Flight Deck Human Factors Issues for Trajectory Based Operations

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This paper outlines strategic flight deck human factors issues in the implementation of Trajectory Based Operations (TBO) and recommends strategies for addressing these issues. Human factors issues were identified through a review of the literature and a series of discussions with Subject Matter Experts. We outline three main areas of strategic research needs: 1) general programmatic issues, 2) flight deck capabilities assumed for “Dynamic TBO”(planned for the 2026-2030 timeframe), and 3) implementation issues associated with TBO. Independent human factors support that provides feedback to the FAA is critical to identifying and remedying issues prior to the implementation of Dynamic TBO and to identifying solutions to issues as they arise. One general recommendation is for FAA develop a TBO Human Factors Roadmap identifying specific capabilities and expected availability. For each of these capabilities, the roadmap would identify any potential issues related to certification, training, and flight deck procedures. The roadmap would track planned research and performance monitoring and include the results of those efforts as well as lessons learned from implementation of the incremental phases of TBO. The roadmap would be a ‘living document’ and be updated on a regular basis.

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	Liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
oz	ounces	28.35	grams	g
		TEMPERATURE (exact degrees)		
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C
		ILLUMINATION		
fc	foot-candles	10.76	Lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	Feet	ft
m	meters	1.09	Yards	yd
km	kilometers	0.621	Miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
mL	milliliters	0.034	fluid ounces	fl oz
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
g	grams	0.035	ounces	oz
		TEMPERATURE (exact degrees)		
°C	Celsius	1.8C+32	Fahrenheit	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	Kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380. (Revised March 2003)

Contents

Acronyms and Abbreviations

ACARS	Aircraft Communications Addressing and Reporting System
ADS-B	Automatic Dependent Surveillance Broadcast
ADS-C	Automatic Dependent Surveillance Contract
AJT	Air Traffic Services
AOCs	Airline Operations Centers
ARTCC	Air Route Traffic Control Center
ASA	Alaska Airlines
ASIAS	Aviation Safety Information Analysis and Sharing program
ATC	Air Traffic Control
ATM	Air Traffic Management
ATN	Aeronautical Telecommunications Network
ATN-B2	Aeronautical Telecommunication Network-Baseline 2
ATSP	Air Traffic Service Provider
B757	Boeing 757
B767	Boeing 767
CAST	Commercial Aviation Safety Team
CASSIS	Controlled Time of Arrival/ATC Integration Studies
CAVS	CDTI-Assisted Visual Separation
CDTI	Cockpit Display of Traffic Information
CMU	Communications Management Unit
CPDLC	Controller-Pilot Data Link Communication
Data Comm	Data Communications
DCIT	Data Comm Implementation Team
DCL	Data Linked Departure Clearance
DM	Downlink Message
EFB	Electronic Flight Bag
EPP	Extended Projected Profile
ETA	Estimated Time of Arrival
FAA	Federal Aviation Administration
FANS	Future Air Navigation System
FIM	Flight Interval Management
FMC	Flight Management Computer
FMS	Flight Management System
FRT	Fixed Radius Turn
GA	General Aviation
GIM-S	Ground-based Interval Management - Spacing
HITLs	Human-in-the-loop Simulations
ILS	Instrument Landing System
ICAO	International Civil Aviation Organization

IM	Interval Management
iTBO	Initial TBO
KDCA	Reagan National Airport
KPHX	Phoenix Sky Harbor International Airport
kts	knots
LNAV	Lateral Navigation
MMO	Maximum Operating Speed (Mach)
MOPS	Minimum Operational Performance Standards
NATCA	National Air Traffic Controllers Association
NAS	National Airspace
NIWG	NextGen Integration Working Group
OEM	Original Equipment Manufacturer
OPDs	Optimized Profile Descents
PBN	Performance-Based Navigation
PCPSI	Pilot Controller Procedures and Systems Integration
RF	Radius-to-Fix
RNAV	Area Navigation
RNP	Required Navigation Performance
RTA	Required Time of Arrival
SAAs	Special Activity Airspace
SC	Special Committee
SESAR	Single European Sky ATM Research
SID	Standard Instrument Departure
SMEs	Subject Matter Experts
STAR	Standard Terminal Arrival Route
TBFM	Time-Based Flow Management
TBO	Trajectory Based Operations
TMA	Traffic Management Advisor
TOD	Top of Descent
UM	Uplink Message
VNAV	Vertical Navigation
VNAV PATH	Vertical Navigation Mode/Path
WG	Working Group
4D	Four dimensional
4DTBO	4D Trajectory Based Operations

Preface

This report was prepared by the Transportation Human Factors Division of the Safety Management and Human Factors Technical Center at the U.S. Department of Transportation, John A. Volpe National Transportation Systems Center. This work was sponsored by the Federal Aviation Administration’s Office of Aviation Safety and the Human Factors Division. Thank you to Aidan Schertz and Janeen Kochan for reviewing the draft report and to Karl Kaufman, Eddie Austrian, and Kathy Abbott for their review and helpful substantive comments.

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Executive Summary

This paper outlines strategic flight deck human factors issues in the implementation of Trajectory Based Operations (TBO) and recommends strategies for addressing these issues. The Federal Aviation Administration (FAA) defines TBO as “an Air Traffic Management (ATM) method for strategically planning, managing, and optimizing flights throughout the National Airspace System (NAS) by using time-based management, information exchange between air and ground systems, and the aircraft’s ability to fly precise paths in time and space”[1]. Flight deck human factors issues were identified through a review of the literature and a series of discussions with Subject Matter Experts. From these issues, we outline three main areas of strategic research needs: 1) general programmatic issues, 2) flight deck capabilities assumed for “Dynamic TBO” (planned for the 2026-2030 timeframe), and 3) implementation issues associated with TBO.

Recommendations for addressing general programmatic issues include the development of a detailed concept of operations for TBO from an operator’s perspective, strong participation in relevant working groups for standardization and global harmonization, a systems approach in the development of flight deck tools for TBO, and routine monitoring of operational experience using objective and subjective measures of system performance. Independent human factors support that provides feedback to the FAA is critical to identifying and remedying issues prior to the implementation of Dynamic TBO and to identifying solutions to issues as they arise.

Human factors research should consider flight deck capabilities assumed for Dynamic TBO, including standardized pilot-controller communications and the ability to load complex clearances on the flight deck. Research should also consider the assumed navigation (e.g., Advanced Required Navigation Performance) and spacing procedures (e.g., Required Time of Arrival) that will be a part of Dynamic TBO.

Several issues in today’s operations will propagate into the Dynamic TBO environment, if unaddressed. The issues will need to be considered in the implementation of TBO, including the specification of required avionics, the development of procedures, and plans for performance monitoring during the initial trials and post-implementation of TBO. Coordination between relevant program offices (e.g., TBO and Data Communications) will help to ensure that the TBO requirements can be supported by avionics on the flight deck. Objective measures of system performance and feedback from the operators should be collected during operations to identify what works well, what is problematic, and to identify any unanticipated consequences.

Finally, it is recommended that the FAA develop a TBO Human Factors Roadmap that identifies specific capabilities and when they are expected to be available. For each capability, the roadmap would identify potential issues related to certification, training, and flight deck procedures. The roadmap would track planned research and performance monitoring and include the results of those efforts as well as lessons learned from implementation of the incremental phases of TBO. The roadmap would be a ‘living document’ and be updated on a regular basis.

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[1] https://www.faa.gov/about/office_org/headquarters_offices/ang/offices/tc/library/storyboard/tbo.html#intro1

1. Introduction

Realization of projected benefits in any program depends on the system (i.e., equipment and procedures) being well-designed from a human factors standpoint so that the system minimizes the probability of human error and allows for unavoidable errors to be detected and corrected before they can result in an undesirable outcome. This paper outlines flight deck human factors issues that require attention (e.g., in the form of further research, monitoring, recommended procedures, changes in policy) in the three stages of implementation of Trajectory Based Operations (TBO) - Initial, Full, and Dynamic TBO. While the paper identifies the issues and their interaction, the risks associated with these issues would need to be individually assessed.

These human factors issues were identified through a review of relevant literature (from the Federal Aviation Administration [FAA], industry, and academia) and a series of discussions with Subject Matter Experts (SMEs). Experts included individuals from air carrier operators, Original Equipment Manufacturers (OEMs), and researchers. Discussions followed a semi-structured format with questions tailored to the individual's expertise. Verbal informed consent was obtained from each participant prior to the discussion with the assurance that his or her input would remain anonymous. Expressed consent was obtained for use of direct quotes (except for those previously published in print).

FAA defines TBO as "an Air Traffic Management (ATM) method for strategically planning, managing, and optimizing flights throughout the operation by using time-based management, information exchange between air/ground systems, and the aircraft's ability to fly precise paths in time and space. TBO will use more precise and shared information on constraints (weather, Special Activity Airspace [SAAs], airspace congestion) and demand (current and future aircraft location and flight planning preferences) to maximize airspace access with minimal deviation or delay" (FAA, *NextGen's Path to TBO*, Transportation Research Board [TRB] Review, March 2018). This is broken down into three evolutionary stages: Initial TBO, Full TBO, and Dynamic TBO. Each stage builds on incremental capabilities for Performance-Based Navigation (PBN), Data Communications, Automatic Dependent Surveillance-Broadcast (ADS-B), and information exchange between air and ground systems to incrementally increase efficiency, flexibility and predictability in the National Airspace System (NAS).

