detroit airport and killed all but one of the passengers on board the aircraft. This was due to the improper configuration of the flaps and slats. A major contributing factor to the crash was the failure of the takeoff configuration warning systems, which the pilots were too reliant on (National Transportation Safety Board, 1988).

In 1989, A US Air B737 failed to take off at New York LaGuardia airport, landing in the nearby river. This was due to the flight crew accidentally disarming the auto throttle system. Neither of the pilots recognized the mistake and as a result the takeoff abort procedure was not executed in a timely manner, which resulted in the loss of the aircraft and two passengers (National Transportation Safety Board, 1990).

In each of these cases the human operators overseeing the automated systems were unaware of critical features associated with the system’s status. Additionally, it is hard for the operators to understand what the problem is even if he detects that something is amiss or wrong. For instance, with the 1989 US Air accident, both pilots attempted to take control of the aircraft but were unsuccessful due to the undetected mis-trimmed rudder. The delay associated with trying to determine what was wrong ultimately resulted in a failed and fatal attempt to abort the takeoff.

Due to their complexity of automated systems, just understanding what the displayed information actually means is a challenge to the flight crew. For example, pilots seem confused at times about the status of their automated flight systems in the aircraft; they wonder what it is doing and why. The latter problems are normally associated with reduced situational awareness.
that results when pilots are taken away from the active role of flying the aircraft and put in the role of monitoring the automated systems.

3.5 Addressing Situation Awareness issues

Automation has, for the most part, worked quite well, and has accompanied a dramatic reduction in many types of human errors. Moreover, it may even improve situation awareness by reducing the display clutter and complexity associated with manual task performance, and through improved integrated displays (Wiener, 1992, 1993). Billings (1991) suggested that automation may also improve situation awareness by reducing excessive workload for the aircraft operators. But, recent research demonstrates a certain degree of independence between situation awareness and workload (Endsley, 1993a). Workload may only negatively impact situation awareness at very high level of workload. Low situation awareness can also accompany low levels of workload. If workload is reduced through automation, this may not translate into higher situation awareness (Endsley, 1996).

In order for the automation to be fully accepted amongst the aviation community, automation not only needs to reduce manual workload, increase productivity, and bring precision to routine tasks that it was initially intended to do, but do so while working cohesive with the pilot in the cockpit. The pilot needs to be fully aware of what the automation is currently doing and what it will do in the future. Even though the Flight Management System (FMS) in the aircraft cockpit has been around for quite a while in the industry, it is still not unusual to see pilots having a hard time figuring out what it is actually doing. In order to avoid this situation, current researches not only focus on automation performance capabilities that the pilots are looking for but, also emphasize on how they can achieve this while maintaining optimal situation awareness. Rather than replacing what the pilot currently doing, the researchers are trying to augment the pilots’ capabilities with displays that back up their knowledge (e.g. Heads Up Display, Enhanced Vision System). The HUD can increase pilot situational awareness by creating the conditions for a smoother transition from head down to head up. This feature is particularly advantageous during approach and landing phases, when it displays trajectory related symbols imposed on the pilot’s actual external view. Also, technologies are being developed to incorporate intelligence that eliminates the need for the pilot to perform tedious computations.
and visualize the results in ways that the pilot can instantly and continuously determine the results of the computation and their effects on their flight. Pilot evaluations will determine whether this approach produces effective decision support systems or continues to lead to what has been described as “clumsy automation.”

Figure 8: Enhanced Vision System (left) and Heads up display (right)
4. Workload

The introduction of an automated support system, depending on the appropriate settings on the type and level, may directly reduce the workload of operators during task performance. (Röttger, Bali, & Manzey, 2009) However, the benefits of automation in reduction of operator workload can seriously be undermined in three ways. First, automation has resulted in workload reduction when the level of workload was already manageable, yet elevated at times of peak task load, a phenomenon referred to as the “irony of automation”. (Metzger & Parasuraman, 2005) Second, through role transition by the operator from direct system controller into system monitor, the operator is exposed to wide range of monitoring responsibilities that require large cognitive demands leading to increased mental workload. (Sheridan, T.B., & Simpson, R.W., 1979) Third, operators perform extensive cognitive evaluation on the benefit of using the automation against the task of performing it manually, which in turn incurs significant cognitive overhead. (Galster et al., 2007)