1.1 Initial TBO

Initial TBO (iTBO), scheduled for implementation during the 2016-2020 timeframe, utilizes existing automated controller tools, surveillance, weather, and data exchange products to conduct time-based flight operations at select locations and phases of flight. This involves air traffic initiatives such as Path Stretch and does not require changes to existing avionics. Bradford (2017) describes this as "an important step on the path to TBO" (p. 13). In iTBO, en route air traffic controllers use the Time-Based Flow Management (TBFM) Path Stretch tool to manually speed up or slow down aircraft hundreds of miles from destination airports so that they arrive in terminal areas in the proper sequence to seamlessly execute Optimized Profile Descents (OPDs). When speed changes are not sufficient to achieve the TBFM system schedule, the system will compute a change in the path and the controller will issue the appropriate vectors (i.e., a path stretch).

This stage of TBO is essentially transparent to the pilot, in that the pilot has no way of knowing that it is a path stretch clearance and it is normal for controllers to issue vectors and/or speed instructions to pilots. However, air carrier pilots report that controllers sometimes request speeds that they cannot operationally comply with due to aircraft performance characteristics (e.g., it would exceed the turbulence penetration speed). Pilots also report that they prefer holding to vectoring – that is, they would rather enter a holding pattern than respond to a series of vectors. According to the pilots interviewed, holding patterns are easier to execute in modern aircraft than a series of vectors, incur less workload than vectors, and have less opportunity for pilot error. Another benefit of holding compared to vectors is that the aircraft behavior is more predictable as the patterns represent a constrained portion of the airspace.

1.2 Full TBO

Full TBO, scheduled for implementation in the 2021-2025 timeframe, is described as "Full TBO capabilities delivered to all domains providing the ability to automate the integration of time-based management data and tools in order to greatly improve strategic planning and execution" (FAA, *NextGen's Path to TBO*, 2018). Full TBO will expand the capabilities and benefits of time-based operations throughout the NAS and to multiple phases of flight. According to Bradford (2017), in Full TBO, an aircraft will arrive at a desired waypoint within seconds of an agreed upon flight plan time, and arrive in terminal areas in the proper sequence to seamlessly execute OPDs (p. 12). The expected benefits of these capabilities are to boost NAS capacity while decreasing congestion and fuel burn and maintaining the current level of safety. "Enabling enhanced flight efficiency while also effectively merging and spacing aircraft during high density operations is the ultimate benefit to time-based flow operations" (Bradford, 2017, p.13). This will help to mitigate the impact of adverse weather, which is responsible for the majority of flight delays.

1.3 Dynamic TBO

Dynamic TBO, scheduled for implementation in the 2026-2030 timeframe, is described as "[using] advanced aircraft and ground automation to enable flight specific time-based solutions for reroutes and aircraft sequencing and advanced aircraft-based pairwise trajectory solutions. Information will be integrated and shared to further improve NAS operations" (FAA, *NextGen's Path to TBO*, 2018). While the performance objectives for Dynamic TBO are more clearly defined from an Air Traffic Control (ATC) perspective, FAA recognizes that these operations "depend upon operator equipage of previously certified flight deck capabilities/avionics to enable higher levels of benefit both system-wide and for equipped flights" (FAA, 2017, p.9). Dynamic TBO is expected to help maximize capacity and efficiency during both normal and constrained NAS operations. These improvements will also support real-time clearance negotiation and flight-specific, four-dimensional (4D) trajectories that allow operators to take business objectives into consideration.

With Dynamic TBO, 4D trajectories will be exchanged between the flight deck avionics, the ground ATC system, airlines, and other NAS operators. A 4D trajectory is defined as 1) a lateral path (consisting of route waypoints) combined with 2) a vertical path (predicted altitude and vertical constraints at each of the waypoints), 3) predicted speed (which includes speed constraints at each of the waypoints), and 4) predicted times over each waypoint or other specified vertical points (such as Top of Descent). Waypoints can be published (i.e., appear on the charts and in the published navigation databases used by the Flight Management System (FMS)) or unpublished (created by the company or the pilot). Unpublished waypoints are defined by one of the following: Latitude/Longitude, Place/Bearing/Distance, or Place-Bearing/Place-Bearing.

These 4D trajectories will be used for "flight planning, strategic operations management, aircraft sequencing, spacing, and separation" (Bradford, 2017, p. 12). This means that in the Dynamic TBO timeframe, operators will have much greater control over how their operations will be impacted when not all traffic demand can be accommodated. Airlines will be able to prioritize the impact to the aircraft in their fleet based on business decisions for individual flights. Airlines typically consider local airport curfews, duty times for crews, number of connecting passengers and their destinations, etc. However, different airlines prioritize individual flights using different strategies. For example, some will consider the number of "elite frequent flyers", while others do not (Sumers, 2019).

The current design standard used by manufacturers of navigation equipment is RTCA DO-283B, *Minimum Operational Performance Standards for Required Navigation Performance for Area Navigation* (RTCA, 2015). While specific capabilities and performance criteria are not yet fully defined for TBO, investments by operators are assumed to be needed to realize the benefits of Dynamic TBO. "Aircraft that have not equipped with additional navigation capabilities (e.g., RNAV [GPS] approach capability with LNAV/VNAV or Localizer Performance with Vertical guidance [LPV]; RNP 1 capability; Distance Measuring Equipment [DME] navigation capability and Radius-to- Fix [RF] capability) may not be able to efficiently access the largest airports" (FAA, 2017, p.20). Additional avionics investments are assumed to leverage ADS-B IN and OUT and Required Time of Arrival (RTA) capabilities. "While aircraft with current Time of Arrival Control capability (using the current Flight Management System [FMS] Required Time of Arrival function) will be able to participate, those who meet the RTCA DO-236C Change 1 compliant standard which improves performance across different aircraft types may be able to more efficiently access airports" (FAA, 2017, p.21).

Both the International Civil Aviation Organization (ICAO) draft *Concept of Operations for TBO* (2019) and the *FAA Vision for Trajectory Based* Operations (2017) identify the introduction of TBO as an evolutionary process. This means that the challenges and operational impacts on the flight deck associated with TBO will need to be periodically assessed as the specific interactions between TBO tasks and other flight deck tasks change over time.

Representatives from both manufacturers and air carriers discussed how the roles of the Airline Operations Centers (AOCs or dispatch), ATC, and pilots are likely to evolve with TBO. The role of ATC will be to enable and support the flights in ways identified by the carriers. In Dynamic TBO, FAA's role will change from supporting individual flight paths to supporting gate-to-gate, NAS-wide trajectory operations as operators and airspace users jointly determine the future position of an aircraft at any given time (Bradford, 2017). NAS users will be able to determine the downstream effects of trajectory changes so that the best overall option is chosen.

2. General Programmatic Issues

2.1 Need for refined TBO Concept of Operations

An operator-focused TBO Concept of Operations would be useful to help guide operator investment decisions and build industry buy-in for those investments. Subject matter experts from manufacturers and airlines noted that information on the benefits expected to be achieved with specific equipage is needed for manufacturers and operators to perform a cost-benefit analysis and support investment decisions.

Specific equipage requirements need to be linked with the services they will enable and the benefits they are expected to provide. Without such a detailed document, it is not possible to determine whether or how the pilots' roles and responsibilities will change, how the pilots' specific tasks will change, and how pilots' information requirements will change. Manufacturers noted that more information is needed to be able to plan for avionics improvements and predict specific benefits for their customers. This includes details as to what capabilities will be required, what functions the avionics will be expected to perform, and how FAA sees these capabilities translating into operational benefits. Similarly, such details are needed for operators to perform their own cost-benefit analysis in support of investment decisions. Finally, efforts should be made to use existing avionics to their full capabilities and make small incremental improvements that will increase capability with minimal investment while supporting future operations.

2.2 Need for Global Harmonization

Global harmonization is needed to help ensure consistency in phraseology and procedures used to negotiate and communicate TBO clearances. Inconsistent phraseology increases the chances of miscommunications between pilots and controllers and pilot error. A current example of variability in phraseology that has led to pilot error is the use of "CLIMB/DESCEND AND MAINTAIN [altitude]" in the context of a Standard Instrument Departure (SID) or Standards Terminal Arrival Route (STAR). The clearance to "DESCEND VIA STAR", serves as an indication to flightcrews that compliance with the lateral track and vertical profile of the STAR is required. In the United States, if ATC assigns an altitude following a STAR ("DESCEND AND MAINTAIN [altitude]"), any published altitude restrictions are canceled unless reissued by ATC. This is contrary to the ICAO procedure in which published SID/STAR altitude restrictions remain in effect unless specifically canceled by ATC. This poses additional complexity for flightcrews, particularly when transitioning to and from the U.S. and Canada (where the ICAO procedure is used). This issue is being examined within the Pilot Controller Procedures and Systems Integration (PCPSI) Phraseology Subcommittee. The goal of this Subcommittee is to progress "global harmonization of phraseology and procedures with initial emphasis on Canada and Mexico" in the areas of "Performance-based Navigation (PBN) and Data Comm." In the April 1, 2020 meeting of this group, it was decided that the instruction to "maintain" should *not* imply cancelling altitude restrictions in a Climb/Descend Via in the U.S. Controllers should explicitly instruct pilots to delete or cancel all altitude restrictions on a procedure when desired. This recommendation, from the PCPSI Phraseology Subcommittee, will progress through the Performance Based Operations Advisory and Rule Making Committee (PARC) to FAA.