This section on workload is organized as follows. Section 4.1 will provide a brief definition of mental workload, followed by models of mental workload in section 4.2 where multiple resource theory and qualitative paradigm models are discussed. The three major workload measurement categories and aviation specific workload measurement tools are presented in section 4.3. Once fully introduced to the concepts, models and measures of workload, section 4.4 will discuss workload issues specific to flight deck automation. Section 4.5 specifically addresses NextGen automation initiatives and their direct and indirect impact on mental workload. Section 4.6 provides evidence for the existence of automation related workload issues based on data compiled by Research Integrations Inc. The section also includes a sample accident report review pertinent to workload. Section 4.7 explains the different task allocation strategies for a human-machine system and their impact on the three automation issues addressed in this paper; namely, workload, situation awareness and skill degradation. The competency of the adaptable automation strategy in addressing these three issues is also put in perspective. Section 4.8 provides a brief conclusion of this section of the document.
4.1. Definition of Workload

Sheridan, T. B., & Simpson, R. W. (1979) motivate their definition of workload in the aviation context by delineating physical workload, which is easily measurable, against those that demand higher cognitive resource commitment and are transient or time constrained. A well suited illustration of the transience of these workload categories is provided through examination of the sudden frantic pilot effort to take control of an unstable aircraft after long hours of a rather dull autopilot monitoring session to avert mid-air collision.

As noted earlier, workload analysis in highly complex tasks such as aircraft operations is predominantly concerned with the information processing and decision making events as opposed to physical events which can be measured through changes in respiration, heart rate and other physiological measures.

With the aforementioned focus as the basis, Sheridan, T. B., & Simpson, R. W. (1979) define mental workload as: “combination of mental effort, information processing and emotion in response to task demand.”

4.2 Models of Mental Workload

Two conceptual models of mental workload are briefly described in this section. The multiple resource theory, primarily constructed to capture the distinctiveness of mental resources across four dimensions, is used to model workload under multi-task settings. The Qualitative Paradigm for mental workload uses information feedback loops to model mental workload.

4.2.1 Multiple Resources Models of Mental Workload

A useful design tool that can aid in the prediction of multitask workload is the 4D (Four dimensional) multiple resource model. According to Wickens, (2008) mental resources are dichotomized along four dimensions.

1. Stages of processing dimension suggests that perception and cognition use different resources from those in response stages. A pilot moving a control in the cockpit by hand (motor response) can read and comprehend the impact of the applied motor action on a display as alphanumeric characters (verbal) or changes on a map or
picture(spatial). This two tasks use distinct mental resources and their simultaneous operation will not contribute to increased workload for the pilot.

2. Codes of processing dimension stresses the difference in resource usage between spatial and verbal codes of processing.

Similar to stages of processing except that this dimension dichotomizes code of processing in a single information processing stage. If a cockpit is designed to present information using predominantly images only, the pilot will be overloaded in his spatial processing resource dimension.

3. Modalities dimension explains the distinction in resource usage between visual and auditory perception mode.

This dimension is self explanatory. A pilot can perform voice communication with an air-traffic controller while visually monitoring the aircraft state from display units.

4. Visual Channels explains the focal and ambient dichotomy of vision.

Weather a visual input is placed in the central or peripheral field of vision determines how it is processed and the two have exclusive resource usage. Displays in the cockpit that require accurate reading and close visual inspection should be placed at or around the line of sight of those less salient displays can be situated at the peripheral field.

Based on this dichotomy, Wickens, (2008) argues that as the extent to which two tasks share similar resources is minimized, task sharing will be better, or alternatively workload will be manageable.
4.2.2 A Qualitative Paradigm for Pilot Mental Workload

Figure 9 below depicts the qualitative paradigm for pilot mental workload as described by Sheridan, T. B., & Simpson, R. W. (1979). In a stark contrast to a “black-box” stimulus-response approach to modeling information processing, the authors have provided an “exploded” view of the “black-box” through postulation of three hypothetical levels of information processing for the human operator in conjunction with two physical blocks emulating the aircraft and physical factors external to the IFR flight. The three components on the left represent the sensory-motor function, supervisory function, and judgmental function in increasing order of planning time span. The aircraft block represents the display and control systems in the cockpit while the environmental factors include among others, weather turbulence and air traffic control. Two decision control loops are also included in this depiction. The larger judgment or experience loop is offline while the smaller intermediate loop monitors performance in real time to affect decisions made by supervisory control in allocating mental effort to obtain desired performance.
4.3 Measures of Workload

This section will provide a brief summary on the challenges of measuring workload directly. Next the three major categories of workload measurement are discussed with their associated strength and weaknesses. Two representative pilot workload measurement techniques used by the National Aeronautics and Space Administration (NASA) are also presented.

4.3.1 Challenges in Workload Measurement

According to Sheridan, T. B., & Simpson, R. W. (1979), the primary reason for measurement of pilot workload is to predict performance. Unfortunately, all mental events, including mental workload, are “intervening variables,” meaning they are not directly measurable even by electrodes in the skull. Rather, the stimuli and response within which the particular mental event of interest (workload) “resides” can be measured and used as proxy for inference on the level of workload.

Performance measure, at the surface, seems an attractive alternative to serve as surrogate measure for workload level. Yet, a closer look reveals the possibility of having identical
performance by two operators while the mental effort they dedicated to accomplish the task is at a considerable level of disparity.

Röttger, Bali, & Manzey, (2009) recommend the use of all the three categories of indicators namely, subjective ratings, primary and secondary-task and physiological activity to have a reliable measure of workload. Below are brief descriptions of each methodology for the measurement of mental workload as explained by Sheridan, T. B., & Simpson, R. W. (1979) with specific tools from NASA included as examples.

4.3.2 Subjective ratings

Subjective rating/subjective judgment of mental workload refers to evaluation of workload either by the pilot or by an observer while the actual or simulated task is being performed.

*NASA Task Load Index (NASA-TLX):* Hart, (2006) describes NASA’s tool for obtaining subjective workload rating. NASA-TLX is a multidimensional scale for obtaining workload estimates for one or more operators while they are performing a task or immediately afterwards. NASA-TLX has six scales for representing six independent variables that can jointly provide a subjective workload rating. The six variables are Mental Demands, Physical Demands, Temporal Demand, Frustration, Effort, and Performance.

![Figure 11: Rating scale (left) & Weighted subscale (right) (adapted from Hart, 2006)](image-url)
The Overall Workload (OW) is represented by the area under the six bars which is the product of the rating provided from the form on the left and the weight assigned for each variable by each subject/pilot.

4.3.3 Physiological Indices

These are scientifically measurable indices, such as heart rate variability, respiration rate, galvanic skin response, pupil diameter, biochemical changes in blood, electroencephalogram, and changes in frequency spectrum of voice and so on. Unfortunately it is hard to establish correlation between these indices and pilot workload level as they exhibit high degree of variability and may be affected by conditions other than workload variability.

4.3.4 Secondary task performance

This method assumes primary task takes a fixed percentage of time and the remainder of time is relegated to the secondary task. The more time a pilot spends on the secondary task, the less the workload. While this method is logical, subjects in experimental settings do not necessarily replicate operational flight scenarios sufficiently because of their tendency to either balance both tasks or provide disproportionate attention to the secondary task thinking it “counts”.

The Multi-Attribute Task Battery (MATB): The Multi-Attribute Task Battery (MATB) is a platform developed by NASA for performing multi-task workload and human/automation interaction experiments. (Santiago-Espada & Myer, 2011) This platform has gained widespread acceptance in the research community for its ingenuity in concisely capturing multiple task models that compete for cognitive resources of the pilot. The schematic of the MATB II window is provided in Figure 12 and brief descriptions of its components are presented below.

1. Systems Monitoring

The upper left portion of the MATBII screen has two boxes that should be monitored for changes in indicator light and corresponding responses in the form of two distinct key presses. The four vertical scales also have indicator lights that move up and down and the pilot’s task is
to use mouse or key to detect when the indicator light moves away from the center and respond with mouse click or up and down key stroke.

2. **Tracking**

The upper center panel involves tracking a target. This task has two modes; automatic and manual. When in Automatic mode, the target center point will fluctuate and stay within the inner box. When artificial “Automation failure” is introduced, the target moves outside the target zone, the mode switches from automatic to manual, and the pilot has to use joy stick to re-center the target.

3. **Communications**

The communication task located at the lower left panel requires the pilot to listen for messages and change the frequency of a specific radio when the message pertains to his/her aircraft.

4. **Resource Management**

The bottom center panel contains the resource management task in the form of a generalized fuel management system. The task pilot’s are required to perform in this configuration is maintenance of fuel levels in tanks A and B within ± 500 units of the initial conditions in each.