Proactive global harmonization is needed to address phraseology for time- and trajectory-based clearances**.** Variabilities in phraseologies are usually unintentional and result from a lack of international coordination before changes are made by individual Air Traffic Service Providers (ATSPs). Continued leadership and strong participation in RTCA/EUROCAE joint working groups and relevant ICAO panels and working groups is needed to foster global harmonization in the development and implementation of advanced concepts. Countries without resources to develop their own systems or procedures readily accept the recommendations for operational improvements and procedures resulting from such groups.

2.3 Interoperability of Ground and Air systems

The realization of planned benefits of any given application or procedure are dependent upon the interoperability of the air and ground systems. The NextGen Integration Working Group noted that the Controller-Pilot Data Link Communications (CPDLC) services available to the aircraft were limited to the information available in the automation systems delivering the clearance (NextGen Advisory Committee, 2018). One result was that the air traffic control tower data link system could not include a specific runway in a loadable departure clearance. Loadable clearances are those that can be entered into the FMS by the use of a 'LOAD' prompt, rather than entering the clearance manually which incurs higher workload and risk of data-entry errors (e.g., see International Air Transport Association, 2015). They also note that since RNAV SID, STAR and RNAV/RNP approach procedures include the runway as part of the procedure, without the runway, the clearance is incomplete (NextGen Advisory Committee, 2018, p. 27).

This example points to the need for the systems and decision support tools for use by ATC and those to be used on the flight deck to be developed based on a concept of operations that defines how they will interact and for such systems and tools to be tested in tandem as much as possible. Many of the respondents interviewed for this study expressed this viewpoint. Specifically, they noted that without such planning, tools developed for the flight deck could optimize an individual flight (in terms of time or fuel-efficiency or combination trade-off) while interfering with the controller's plan based on the ground decision-support tools.

2.4 Allocation of Functions

A holistic systems approach should be taken to: decide what functions should be performed by whom (i.e., company/dispatch/AOC, pilot, ground station/ATC, controller, ATM); define what capabilities are to be included in TBO (in all stages of implementation); and determine what information is needed by whom, when it is needed, and in what format it should be presented. On the flight deck, there is a need to decide which functions should be performed by the FMS and which could be performed safely by an Electronic Flight Bag (EFB). Functions performed by the FMS are highly regulated, as they must meet strict certification standards (e.g., for security, reliability, and integration with other FMS functions). These standards also affect the time and expense involved in making any changes to the FMS. Even when software changes are made available, it can be years before they are implemented by the operator. Due to the complexities involved in adding functions onto the FMS, non-integrated systems have more flexibility and are preferred for implementation for non-critical functions. Decisions as to which functions are appropriate to allocate to which systems can be complex as they have engineering, safety, certification, and human factors implications. For future functionality, guidelines for implementing a systems approach to allocation of function to the FMS or non-integrated systems would help system designers anticipate certification requirements that have yet to be defined.

2.5 Continuous Performance Monitoring

Operations must be continually monitored using objective and subjective measures of system performance including feedback from the operators to identify what works well, what is problematic, and to identify any unanticipated consequences. For example, at least one air carrier representative said that the implementation of PBN resulted in a significant increase in the use of speed brakes in its fleet. The most extensive study of flight deck automation, *Operational Use of Flight Path Management Systems* (FAA, 2016) recommends the "identification, gathering, and use of appropriate data to monitor implementation of new operations, technologies, procedures, etc. based on the specified objectives for safety and effectiveness. Particular attention should be paid to human performance aspects, both positive and negative" (p.9).

2.6 Programmatic Decisions should be Data-driven

When no performance data exists, design and procedural decisions are often made based on input from potential users and other SMEs. It is important to note that there are multiple examples of mismatches between users' stated design preferences and the designs that yielded optimal performance (Andre and Wickens, 1995). Typically, users will prefer more information or details than are actually useful. When dealing with new uses of implemented flight deck systems, it is important to measure the performance of the system in the context in which it is being used with outcome-based performance metrics, rather than rely solely on user preference and subjective input. When possible, programmatic decisions should be based on objective results of assessments that are conducted using representative sets of users (e.g., pilots and controllers), tasks, and operational environments.

2.7 Outcome-based Performance Metrics

Performance metrics for TBO are often described in terms of fuel savings, reduction in emissions, and increased capacity in terms of increased runway throughput. Performance metrics for flight deck operations include the number and type of errors and subjective measures of workload. While specific measures of errors will need to be tailored to the procedure or capability being examined, typical examples include number and types of: communication errors, altitude deviations and navigational errors associated with new clearances, and errors entering new clearances into the FMS.

System performance (including performance of pilots, controllers, and dispatch) should be monitored on a routine basis in an environment with a strong safety culture where errors can be self-reported without the fear of punishment for honest mistakes as new capabilities are implemented. Such data can help to identify areas of risk and implement risk mitigation strategies to improve overall system performance and realize projected benefits.

2.8 Early and Continuous Human Factors Support

Independent human factors support that provides feedback to the FAA (e.g., the TBO Program Office) is critical to identifying and remedying problems prior to implementation and to identifying solutions to problems as they arise. Human factors experts working for system developers can provide human factors guidance, but in the end must comply with the system requirements put forth by the representative user groups (e.g., Air Traffic and the National Air Traffic Controllers Association [NATCA]). Human factors expertise is sometimes viewed as an ‘unaffordable luxury’ within a program. While it is true that human factors specialists often identify issues as potential problems and recommend such issues be remedied, it is always the purview of the program to determine if a proposed remedy is cost-effective. It is also important to note that human factors specialists working with potential users can identify potential problems prior to implementation, and problems are easier to fix in initial, rather than full, implementation. Finally, human factors specialists can serve as ‘honest brokers’ by identifying unreasonable expectations for pilot and controller performance. Such an objective viewpoint is also needed when balancing requirements for ground and air capabilities when investments are required but resisted by all parties. In such an environment, human factors specialists can identify where the responsibilities for specific functions *should* reside to maximize projected benefits. It is never the purpose of a human factors assessment to ‘grade’ others’ work. Rather, the main objective is to identify areas of improvement needed to ensure that planned programmatic benefits are achieved and safety is not compromised. Often, a collateral objective is to identify lessons to be learned to benefit similar programs.

2.9 Operational Testing and Evaluation Prior to Implementation

Prior to implementation, operational testing and evaluation of complex systems or procedures required for TBO is essential to help ensure that the systems and procedures function as intended, do not induce pilot errors, and do not result in unanticipated service interruptions. Such testing also helps instill pilot confidence in the system and manage expectations for how the system will work.

3. Assumed Flight Deck Capabilities for Dynamic TBO

Dynamic TBO can be thought of as the intersection of CPDLC and other NextGen applications. This intersection of capabilities can support the use of relative spacing between aircraft. Separation standards based on relative spacing rely on aircraft crossing a point in space within a specified interval after another aircraft. Use of relative spacing can increase capacity and runway throughput with reduced physical separation between aircraft compared to the standard absolute spacing, which requires a specified physical distance between aircraft. The complexities of CPDLC, other NextGen applications, and their interactions cannot be overestimated. The technical risks and their human factors implications associated with Data Comm, PBN, and relative spacing techniques (e.g., Interval Management [IM] and CDTI Assisted Visual Separation [CAVS] will need to be continuously monitored and assessed to identify needed changes to ensure successful implementation and realization of projected benefits. This section outlines research considerations for flight deck capabilities that are assumed for Dynamic TBO.

3.1 Controller-Pilot Communications

The flight deck human factors associated with controller-pilot communications that must be considered for successful implementation of TBO fall into the following categories: 1) use of the current CPDLC message set; 2) pilots' ability to load the clearance into the FMS and verify the entry; and 3) air/ground interoperability.

Complex clearances needed to support Dynamic TBO will need to be loadable (to preclude the need for error-prone manual entry) and able to be verified by the pilot so that there is a common understanding between the air and the ground of the clearance and 4D trajectory. Voice phraseology may need to be developed to support clarifications to TBO clearances as needed. The clearances intended for use in TBO will need to be tested by all users (air and ground) in tandem in the environment in which they are to be used. Progressing toward loadable complex clearances will require substantial operational research with a strong human factors component. Extensive testing and trial operations will be needed to identify and resolve technical issues that could result in pilot error, unnecessary increase in pilot workload, and loss of pilot and controller trust and confidence in the system.