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**Figure 12:** Multi-Attribute Task Battery II (adapted from Santiago-Espada & Myer, 2011)
4.4 Impact of Automation on Workload

The impact of automation on pilot mental workload is addressed in this section. Special focus is given to mechanisms by which the benefits of automation can be undermined by pilots’ attainment of sub-optimal workload levels because of automation during less frequent and transient aircraft operational states.

Sheridan, T. B., & Simpson, R. W. (1979) cite among others, increasing air traffic in metropolitan area, more stringent fuel constraints and stricter noise regulations as events directly or indirectly leading to increased pilot workload. While conceding to the realization of reduction in workload via automation in more sophisticated aircrafts (through reduced direct manual control), they also point out the wide range of the monitoring responsibilities the user of a highly automated cockpit faces at the new role as “flight manager”

Harris & Hancock (1995) relate the impact of automaton on workload based on resource theory. This theory can explain the possible benefits of automation in multi-task environments where tasks compete for limited mental resource. The automation of some components of the task will decrease mental demand presumably resulting in better performance for the remaining non-automated components of the task. However, this benefit is not without its own cons. For example, the touted benefit of information automations such as Data Communications (Data Comm) in NextGen, where controller to flight crew communication will be predominantly text based, in terms of reduction in operator workload contradicts this assertion. Based on the multiple resource theory both display monitoring (which is the current day operating mode for the cruise phase of an automated flight) and text reading (after the implementation of Data comm) involve the visual mode of perception and to the extent those tasks are voluminous, the operator can significantly be overloaded.

Endsley & Kiris (1995) on the other hand have rightfully disputed the conclusive claim that automation has on reducing operator’s workload. While acknowledging the possibility of reducing excessive workload through automating routine tasks, they also stressed that when workload is at its highest, which usually is depicted by moments of complex decision demands, automation has not provided the anticipated relief. Further, the benefit of reducing excessive workload is realized only when augmented by improved situation awareness through allowing
expanded cognitive resource. However, Endsley & Kiris (1995) have pointed out the possibility of lowered workload not necessarily translating into improved situation awareness, which is critical for ensuring the efficient performance of the monitoring task.

Metzger & Parasuraman (2005) identify implications of cockpit automations that have resulted in increased workload for pilots. A principal objective in pursuing automation is the attempt to reduce the operator’s workload during periods of peak task load. However, counterproductive outcomes have been observed. For example, automation in the flight deck has proved to have no impact on reducing the level of workload when the operator is already under-loaded. The cruise phase of a flight is one such example where the pilot's level of workload is at or below the acceptable upper limit. On the other hand, automation has the undesirable effect of elevating workload on operators that already are overloaded during critical flight phases such as landing. One such example is the added requirement of reprogramming the flight management system during final approach.

Galster et al., (2007) also include “cognitive overhead”, which is the extensive cognitive evaluation of the benefit of automation versus the cost of performing the task manually, as a contributing factor for automation induced workload elevation.

Metzger & Parasuraman (2005) identified similar mechanism, as was noted by Sheridan, T. B., & Simpson, R. W. (1979), by which automation increases workload. Here the role transition by the human operator from manually controlling the system to automation supervision/”flight management” is recognized as imposing a considerable supervision workload on operators.

Galster et al., (2007) reiterate experimentally verified detection failures that tie workload and automation. The argument presented states that when workload is increased, over-trust or complacency develops with automated systems and coupled with vigilance problems this is likely to lead to failure to detect performance deviations and decrements in automation performance.
4.5  Automation in NextGen and its Impact on Workload

This section discusses the impact of NextGen automation initiatives on pilot mental workload. While automation targets in NextGen are not limited to Automated Dependent surveillance-Broadcast (ADS-B) and Data Communications (DataComm), the scope of this section will be limited on these two.

4.5.1 ADS-B and its role in Free Flight (FF) and Distributed Air/Ground Traffic Management (DAG-TM)

The concepts of FF and DAG-TM dictate the possibility of providing levels of autonomy to the flight crew in choosing flight parameters such as heading, altitude, speed and route. Together with this freedom, in the FF concept the pilot assumes the primary responsibility of maintaining separation. However controllers will still be in place to manage exceptional traffic scenarios.

A rather interesting insight provided by Metzger & Parasuraman (2005) is the indirect workload impact cockpit automation has on remote operators/controllers. The concepts of Free FF and DAG-TM are anchored on the availability of automation providing self-separation capabilities. One such piece of automation for potential realization of self-separation is the Automated Dependent Surveillance- Broadcast (ADS-B). The connection to be made here, as far as the indirect impact automation has on remote operators’ workload is concerned, is presented below.

Through simulated FF experiment Metzger & Parasuraman (2005) have shown that when the exceptional traffic scenario presents itself and ground controllers have to perform the task of conflict detection and resolution (CD&R), the fact that they now have no information on the pilot intent (because the pilot freely chooses his/her flight parameters) make the CD&R task highly difficult resulting in a significantly elevated workload on the controllers.

4.5.2 Data Communications (Data Comm)

According to the Federal Aviation Administration (FAA) NextGen Program overview, Data comm will be the predominant mode of communication enabling air traffic controllers to
send digital instructions and clearances to pilots. While this approach is advantageous in overcoming certain elements of the airborne to ground communication ambiguities, it also entails significant human factors issues. Measured by the multiple resource paradigms, which was established in section 4.2, introduction of automation units that will compete for pilot mental resources that are nearly or exhaustively over-loaded will have impact on performance. Pilots in the glass cockpit are already inundated with display information on traffic, navigation, aircraft state, and weather. The addition of the currently voice communication into this array of display information will compete for resources and performance will adversely be impacted according to the multiple resource theory. An experimental study closely related to the Data comm implementation issue is conducted by Wickens & Colcombe (2007). Here the impact of concurrent performance of a tracking task with simultaneous monitoring of air-traffic conflicts is studied and proved to impact performance. The authors recommended the establishment of a comprehensive understanding of the performance consequences of new technology, which can be attributed to the human factors issues of workload, reliability and, trust, and the efficacy of potential mitigating design features within the specific context desired.

4.6 Evidence for existence of workload issues

This section provides empirical evidence on the existence of automation related pilot workload issues based on a rigorous enumeration of automation related issues cross-checked against a large body of corresponding research, and related documentations by Research Integrated Inc. The data source, rating description and elements of evidence compilation are presented in greater detail in section 2.3.1. A sample accident report is also summarized and identification of automation induced workload increase as the main contributing factor to the accident is put in perspective.

4.6.1 General Evidence

The percentage of documents supporting the existence of workload issues associated with automation is over 51%. This serves as a ground for making the case for consideration of the undesired workload consequences of automation.
4.6.2 Accident Analysis Data

On January 20 1992 Air Inter Flight ITF148, an Airbus A320, took off from Lyon (LYS), France on a domestic service to Strasbourg-Entzheim Airport (SXB) and crashed 12.2 miles SW of Strasbourg-Entzheim Airport (SXB), France. The unavailability of the initial crew requested runway necessitated reprogramming for lateral correction. Working under peak task load, the crew confused the HDG/V/S (heading/vertical speed) mode with TRK/FPA (track/flight path angle) mode resulting in the crash. Details of this accident can be found by referencing the following source (“ASN Aircraft accident Airbus A320-111 F-GGED Strasbourg-Entzheim Airport (SXB),” 1992)

The “Mechanism of Accident” section of the report details the fact that the crew was faced with sudden workload pick because of the reprogramming task needed to make lateral corrections, supporting the argument that automation rather has the adverse effect of increasing workload at moments of peak task load.

4.7 Task Allocation Strategies

With the existence of automation related workload issues firmly established, the next logical inquiry of interest is what leverage the human-machine system designer has that can help her/him mitigate this issue. This section, therefore, looks in greater depth into the concept of task
allocation strategies and the choice of the strategy that has greater competency in addressing the challenges identified in earlier sections. Spectrum of tradeoff motivates this section, which will be followed by a revisit on the levels of automation. With the spectrum of tradeoff laying out the limits on workload and system unpredictability under varying levels of responsibilities for human and automation, the levels of automation concept and its use in providing a stratified framework for current day task allocation between human and automation is reviewed. Capitalizing on the drawbacks of this approach, the new paradigm of flexible interaction between human and automation, otherwise known as, adaptable automation will be presented together with its potential merits of mitigating the three flight deck automation issues studied in this paper.