3.1.1 Voice Phraseology

While it is widely assumed that complex clearances associated with TBO will be transmitted via CPDLC, it is also assumed that voice frequencies will be used for time-critical communications. (Note, however, that from an operational perspective, "time-critical" has not yet been defined.) Voice will also be used for clarification of TBO clearances when needed. For these reasons, voice phraseology is needed to support complex clearances in addition to the necessary CPDLC message set. Human factors issues associated with controller-pilot communications have already been identified for one capability on the TBO roadmap. Newly implemented Metroplex PBN flight procedures were designed to provide more direct flight paths, enhance airspace capacity, improve on-time airport arrival rates, and reduce aircraft emissions and fuel burn. In a recent review of these operations, the Office of Inspector General identified controller-pilot phraseology as an issue that needs to be addressed. "Controllers expressed ongoing issues with phraseology, including inadequate or unclear language in the air traffic controller handbook, such as abbreviating PBN speed and altitude restrictions; insufficient training for controllers and/or pilots, which has created confusion; and… increased complexity for controllers due to the need for additional communication with aircraft crew" (US DOT Office of Inspector General, 2019, p.14). While this analysis was from the perspective of ATC, the implications for the flight deck are clear. Confusions involving phraseology on the ground result in similar confusions in the air; "additional communications with aircraft crew" add to the task complexity of the pilots as well as the controllers. In order for voice phraseology for new procedures to be clear, it needs to be intuitive and globally standardized.

3.1.2 CPDLC

The messages that pilots and controllers exchange via CPDLC today (Future Air Navigation System [FANS] 1/A defined in DO-258A) along with the pilot interface used to execute these communications were based on requirements for operations in the South Pacific. This message set has been in use since the 1990s. The loadable clearance messages in initial services and those planned to be used in full services (planned for 2023) are a subset of these messages.

Air carrier pilots interviewed noted some of the challenges using today's avionics for CPDLC and noted how the complexity of Dynamic TBO will likely require changes to the avionics. While each flight deck is different, most aircraft use aural and visual indications to notify the pilot of a newly arrived message to be displayed, but the alerts for an ATC clearance waiting to be displayed can be the same as the alert for a message from the company (e.g., dispatch). Furthermore, as noted earlier, in some aircraft, the aural alert for a CPDLC message or a message from the company is the same as the one used to indicate a call from the flight attendants or that there is a message on the printer. Clearances that impact the trajectory of the aircraft are treated no differently than notifications from ATC (such as the "Welcome" message to indicate a CPDLC connection is established). As unread messages can stack up while pilots attend to other tasks, it is impossible for pilots to discern how many messages are waiting to be displayed or if there are clearances – or even emergency messages from ATC– embedded in the list, without reviewing them. We know of only a few flight deck implementations that include an indication of how many messages are waiting to be displayed. The next generation of communications avionics may require a dedicated display for CPDLC messages in order to ensure the pilot response times needed by ATC and to assist the pilots in task management.

Significant changes to ATC and aircraft CPDLC capabilities will be required for the more sophisticated NextGen applications. Recognizing that changes to the current message set would be needed to support future operations and today's operations outside of the oceanic environment, the FAA requested that RTCA form a Special Committee (SC) to support the NextGen initiatives in defined environments through 2025. The joint RTCA SC-214/EUROCAE Working Group (WG)-78 developed Safety and Performance Requirements Standard for Baseline 2 ATS Data Communications (i.e., DO-350A, RTCA 2016). This document details substantial improvements for the messages to be sent by pilots and controllers via CPDLC that will be needed to support TBO, IM, and other NextGen applications and Single European Sky ATM Research (SESAR) operational improvements. Aeronautical Telecommunications Networks (ATN)-based applications are planned to replace the current Aircraft Communications Addressing and Reporting System (ACARS)-based applications to support operations such as Dynamic RNP. On the flight deck, this means that the RTCA ATN-Baseline 2 (ATN-B2) CPDLC message set is expected to replace the current FANS message set and the ATN will support data exchange between the aircraft and ATC. The ATN-B2 message set was initially assumed to be in place by 2026 to support Dynamic TBO. However, given the uncertainty about the schedule of implementation of ATN-B2 in the U.S., the feasibility of using the current FANS 1/A message set should be explored.

After publication of DO-350A, RTCA SC-214/EUROCAE WG-78 went into hiatus with the intention of reconvening to revise the standards for Baseline 2 after SESAR and FAA progressed their requirements and procedures for advanced applications such as 4D-Trajectories and Advanced Flight Interval Management (FIM). (See, for example, Jackson, Gonda, Mead, & Saccone, 2009). While the published document has identified placeholders for messages for these advanced applications, it was clear that the specific messages would need to be refined as the specific operational concepts and procedures were fully defined.

3.1.3 Loadable Complex Clearances

One of the existing sources of risk in the current aviation system identified by the Commercial Aviation Safety Team (CAST) Flight Deck Automation Working Group was errors in FMS programming of clearances where 1) the clearance or procedure was complex or difficult to understand and/or program, or 2) the clearance was incompatible with the flight deck automation and/or published procedures. (FAA, 2013, p. 228).

CPDLC is one of the foundational capabilities of Dynamic TBO, in part, because of the ability to load complex clearances into the FMS while minimizing the errors associated with manual data entry. This presumes, however, 1) that the clearance is understood by the pilot, 2) it can be supported by the avionics, 3) that the pilot knows how to enter the clearance into the FMS, and 4) that the pilot can verify the clearance was entered correctly. As we have seen, this is not always the case. In 2009, Boeing noted that, "ground system automation designers need a good understanding of how the uplinks are processed by the airplane avionics systems, so that the systems they design can construct clearances that the airplane avionics will load in the way the controller intends" (Boeing, 2009, p.5). With that said, neither the controller nor the ground system should be responsible for distinguishing between different avionics. Ideally, these differences would be anticipated in advance and considered in the design of the ground system. It would also be ideal if the current and forecast capabilities and limitations of the ground system could be considered in the design of the avionics. The successful progress of future operations with the current systems will rely on close coordination among all stakeholders. One example of this type of coordination is the Data Comm Implementation Team (DCIT). This team identifies operational issues in Data Comm implementation, and involves operators and industry stakeholders to identify potential solutions. The DCIT will continue to identify situations in which pilots have trouble interpreting or responding to a clearance correctly. It will be important to resolve these situations in ways that will be able to support future NextGen applications, such as TBO.

It is likely that clearances needed for TBO will not be able to be accommodated with the current FANS message set. It is unknown whether the message set designed for future implementations (RTCA, 2016) will be sufficient. In today's operations, when a FANS message does not exist in the message set to accomplish an operational goal, the ATSP can construct a standardized free text message. This is the mechanism used to transmit Departure Clearances via CPDLC. In order to implement TBO with the current FANS message set, standardized free text messages are likely to be needed to convey clearances. Both the FANS message set and the *Global Operational Data Link (GOLD) Document* (ICAO Doc 10037) were designed to address oceanic data link operations. The guidance in GOLD states that, "The controller should not compose a free text message to send a clearance. The controller may compose a free text message element to supplement the clearance" (Section 3.3.3.2 ICAO, 2020). As the text explains, the intent of this is to minimize the risk of input errors and misunderstandings.

It is also the case that free text messages can only be responded to with a "ROGER" as "WILCO" and "UNABLE" are not available response options. There are various ways to work around the limitation of a lack of "WILCO" and "UNABLE" as response options, but each has accompanying risk. For example, one option is to send the free text message with a clearance with a WILCO/UNABLE option; this can be error prone when a non-loadable free text element is combined with a loadable clearance as pilots might assume that the entire message was loaded when in fact it was not. Any proposed solution would need to be examined in the context of the individual clearance, free text, and the intended operation to ensure that such work-arounds do not introduce additional risk.

Airbus (2011) performed a safety analysis of the use of free text by ATS ground systems for message elements of the RTCA SC-214/EUROCAE WG-78 message set (RTCA, 2016) for which no equivalent currently exists in the FANS message set. This report concluded that while the use of free text to accommodate needed messages that are not in the FANS set is globally acceptable, it is not recommended for clearances (i.e., messages that require a WILCO/UNABLE response) and would be particularly problematic for complex clearances. Specifically, the report concluded that free text should not be used for any message that was judged to require flight deck integration by RTCA SC-214/EUROCAE WG-78 (Airbus 2011). These clearances are shown in Table 1.

Table 1. Baseline 2 Messages Requiring Flight Deck Integration per RTCA SC-214/ EUROCAE WG-78 (RTCA, 2016)

Message ID	Message Intent / Use	Message Element
UM74R	Instruction to proceed directly to the specified position.	PROCEED DIRECT TO [*positionR*]
UM76R	Instruction to proceed, at the specified time, directly to the specified position.	AT TIME [*time*] PROCEED DIRECT TO [*positionR*]
UM77R	Instruction to proceed, at the specified position, directly to the next specified position.	AT [*position ATW*] PROCEED DIRECT TO [*positionR*]
UM78R	Instruction to proceed upon reaching the specified level, directly to the specified position.	AT [*level single*] PROCEED DIRECT TO [*positionR*]
UM79R	Instruction to proceed to the specified position via the specified route.	CLEARED TO [*positionR*] VIA [*departure dataO*] [*route clearanceR*]
UM80R	Instruction to proceed via the specified route.	CLEARED [*departure dataO*] [*route clearanceR*] [*arrival approach data*]
UM83R	Instruction to proceed from the specified position via the specified route.	AT [*position ATW*] CLEARED [*route clearanceR*] [*arrival approach data*]
UM266	Instruction to proceed from the first specified position to the second specified position via the specified route.	AT [*position ATW*] CLEARED TO [*positionR*] VIA [*route clearanceR*]
UM345	Concatenated with a route clearance to define the RNP for the route, as a series of sets of pairs of procedure name, airway or waypoint (including navaid or NDB) name and RNP value.	RNP ROUTE [*RNP data*]

Message ID	Message Intent / Use	Message Element
UM346	Concatenated with a route clearance to define the specified transition radius for the route as a series of (departure or arrival) procedure name, airway, waypoint (including the navaid or NDB) name and transition radius.	FIXED RADIUS TURNS [*RNP fixed radius transition*]
UM347	Instruction to proceed via the specified DNRP procedure, providing the name and a sequence of waypoints, beginning with an IF leg, followed by TF and RF legs. A procedure can also contain a list of speed and/or altitude constraints to be applied to certain waypoints.	CLEARED DNRP [*DRNP unpublished procedure*]

3.2 Advanced RNP

FAA has described Advanced-RNP functions to include radius-to-fix (RF) legs, parallel offsets, Area Navigation (RNAV) holding, scalable RNP, fixed radius turns (FRT) and Time of Arrival Control (FAA Performance-Based Navigation Strategy 2016, p.5). Furthermore, "Time of Arrival Control guidance and automation" is identified as a minimum PBN capability in the 2026-2030 timeframe for operations in the top 10 Large Hub airports by operations, as well as clusters of three or more Large Hub airports within 100 NM of one another (National Service Group 1, p. 26). It is also identified as a potential requirement to support 4D-TBO (p.24).