4.7.1 The spectrum of tradeoff

Galster et al., (2007) portray the potential benefits of automation in different areas. Automation can make it possible for machines in general and aircrafts in particular to perform their task faster. The tendency to commit error on a well established procedural routine is dramatically reduced through the accuracy of automation. Fuel, which is the leading player in the financial welfare of the global airline industry, can be optimally managed through introduction of automation. Unfortunately all the merits listed are jeopardized when tasks are automated just because they are easy or beneficial to automate. The correct approach while deciding what to automate should be based on a rigorous investigation of the eligibility of the task for automation. Even when certain specific functions of a task can be performed better through automation, the overall performance of the system could benefit more through the increased allocation of functions to humans. The aforementioned discussion is presented as a prelude to motivate the discussion that follows namely, design for flexible interaction between humans and automation. An interesting insight from (Christopher, 2007) on the relationship between system competency, workload, and unpredictability, named spectrum of tradeoff will provide the ground work on development of an effective human-automation collaboration.

Before dealing with the details of the “Spectrum of trade-off” relationships, we believe it will be in the interest of the reader to revisit the concepts of levels of automation that was presented
in section 3.3 and construct the relationship with spectrum of tradeoff and task allocation strategies.

Christopher, (2007) clearly contrasts the difference in the target levels of automation, technologists and human factors engineers prefer. The “technological imperative” tends to always push for more automation while human factors engineers put a proportionate weight on the safety of the automated system and the human role in such systems. Both extremes cannot yield the optimal human-machine configurations as evidenced by experimental results. Intermediate level of automation hence has the benefit of comprising the best of both. Fundamental sets of questions that have been approached differently by different researchers then are what should be automated, how much should we automate, when should we automate, and finally who should control the task allocation. The “Spectrum of trade-off” is a conceptual view on which to base decisions for some of the questions mentioned.

![Diagram of spectrum of tradeoff relationship among system competency, human workload, and unpredictability](image)

**Figure 14**: The spectrum of tradeoff relationship among system competency, human workload, and unpredictability (Miller, et.al)

Competency describes the frequency that the system behaves correctly or provides a great number of contexts. Any man-machine system that consistently functions as per the desired design specification and have many contexts (functional attributes) can be considered to have a good level of competency.
The Mental workload for the human to interact with the system refers to the attention and “cognitive energy” the human must exert to use the system.

Unpredictability refers to the inability of the human to know exactly what the automation will do when. If the human is not personally responsible for taking all the actions in the system it is natural for unpredictability to manifest.

Here is how to decipher the “Spectrum of tradeoff” concept. Performance of a system, to a given level of competency, can be achieved through some mix of workload and unpredictability. The given/specified level of system competency is represented by the base of the triangles with fixed size. Workload can be reduced through allocation of some functions to the automation, as depicted by the smaller side of the triangle for workload as one moves in the direction of increasing automation. Yet this is only achievable through increased level of unpredictability. Alternatively, unpredictability can be reduced as one moves to increased level of human management, and once again at the cost of increased workload. The only way to reduced both workload and unpredictability, while maintaining the given level of system competency, is to shorten the height of the triangle through better design.

A range of human-automation mixes are possible between the extremes. These ranges can be constrained based on limits on human/automation capabilities. There is however an optimal choice within the feasible range. If the choice of this optimal setting is made by the system designer then the task is part of initial system design. If a human operator makes the choice before or during operation, this task is called delegation or tasking.

4.7.2 **Flexible interaction between human and automaton**

The stratification of levels of automation across two dimensions was discussed in section 3.3 in the situation awareness context. We have presented a slightly different version of this stratification scheme to help us relate it to the concept of flexible interaction between human and automation.

One-dimensional level of automation (LOA) for a system has been proposed by Sheridan & Verplank (1978), while a second dimension was added by Parasuraman, Sheridan, & Wickens,
(2000) to this same framework in terms of the human information processing stage abstraction. The first dimension by Sheridan & Verplank has ten levels as shown in the table below.

The second dimension sub-stratifies these ten levels under four levels of human information processing stages, namely, “Information Acquisition”, “Information Analysis”, “Decision selection”, and “Action Implementation”.

<table>
<thead>
<tr>
<th>Levels of Automation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Human Does it all</td>
</tr>
<tr>
<td>2. Computer offers alternatives</td>
</tr>
<tr>
<td>3. Computer narrows alternatives down to a few</td>
</tr>
<tr>
<td>4. Computer suggests a recommended alternative</td>
</tr>
<tr>
<td>5. Computer executes alternative if human approves</td>
</tr>
<tr>
<td>6. Computer executes alternative; human can veto</td>
</tr>
<tr>
<td>7. Computer executes alternative and informs human</td>
</tr>
<tr>
<td>8. Computer executes selected alternative and informs human only if asked</td>
</tr>
<tr>
<td>9. Computer executes selected alternative and informs human only if it decides to</td>
</tr>
<tr>
<td>10. Computer acts entirely autonomously</td>
</tr>
</tbody>
</table>

Figure 15: One dimensional level of automation (Sheridan & Verplank, 1978)

Figure 16: Two dimensional levels of automation (Parasuraman, Sheridan, & Wickens, 2000)
A system designer can set the level of automation for the four stages of information processing at any of the ten levels during the design phase of the system. This approach however is static, lacking flexibility for adaptation to specific sets of operating situations. Current day cockpit automation systems fall in this category.

(Prinzel et al., 2003) propose yet another mechanism for specification of the level of automation. In their work they have experimentally verified the possibility of tracking performance and workload through changes in Psychophysiological states and adaptively switching the operating mode between manual and automatic contextually as opposed to the static “design time” task allocation.

While adaptive automation is better in the sense that the task allocation is contextual, the control over who performs what and when is still not under the exclusive authority of the operator. Moreover, as was described previously, changes in physiological indices are hard to uniquely map to operator workload level.

(Christopher, 2007) on the other hand proposes a third mechanism of selecting the level of automation which is adaptable automation. The underlying concept under this mechanism is the automation is treated as a subordinate that collaborates with the human component, where the human maintains authority in deciding which tasks to subordinate, how much to dictate the automation in how to perform the subtasks, and how much attention to devote in monitoring, approving, reviewing and correcting task performance. The transformation of the flexible delegation concept into a working model requires the development of interface through which the human and automation components can communicate. An example of such system applied to UAV mission control from ground stations is provided.

4.7.2 Tasking Interfaces

The general tasking interface architecture for implementation of flexible delegation concept is shown in the figure below. The two primary components of the tasking interface are the user interface for the human and the automation components to communicate, the analysis and planning component for the automation component to perform planning alternatives, evaluating feasibility and expanding alternatives to produce fully executable plans.
Central to the workability of the flexible delegation model is explicit task decomposition together with development of alternative methods of achievement for each task or goal. Decomposition of tasks into subtasks at a level that is finer grained even much more exhaustively than the four levels of information processing as proposed by (Parasuraman et al., 2000) is essential for the realization of the flexible delegation concept. (Christopher, 2007) relates the importance of having hierarchically decomposed tasks which comprise both the functional and sequential relationships among tasks, emulating the mental model used by supervisors and workers in supervisory control domain. According to (Christopher, 2007), delegation can be defined as the assignment of roles and responsibilities for the subtasks of a parent task for which the agent in charge of delegation has complete authority and responsibility. Projecting this concept to design of the human-machine flexible collaboration system involves the detail decomposition of tasks into subtasks in a language that can be understood both by the human and the automation agent.

4.7.3 **Playbook approach to tasking interfaces**

A proof-of-concept for flexible delegation system is provided by (Christopher, 2007). Here a ground based tasking interface to be used for a priori mission planning of UAV operation is presented. Although the demonstration provided deals specifically with UAV operation, the authors believe the concepts are transferrable to in-flight cockpit operations.
The tasking interface shown above is for a UAV mission named “Airfield Denial”. The operator has the option of providing the automation system with varying levels of task delegations. This ranges from delegating complete autonomy to the automation, to alternatively laying out very detailed instructions and specifications to the primitive levels of subtask decomposition. The optimal level of delegation to the automation is now under the authority of the human operator, this new automation paradigm therefore is named the “run time” automation decision. Contextual factors such as time constraint, Mission complexity and trust can guide the operator in choice of the level of automation.

A benefit of this new paradigm of automation is the realization of real time adaptation while keeping the operator in charge. Psychological issues associated with the traditional approach to automation namely, frustration, stress and lack of acceptance can be mitigated through this new mechanism. Improved situation awareness in comparison to the fixed mode of adaptive automation and improved workload without compromising situation awareness are
major advantages to be derived from the flexible delegation model. The only caveat worth mentioning as far as the minuses of flexible delegation (adaptable automation) is concerned is the possibility of costs of decision making on the level of automation to employ overwhelming the benefits identified. Whether such workload induced by the need to make decisions on the level of automation during “run time” is manageable or otherwise is not addressed yet. Nevertheless, the concept of flexible delegation remains the single mechanism that outperforms the other models in mitigating the expenses of automation.