In September 2008, the Controlled Time of Arrival/ATC Integration Studies (CASSIS) project conducted a set of Controlled Time-of-Arrival trial flights (in European airspace) to examine the potential of airborne time control in the near and mid-term as well as the issues associated with it. These trials demonstrated that current generation avionics can achieve time control with 4-second accuracy at the initial approach fix, and less than 15 seconds at the runway threshold. Observed factors affecting the accuracy of the time control included the speed and altitude restrictions in the arrival procedure, wind modeling accuracy, and the location of the landing configuration extension (Klooster, Amo & Manzi, 2009).

A successful demonstration of the operational concept for 4D TBO in China assumed several flight deck capabilities, including RTA capability in FMS, CPDLC and Automatic Dependent Surveillance – Contract (ADS-C) to generate and downlink the Extended Projected Profile (EPP) of the predicted 4D trajectory (Cheng, Jackson, Qi, & Zhao, 2016). In the U.S. and Europe, flight deck capabilities for RTA include CPDLC, ADS-C and ADS-B - IN and OUT. These capabilities will be needed for the most advanced implementation of TBO (Dynamic TBO).

3.3 Spacing Capabilities

3.3.1 Ground-based Interval Management – Spacing (GIM-S)

GIM-S, a current component of Time-Based Flow Management (TBFM), uses ground automation to prescribe speed advisories to assist in the delivery of aircraft to a Meter Point/Meter Fix at a specified time. Initial performance assessments of GIM-S operations at Phoenix Sky Harbor International Airport (KPHX) showed that a +/-30 second meter fix arrival accuracy could be achieved with 80% reliability and +/- 1 minute arrival accuracy could be achieved with 95% reliability (Lascara, Weitz, Monson, & Mount, 2017). It should be noted speeds issued in GIM-S are in 5-knot increments. Currently, speeds issued via CPDLC (in the oceanic environment) are issued in 10-knot increments.

Ground automation cannot be expected to be able to predict aircraft trajectories with the same accuracy that can be predicted by the aircraft. The FMS creates trajectories with the advantage of aircraft-specific parameters such as aircraft weight and the descent mode (which the ground system currently cannot access). This is one reason why trajectory sharing is a critical capability. A current flight deck capability that could be used to orchestrate the time an aircraft flies over an arrival fix is the FMS RTA function (see Ostwald, 2006).

3.3.2 Required Time of Arrival (RTA)

In discussions with SMEs, RTA was identified by many as an underutilized flight deck capability. Pilots who have used the RTA function in the oceanic environment generally report that it is easy to use but that in the en route environment there is little potential operational variability in the speed and that the function can 'overreact' moving the throttles more than needed or desired. Several pilots said that they would enter the RTA into the system but then use their own estimates of speeds to avoid the vacillations between speeding up and slowing down.

Several studies have been conducted in which both pilots and controllers considered use of the RTA function as a feasible method for meeting scheduled arrival times at an arrival fix prior to Top of Descent (TOD). An early survey of RTA capabilities across Flight Management Computers (FMCs) showed that most of the RTA functions in the aircraft tested had an accuracy of ± 30 seconds, but functioned in only the cruise portion of the flight (Villani, 2010). The B737NG with the GE FMC could operate in all phases of flight with an accuracy of ± 5 seconds (Villani, 2010). Balakrishna, Becher, MacWilliams, Klooster, Kuiper, and Smith (2011) showed that with the current generation of avionics, flights could use RTA clearances to meet meter fix crossing times (assigned by the Traffic Management Advisor [TMA] flow management tool) within 20 seconds. Pilots reported increased workload overall, but the increase occurred during periods of lower workload. In general, feedback from the pilot questionnaires regarding the use of the RTA clearances was positive, but it was not unanimous (Balakrishna et al., 2011, p.9)

TBO flight trials were also performed from November 30 to December 22, 2011 at Seattle-Tacoma International Airport (Wynnyk, Balakrishna, MacWilliams, & Becher, 2013). These flight trials evaluated the use of RTA as a tool for meeting metering times into the terminal area. In these trials, all RTA assignments were on the minute, with the FMS configured to a ± 20 second RTA tolerance. Flightcrews were instructed to: review and accept uplinks of forecast wind, performance limits, and temporary RTA; manually enter RTA assigned by the controller; inform the controller if the RTA is unachievable; and check in on a new frequency with RTA time.

A total of 833 Alaska Airline (ASA) revenue flights (on a Boeing 737Next Generation) participated in the trials; of these, 595 aircraft (71%) executed an RTA to completion, and 575 of those 595 (96.6%) arrived within a 30 second tolerance. Of the flights that were issued RTAs, 16% had their RTAs canceled due to either ATC or pilot concerns. Therefore, the authors suggested that several operational issues should be addressed before widespread deployment. These issues included "controller and pilot concerns with RTA speed profiles, pilot workload in managing RTA speeds and auto-throttles in descent, controller workload in managing spacing in heavy traffic, roles and responsibilities associated with providing updated wind forecasts, and the overall fragility of RTA under current operating conditions" (Wynnyk et al., 2013, p.8). The authors noted that, "Pilot feedback was sparse but generally positive. Approximately two thirds of the 16 respondents indicated that there was no increase in pilot workload. However, half noted that speed control was an issue during RTA execution, particularly dealing with auto-throttles during descent. During a Vertical Navigation Mode (VNAV PATH) descent, the autothrottles will not advance unless the actual indicated airspeed is less than the commanded speed by more than 15 knots. This functionality can potentially result in the aircraft flying slower than the preferred speed in descent" (Wynnyk et al., 2013, p.7).

Interviewed pilots from Delta and United relayed that their airlines implemented the "Attila™" program, which allowed the carrier to prioritize flights into an arrival stream by issuing RTAs to their own aircraft (Baiada & Bowlin, 2015; Greer Chandler, 2013; Leib, 2008). With this program, RTAs were issued in Detroit, Minneapolis, and Atlanta Center airspace. Pilots reported two problems with these RTAs. One was that the controllers would sometimes assign a speed that contradicted the previously assigned speed with the RTA. The other issue was that the RTA would sometimes assign a speed that the flightcrew deemed operationally unacceptable. It should be noted that these RTAs were not assigned by ATC; they were 'assigned' by a program implemented by the airline that did not have input or interaction with ATC. The display of the RTA is the same for the pilot whether it is assigned by ATC or the airline. Furthermore, controllers have no way of knowing if the aircraft is 'assigned' an RTA by the airline. Controllers and pilots should have a way of identifying the source of such information to inform their decision-making and communications. While this program is not currently implemented in a fleet-wide fashion, pilots report that dispatchers continue to use RTA as a scheduling tool. Dispatchers will impose an RTA for operational reasons such as to prevent an early landing at Reagan National Airport (KDCA) in conformance with locally imposed curfews and prevent incursion of fines.

Tom Hendricks, Delta General Manager, Line Operations stated, “When Attila™ began its limited rollout, we began to receive feedback that the RTA solutions seemed to work against the aims of a particular flight. For example, ‘My flight was late and I got an RTA message to slow down!’ and, ‘I was given an RTA message to speed up and was put into holding!’ The critical piece to remember about Attila™ is that it is a system solution, not an individual flight solution. What is transparent to a crew faced with situations like these is the recovery of unused slots in the queue that might be fifteen aircraft ahead of or behind you (and possibly on a different frequency). The data that ATH (the manufacturer of Attila™) provided convincingly shows that when Attila™ is operating, we are recovering unused slots. This means a much more efficient flow of aircraft into Atlanta” (Hendricks, 2007, p.3). It should be noted that the reasons that the program is no longer used by Delta and United could not be determined.

In 2007, the Professional Pilots Rumor Network hosted a blog[2] to solicit feedback on the use of RTA in Europe as a potential tool to stream aircraft in the terminal environment, improve the predictability of the aircraft trajectory, and minimize the need for radar vectoring. The feedback from the pilots in 2007 mirrored the input from the pilots interviewed for this work:

> *The problem is that RTA works very well for a waypoint in cruise, but NOT for a descent waypoint, VNAV PATH is in sole control in this phase. (At least for Boeing aircraft, I cannot speak for Airbus).*
>
> *They do it in Singapore (in terminal airspace), after giving standard arrival, ATC gives you required time arrival over certain waypoint.*
>
> *I have played around with the RTA function of the FMS on the various 'busses I have flown and personally find it very poor for several reasons: For the system to have any chance of accurately predicting an arrival time it needs the proper route programmed into it and followed. So shortcuts, weather diversions, altitude changes etc. all combine to reduce accuracy. Also the forecast winds need to be accurately inserted for all applicable levels AND they need to be similar to the actual winds. Whenever any of these parameters change, the systems responds by varying the cruise speed. Several hours out it might only be by Mach.01 but the closer you get to the time restricted point I've seen speed fluctuate from just below MMO (Maximum Operating Speed) down to Green Dot (minimum speed).*

Another pilot on the blog stated:

> *I actually think the RTA feature on the B737 works really really well! I know that is not the opinion of the vast majority who try it. I agree it CAN really muck you around and cause all sorts of issues on descent such as choosing a descent speed lower than that required at the waypoint in question and/or changing the descent speed midway during the descent which can have a profound effect on the descent path (steeper/shallower). However if you keep a number of points in mind, you can [consistently] make good an RTA to within 15-20 seconds (yes even those ones on descent) and if required loose around 5-7 minutes per 100 nm.*

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[2] https://www.pprune.org/tech-log/263558-rta-arrival-manager-tool.html

The same pilot then laid out the details of a complex ‘workaround’ (See Appendix). While the pilot who authored this ‘workaround’ found this solution operationally acceptable, the complexity and workload involved would likely be unacceptable to many pilots. The feasibility of any such ‘work-around’ would also likely vary between FMCs.

3.3.2.1 Effect of wind info on RTA

It is well known that the accuracy of wind information affects RTA and 4D TBO performance. Reynolds, McPartland, Teller, and Troxel (2015) examined the degree to which wind forecast error and automation capability affected RTA performance. They reported that:

- all forecast models have significant performance variability over time,
- errors increase with forecast look-ahead time,
- large errors may persist for hours or days,
- wind forecast errors closer to the RTA fix cause greater magnitude RTA time error,
- flights at lower cruise levels are more tolerant of wind forecast errors compared to flights at higher cruise levels, and
- greater accuracy can be achieved by using more wind forecast points.

The FMS can only accept wind inputs at waypoints in the flight plan and only at a limited number of altitudes per waypoint. Therefore, if the waypoints are far apart, as they often are in the en route domain, the FMS wind forecast may not be representative of the actual winds in between the waypoints. This results in poor predictions for the TOD location and Estimated Time of Arrival (ETA). In the future, aircraft could downlink data such as planned descent speed, ETA, and TOD; this information could be used to improve the ground-based trajectory modeling.

Different aircraft have different capabilities in terms of the amount of wind information that can be entered into the FMS. For example, in one aircraft, only a single wind per cruise waypoint can be entered and only three altitude-based winds can be entered in descent. Another FMS allows for up to 10 altitude-based winds and temperatures in both climb and descent; it also accepts four winds for cruise waypoints (all at the same four altitudes). Manually entering this additional wind information would add to pilot workload, but the wind information could also come from an EFB and be sent to the FMS via a Connected FMS (CFMS) interface. In the future, winds could be updated as often as desired. However, the implications of ‘pushing’ wind and other information to the aircraft on pilot workload and potential errors should be investigated.

3.3.2.2 Use of RTA as a tool for Arrival Management

Time-based metering traditionally places a control point (meter fix) at some point during the descent. This point is a likely candidate for a RTA. Use of the existing FMS RTA function has been identified by many as a useful tool for management of arrival traffic to an airport. Use of this RTA capability at an arrival-oriented waypoint (e.g., TOD, an arrival fix in the descent or the runway threshold) could provide a way to implement the scheduled times provided by TBFM. As the NextGen Advisory Committee pointed out, in the near term, “an RTA target could be derived from TBFM which controllers would issue to aircraft via voice. This flight deck resource could be used to assist in conditioning traffic flows and potentially reducing controller workloads” (NextGen Advisory Committee, 2016, p. 14). The RTA that the FMS computes is cost-effective for the operator and is accomplished with minimal pilot workload. Air carriers can also use the RTA function to prioritize their own flights on arrival to meet business objectives of their choice.

However, feedback from FAA Air Traffic Services (AJT) indicated that RTA was considered operationally impractical for the ATCs to optimize aircraft flows, in part because the RTA message is not currently in the subset of messages allowed to be sent by en route controllers. Furthermore, the current message (in the FANS message set) identifies RTAs in minute increments. Another operational issue is that very few General Aviation (GA) aircraft have RTA capability. Additional controller concerns are the timing of the flightcrew response to the message, the time required to comply with the clearance, and the unpredictability of the aircraft speed. In RTA mode, the FMS could adjust its speed schedule multiple times in order to align its ETA with the assigned time constraint. This can be perplexing and annoying to pilots and considered operationally unacceptable to controllers.

Additionally, because inaccurate wind information entered into the FMS has been shown to increase the number of speed adjustments made by the FMS, accurate wind forecasts are critical for use of RTA as an air traffic tool. It is also the case that overly constraining the FMS, for example with multiple RTAs or altitude and speed constraints, negates the benefits that the operator enjoys when allowing the FMS to fly the most economically. These tradeoffs will need to be considered in constructing the use cases.

With such a wide range of factors affecting the accuracy of the RTA, additional research needs to be conducted to explore the feasibility of using RTAs, particularly on descent. Required RTA tolerance and level of specificity of the 4D trajectory needs to be defined for the intended use in various operational environments. In general, upper wind prediction errors are a factor in determining how accurately an RTA can be achieved. The FMS will perform its calculations of the plan to meet an RTA based on entered winds and will attempt to compensate for any wind error encountered during the execution of the maneuver. Further investigation of the impacts of winds is warranted.

4. Issues to be Considered in TBO Implementation

Several flight-deck human factors issues that exist in today’s operations will propagate into the TBO environment, if unaddressed. The issues, described in this section, will need to be considered in the specification of required avionics, development of procedures, and plans for performance monitoring during the initial trials and post-implementation of TBO. While human factors issues associated with the implementation of TBO from the air traffic perspective are equally important, they are outside the scope of this work.

4.1 Variance in FMS/Aircraft Performance

Different FMSs will implement the same instruction in different ways and perform similar functions in different ways (Fennell, 2018; Sherry, Feary, Polson, & Fennell, 2003). This could influence things like the tightness of a turn and what route information is reported to ATC in an EPP. While this has the potential to create more issues for ATC (e.g., ground-conflict prediction tools) than for pilots, it is critically important that pilots and controllers have a common understanding of the projected path of the aircraft. This section will explore known issues with differences in FMSs, the human factors implications for them and what can be done to mitigate their effects.

The CAST Flight Deck Automation Working Group reported that “One operator explained how a seemingly simple en-route descent requirement – to be at a specific level by a waypoint – could not be correctly programmed into a specific type of FMS. Of even more concern is that the requirement could be entered in the same way crews entered altitude restrictions in the climb or descent phases and, at a cursory inspection, may appear to be correct when the projections and guidance supplied would be erroneous”(Flight Deck Automation Working Group, 2013, p.42). While this particular issue is anecdotal (and has likely since been remedied), it is important to note that any given clearance may need to be entered and executed in different ways depending on the aircraft. For example, one clear advantage of CPDLC is that it supports ‘loadable’ clearances. This allows ATC clearances to be loaded into the FMS by the use of a ‘LOAD’ prompt, rather than entering the clearance manually which incurs higher workload and risk of data-entry errors (e.g., see International Air Transport Association, 2015). The NextGen Integration Working Group identified the benefits of loadable clearances as follows: “Loading complex route changes provides benefits through reduced communication errors for complex communications, enabling increased information exchange leading to increased airspace efficiency. The increased airspace efficiency creates an environment in which there are reduced flight delays and more optimal flight routes enabling lower fuel burn” (NextGen Advisory Committee - NextGen Integration Working Group, 2018, p. 27).

There is tremendous variability in which clearances are currently loadable on which aircraft. (For examples, see Boeing, 2009, p. 14 for a list of loadable clearances by Boeing aircraft type; see also Boeing, 2010). Extensive research has examined how the same clearance or procedure can be executed by different pilots using different FMSs and result in different tracks being flown by the aircraft (e.g., Herndon, 2012; Herndon, Cramer, Nicholson, Miller, & Rodriguez, 2013; Herndon, Cramer, & Sprong, 2008; Ottobre, O’Neil & Herndon, 2005). Specifically, Herndon, Cramer, Sprong, and Mayer (2007) note that the observed differences in tracks are due to the following aircraft factors:

- “Flight Management Computer [FMC] equipment installed on the aircraft: The same type of aircraft may have FMCs from different manufacturers and/or different FMC models from the same manufacturer. Also as expected, different types of aircraft will have FMCs from different manufacturers installed.
- Procedure coding into FMC database: Different versions of ARINC 424 used in the FMC, as well as database suppliers interpretation and coding of a procedure, can have an impact on how the aircraft complies with the LNAV (Lateral Navigation) and VNAV (Vertical Navigation) track.