4.8 Concluding remarks on impacts of automation on workload

While the trend towards increased automation in new generation aircraft is contributing to reduction in pilot workload through steep decrement in direct manual control of the aircraft, there remain significant counterproductive issues that undermine the touted benefits. Literature has demonstrated through experiment, observation, accident and incident report review, and expert opinion that automation adversely impacts pilot workload by making pilot workload levels sub-optimal during critical and time constrained flight phases. The role transition by the pilot from direct system controller into mere system monitor has placed a disproportionately high cognitive demand on the pilot mental resource. Additionally pilots are faced with the extensive cognitive evaluation task of whether or not to apply automation on certain components of the flying task. The movement towards more automation in the cockpit as part of the NextGen technological advancement initiative tends to overlook the impact of loading multiple digital information automation display units that can result in mental overload and consequently to performance breakdown.

With the evidence for existence and continuation (through initiatives such as NextGen) of automation related workload issues established, potential remedies are discussed. Optimal decision on the adoption of task allocation strategy is one such approach. Static (current day), adaptive (with the disadvantage of exclusive control being maintained by the automation component), and adaptable (with the automation working as a human subordinate) strategies are discussed with adaptable strategy approved for its multitude benefit in addressing most of the flight deck automation issues studied.
5. Conclusion

The necessity for direct human control of the flying operation has progressively been removed and replaced by automation through a mix of economic, environmental and social incentives. Through automation, the tendency to commit error on well established procedural routines is dramatically reduced. Fuel, which is the leading player in the financial welfare of the global airline industry, is optimally managed and crew training time is reduced. Sustainable maintenance of these desirable automation driven benefits however requires the consideration of human factor issues that are detrimental to safe aircraft operations. Skill degradation, Situation Awareness and Workload are the three major human factors issues addressed in this paper.

The skill degradation component of this paper has identified the mechanisms by which automation affects manual flying skills, namely psychomotor and cognitive skills. The work has gone beyond the theoretical arguments augmenting the existence of automation related manual flying skill degradation with supporting evidence from empirical studies. After establishing a correlation between flight phases and accident statistics at the respective phases, a compelling case is made for the importance of improving recency of manual flying to improve manual skills at the critical phases of takeoff and landing.

The pilot who is kept out of the automated system loop does suffer from skill degradation in the long-term. Short term critical human factor issues that affect the performance of the pilot in-flight are also addressed in the paper. One such human factors issue researched is situation awareness. The situation awareness component of this paper has identified issues such as vigilance, complacency, pilot’s passive role in the flying operation, lack of feedback from automated systems in the cockpit and lack of complete understanding of the automation system. Similar to the skill degradation component, the impact of automation on pilots’ situation awareness is supported by empirical evidence. Accident data analysis has also been presented to depict correlations between accidents and situation awareness loss issues attributed to automation. Technologies such as Heads up Display (HUD) that potentially can better pilots’ level of situation awareness are suggested as partial remedial. Automations under development with intelligence for computational capabilities that can relieve the pilot of tedious calculations are presented with the potential for directly and indirectly improving situation awareness.
The reduction in situation awareness can be aggravated by imbalance in workload level during the operation of aircraft with heavy automation. The third component of this paper, therefore, addresses the impact of automation on pilot workload. The intense cognitive demand placed on the pilot of today’s automated aircraft because of his role transition into a system monitor is detailed in this section. Other mechanisms of workload imbalance reviewed included cognitive overhead on decision on the use of automation and the irony of automation where level of workload peaked and dipped at phases of the flight that required the opposite effect. Automation initiatives in NextGen and their impact on pilot workload are also identified. Supporting evidence is also provided to establish the existence of automation related workload issues. A paradigm shift in task allocation strategy from current day static allocation into adaptable automation is presented with the potential of mitigating workload, situation awareness and skill degradation costs of automation.

Based on the research we conducted, we strongly feel the existence and criticality of human factors issues related to cockpit automation. While automation should still remain the major vehicle for quantum leap in the aviation frontiers, the human factors issues we studied among others should be considered as integral parts of the design process to fully realize the benefits of automation.
References


National Transportation Safety Board. (1990). *USAir, Inc., Boeing 737-400, N416US.*

*LaGuardia Airport. Flushing, New York. September 20, 1989 (AAR-90/03).*

Washington, DC.