- Aircraft to FMC interface and associated aircraft performance capabilities: FMC manufacturers often supply their systems to different aircraft manufacturers…These different airframes when joined with different engine combinations will, as expected, have performance capabilities that differ; for example, acceleration, climb rate, maximum allowable bank angle, etc." (p.3).

While the effects of these factors on the repeatability of LNAV and VNAV paths, and other ATC considerations have been explored, the effects of these factors on the pilots who may have to transition from one variant to another within their fleet have not been explored. As of 2019, there were over 100 different airframe and engine configurations of the B737 with the GE Aviation FMS (Hochwarth, personal communication).

Herndon et al. also note the additional influence of variants in flightcrew procedures and training. "Airline flightcrews and general aviation crews will have extensive differences in training requirements and standards as well as different operating philosophies and procedures. For example, speed schedules may vary considerably and some flightcrews may be instructed to use all available FMC and autopilot guidance and FMS automation provided while some operators explicitly limit what flightcrews may use." (Herndon et al., 2007, p.3). For each specific advanced flight deck capability, potential interactions of operating procedures that can affect the trajectory of the aircraft need to be understood and communicated to the flightcrew.

4.2 Mixed Equipage

Aircraft with various levels of capabilities are expected to continue to operate in the same airspace. This issue of 'mixed equipage' is usually considered only as it affects the complexity of the controllers' tasks. This issue, however, is increasingly affecting pilots tasks as the variability in interfaces and levels of automation within a fleet of a given aircraft type increases. Flightcrews are type-certified and trained on specific airframes. They are required to receive training when transitioning to different airframes or when there are significant changes to the avionics (e.g., FMS). However, the increasing complexities of the flight deck designs can increase the challenges to achieve effective differences training.

As the CAST Flight Deck Automation Working Group (2013) found, "there is significant variation in flight deck equipment design, in both flightcrew interfaces and in system functionality. Such variations can have important consequences for flightcrews (pilot error, increased training time, negative transfer of learning, etc.) and airspace operations (potential differences in the flight paths within the airspace), especially considering future airspace changes. Although standardization can reduce such variations, comprehensive changes to standardize existing equipment may not be realistic and complete standardization may inhibit advances in technology" (p.4).

The pilots interviewed also expressed concern that less capable aircraft may be allowed to participate with workload-inducing pilot 'workarounds' which would introduce additional risk and opportunities for error. As the CAST Automation Working Group (FAA, 2013) found "…data suggest that the highly integrated nature of current flight decks, and additional "add-on" features and retrofits in older aircraft, have increased flightcrew knowledge requirements and introduced complexity that sometimes results in pilot confusion and errors in flight deck operations" (p.4).

4.3 Programming of FMS

It is well-known that programming the FMS and understanding (and anticipating) FMS operations can be a complex and error-prone task. "The data show that FMS programming by the pilots continues to be an area of concern…In addition to pilot interface and data entry vulnerabilities, the FMS uses algorithms and protocols to compute descent/deceleration profiles that by their very nature are complex (power on/idle/geometric segments, headwinds/tailwinds, crossing restrictions etc.) even if a pilot enters the data correctly, certain FMSs may not be able to accomplish the desired flight path required by the procedure or expected by the pilot, requiring the pilot to recognize the impending deviation in a timely manner and to take appropriate action" (CAST Flight Deck Automation Working Group, 2013, p.42).

One reason the flight path in the FMS may be different from what the pilot intends involves waypoint sequencing. Different aircraft sequence and report waypoints to ATC in position reports in different ways. Waypoint sequencing will only occur in the intended sequence (i.e., A to B to C) when the aircraft is within a given distance of the waypoints on the active flight plan route. Depending on the aircraft, this distance varies between 5 and 21 Nautical Miles (NM; See the *Global Operational Data Link [GOLD]*, ICAO Doc 10037, 2016, Appendix C for distance by major aircraft type). This means that when the aircraft is outside these limits, the aircraft will be unable to sequence the waypoints, resulting in a discontinuity. Another result of exceeding the distance tolerance is that ADS-C waypoint change event reports and other programmed reports to ATC (e.g., REPORT PASSING [waypoint]) will not be transmitted automatically. Additionally, when the FMS does not sequence the waypoints as expected it can result in the aircraft flying a route other than the route that the pilot intended (e.g., to a waypoint behind the aircraft).

It is important to note that due to the complexities of the FMS and mode-specific capabilities, the reasons for aircraft behaviors (such as waypoints not sequencing as expected) – and the resulting implications for the trajectory of the aircraft – are not always clear to the pilot. In our interviews, one very experienced pilot described an incident in which the FMS did not sequence the waypoints as expected, which resulted in the wrong missed approach procedure being called up. He said that while it is possible that he accidentally switched to the Instrument Landing System (ILS), "I still don't know what happened, and I'm pretty FMS savvy."

An FMS can rename a waypoint internally, and then not be able to rejoin a route if it cannot match the renamed point with the original. There are aircraft that are known to send abeam points as part of the FMS route, although these are unknown to the ATC system. If abeam points are created by the FMS during a flight plan revision, the aircraft system may include information about these non-ATC waypoints in the ADS-C reports. As a result, the ADS-C report will include information about the non-ATC waypoint (which does not conform to what is expected by the ATC ground system). Clearly, aircraft equipment that creates abeam points should not send these points as part of ADS-C and other route conformance messages. With that said, pilots should not be expected to manually edit the flight route to delete such equipment-generated points.

The following are two other counterintuitive FMS behaviors that were offered by pilots interviewed; these serve as examples of FMS behavior that pilots and controllers would not anticipate. These FMS behaviors are also expected to promulgate into the TBO environment until the Baseline 2 CPDLC message set is implemented. First, the instruction to "CROSS XYZ AT OR BEFORE TIME" or "AT OR AFTER TIME" is treated by many FMSs like an "AT TIME" not recognizing the flexibility of the instruction. This can result in over-aggressive speed changes as the FMS tries to hit the point exactly on time. Second, when an uplink such as "CROSS XYZ AT OR BEFORE TIME" or "AT OR AFTER TIME" is loaded, RTA cruise speed is engaged (which changes the speed to meet the restriction), even on aircraft that do not have the RTA option installed.

Revised clearances pose the additional risk that the pilot will miss the change in the clearance and assume that the revision is the same as what was already loaded into the FMS. According to an unpublished analysis of reports submitted to that Aviation Safety Information Analysis and Sharing program (ASIAS), pilots have failed to notice a route change or change to the Standard Instrument Departure (SID). Other errors reported to ASIAS were that pilots:

- did "not know or notice" that the SID was removed after loading the new route;
- failed to manually load the transition after successfully loading the new route (an additional step that they either did not recognize as required or forgot to do);
- attempted to manually load a route from free text and missed assigned fixes or deleted previously assigned fixes (Briefing by Chad Geyer [NATCA] to PCPSI Work Group, July 2019.)

4.4 Progression of Data Communications (Data Comm)

The Data Comm Program has implemented CPDLC in pre-departure clearance delivery and in the en route (Air Route Traffic Control Center [ARTCC]) environment. CPDLC is considered a foundational capability of TBO. While there are significant differences between the present and planned systems, there are several lessons learned from the Data Comm program that can be applied to the implementation of TBO.

4.4.1 Air-ground interoperability

"Air-ground interoperability issues present challenges to operational acceptability of domestic en route Data Comm" (Jesse Wijntjes in a briefing to Data Comm Implementation Team [DCIT] July 16, 2019). While the FAA has made multiple changes to the ATC ground system, there are several remaining issues in the avionics. In fact, as late as October 8, 2019, aircraft technical issues resulted in the FAA requesting that operators only file for En Route CPDLC (FANSE or FANSER DAT code) if aircraft meet specific avionics configurations (listed in the Data Comm Recommended Avionics Versions document found on the Harris Data Comm site). This points to the need for clearly defined avionics requirements for TBO applications; such requirements should be based on extensive testing.

The Data Comm program had the advantage of offering pilots involved in the DCIT interactive demonstrations of the Data Comm functionality at the FAA Technical Center. This gave pilots the opportunity to see how clearances and other messages would be displayed, and what the controllers would see as the messages were exchanged. This was universally regarded as a very valuable exercise. One pilot even suggested that such demonstrations would be useful to record and use in training. However, *demonstrations*, even interactive demonstrations, are not a valid substitute for operational testing and human factors assessments of new equipment and new procedures. This involves testing the systems in the environments in which they will be used. The Data Comm Program Office did not invest in extensive operational testing prior to implementation, in part because the FANS message set had been used in the oceanic environment for many years. While changes to the communication avionics were not initially envisioned to be required to meet minimum capability requirements for use of Data Comm en route, this changed after implementation.

In actual operations, it was learned that the avionics can process the same FANS messages differently in different environments (e.g., different aircraft configurations). For example, in one aircraft type, the same message (i.e., Uplink Message [UM] 80 that includes an arrival procedure) loaded correctly on the ground, but not in air. In air, the uplink message resulted in discontinuities being added to the route and the repeating of the en route transition. To make matters worse, the ‘partial clearance loaded’ scratchpad message—which would have alerted the pilots to a problem – was not displayed as it should have been. This necessitated a software fix so that the message loaded properly.

UPS and FedEx decided to test the uplink messages before using them in actual en route operations. Using the high-fidelity testing facilities at the FAA Technical Center, they sent and received Data Comm messages between equipped aircraft and the FAA processor (simulating an FAA facility). This testing revealed that in rare cases, when a full route clearance (UM80, “CLEARED [routeclearance]”) that included a Standard Terminal Arrival Route (STAR) was issued and loaded, the second waypoint on the STAR was no longer on the flight plan in the FMS. This occurred without resulting in a discontinuity (which would have alerted the crew to a problem) or any other indication to the flightcrew that the flight plan had changed. Subsequent testing revealed that the same problem was possible with a UM83, “AT [position] CLEARED [routeclearance]”. As a result, the STAR had to be removed from these route clearance messages, was handled separately by the ground system, and transmitted to the crew via free text. It should also be noted that UM83 is currently not being used (except in the oceanic environment) due to additional processing issues between the ground and avionics.

The Data Comm Program Office documented several instances on the Boeing 757 (B757) and Boeing 767 (B767) with Pegasus 1 FMS where a message from a previous flight was displayed to the crew. This led to an interruption in services for all B757 and B767 aircraft with Pegasus 1 FMS. Various solutions to this problem are currently being explored; one mitigation suggested is to power down the aircraft after every flight (sometimes accomplished by pulling a circuit breaker). This is an example of an operational problem where a potential fix to an avionics issue would impose more workload on the pilot.

Another existing issue that has not been demonstrated to be problematic in the oceanic environment, but that is operationally unacceptable in the more time-sensitive en route environment, is labeled “ack and toss”. There have been several instances (across several aircraft types) in which the communications avionics (i.e., Communications Management Unit [CMU] or equivalent) acknowledged (i.e., “ack”) receipt of a FANS uplink message via the ACARS, but did not process it further (i.e., “toss”). Normally, upon receipt on the aircraft, the uplink message would be sent to the avionics that host the FANS applications, then displayed to the pilot. In cases of “ack and toss”, the aircraft acknowledges receipt of the uplink, but the message is not displayed. This means that the controller sees that the message was sent, the ground system receives a “message assurance report” indicating successful delivery, but the message is never presented to the pilot. This problem has been remedied for some aircraft (B777) with an avionics software change.

4.4.2 Timing of CPDLC messages

CPDLC messages that come in close temporal proximity can cause distraction and increased workload on the flight deck. In a 2020 meeting of the DCIT, the problem of pilots receiving multiple CPDLC messages in quick succession was discussed. Pilots reported receiving several CPDLC messages within minutes. In one example, a crew in en route descent (approx. FL230) received three messages within 32 seconds. The third message was uplinked eight seconds after the second message. The crew was reviewing the second message while the third message was received. They responded WILCO to the third message without seeing it (thinking they were responding to the second message). In this case, the messages were: “Descend and maintain FL190”, “Proceed Direct To CHERI” and “Cross CHERI at and maintain 11,000FT and 250KTS”. Pilots report that these are clearances are often conveyed in one radio transmission. From a human factors standpoint, this is more information than would be recommended to be conveyed in a single voice transmission (Cardosi, 1993). However, the risks associated with a readback/hearback error are arguably lower than the risks associated with distraction (from receiving multiple messages in quick succession) or with responding WILCO to a clearance that was never viewed. In at least two cases (one described above as reported by a DCIT participant and another found in ASRS report [ACN number 1587518]), a rapid succession of CPDLC messages resulted in pilots thinking they had processed the last message in the chain when, in fact, they had not seen it. From a human factors standpoint, the ‘rapid fire clearances’ present several operational risks. Each CPDLC message provides an aural alert to indicate that a new message has arrived. This aural alert is not unique to CPDLC messages. This means that the pilots must first determine the source of the aural alert (e.g., call from flight attendants, printer, etc.). While flight decks vary, this aural alert means either that a new message is displayed or, more commonly, means that there is a new message waiting to be displayed and the pilot must follow a sequence of actions to display it.

The current ground en route system (as of March 2020) does not allow controllers to concatenate messages. This means that unlike oceanic controllers, en route controllers cannot chose to combine messages in a single transmission and must instead send them sequentially. This includes messages that they would normally be contained in a single voice transmission. As of this writing, Harris is compiling additional information on the frequency of this occurrence to progress the discussion at future DCIT meetings as to the extent of the problem and possible mitigations. After the information is compiled, DCIT plans to convene a working group of DCIT members to assess and address the issue.

4.5 Clearance Negotiation

A recent analysis (Lennertz, Cardosi, & Yost, 2019) of the effects of conditional clearances on altitude deviations identified a need for additional guidance on the negotiation of even simple clearances (e.g., "WHEN CAN YOU ACCEPT [altitude]?"). In two of 46 Large-Height Deviations (LHDs) attributed to pilot error occurring in North Atlantic Airspace in 2017, ATC asked the flightcrew when they could accept a higher flight level, and the flightcrew erroneously climbed to that higher level without clearance. In one case, ATC asked at what time the aircraft could accept Flight Level (F) 380. After responding, "able F380 anytime" via voice (High Frequency [HF]), the aircraft immediately climbed without a clearance. In another instance, ATC asked what time the aircraft could accept F350 or F360. The aircraft responded "now" and then climbed without a clearance. In both of these cases, the pilots were asked (via CPDLC) "WHEN CAN YOU ACCEPT [level]". Use of the standard message "WHEN CAN YOU ACCEPT [level]" prompts the pilot of an equipped aircraft to respond with either a TIME or POSITION at which they can accept the altitude. In both of the pilot errors observed in 2017 with this clearance, the pilot responded via either HF or free text and climbed before any clearance was issued. The two LHDs described would likely not have occurred if the flightcrew had replied with a prompted downlink response, rather than free text or voice. These errors indicate that the flightcrew misinterpreted this question as a clearance, in part due to the message format.

In the near term, as traffic increases over the ocean, so will the frequency of altitude negotiation—with pilots questioning about the availability of flight levels and controllers querying the pilot about the ability to accept a specific level. When the flight level that the pilot has requested is not currently available, but will be available at a future time, the controller may issue a conditional clearance that allows the pilot to change flight level at a future time. This adds a layer of complexity to the pilots' task and can result in an altitude deviation if the pilot initiates the maneuver early.

Such negotiations will become more frequent as NextGen technologies enable aircraft to routinely modify their route of flight. Consequently, for this simple altitude negotiation, the authors recommended that controllers use the standard message element "WHEN CAN YOU ACCEPT [level]" (and not free text) when negotiating an altitude clearance via CPDLC. Pilots should be advised to reply with either standard response message "WE CAN ACCEPT [level] AT [time]/[position]" (and not free text) and to ensure that such negotiations are not interpreted as a clearance. This recommendation is planned to be incorporated into the next edition of the ICAO *Global Operational Data Link Manual* (ICAO Doc 10037). Another source of miscommunication with clearance negotiation involves the interpretation of the question "WHEN CAN YOU ACCEPT [level]". To respond, the flightcrew must determine when the aircraft performance could meet the level restriction. In one error, the pilot responded to this inquiry with a time, but the clearance sent was not "AT [time] CLIMB TO [level]", but rather, "CLIMB TO REACH [level] BY [time]". It seems as though the pilot was indicating the time at which they could accept the clearance, but the controller interpreted the response as when the level could be reached.

Capabilities for both clearance negotiation and the delivery of complex clearances via CPDLC are expected to increase as TBO evolves. Procedures for clearance negotiation (voice and CPDLC) and the transmission of complex clearances via CPDLC need to be designed to help prevent a concomitant increase in pilot errors. The best uses of CPDLC for clearance negotiation and the delivery of complex clearances need to be understood to support the implementation of advanced NextGen concepts. If not standardized, recommended practices for controllers and pilots should be developed and disseminated.

4.5.1 Global Harmonization

Both NextGen and SESAR have the similar goals of increased capacity, efficiency, and predictability with reduced fuel burn and emissions. Both programs identify CPDLC as an enabling technology for planned implementations to effect these goals. As the 2018 report on the State of Harmonization between the U.S. NextGen and European SESAR programs states, the modernization strategies for DataComm by NextGen and SESAR do not completely align in terms of present and planned capabilities (SESAR Joint Undertaking /Federal Aviation Administration, 2018). This means that pilots will continue to deal with differing capabilities in different airspaces. Continued participation within ICAO and RTCA will help to ensure that the modernization efforts are as harmonized as possible and specific differences in phraseology used for clearance negotiation can be highlighted to U.S. users and monitored as appropriate to determine that no safety issues exist. It also affords an opportunity to learn from the experiences of other ATSPs as they implement CPDLC capabilities such as the EPP and taxi instructions before the U.S.

4.6 Future Spacing Capabilities

4.6.1 CDTI-Assisted Visual Separation (CAVS)

While some manufacturers and researchers consider RTA, CPDLC, and ADS-C sufficient to accomplish TBO, other interviewed SMEs maintain that in order to increase capacity in the terminal environment, relative spacing will need to be used instead of absolute spacing. A transition point from absolute to relative spacing will likely be needed at or near the boundary into terminal airspace, wherever capacity is an issue. While RTA can help to provide absolute spacing, relative spacing can only be achieved via visual separation, CAVS, or Interval Management (IM).

A limited human factors and benefits assessment was conducted on CAVS (FAA, 2016; Cardosi, Lennertz, & Donohoe, 2015). Generally, the pilot responses were positive with little or no increase in workload attributed to the CAVS procedure. Interviews revealed that pilots found other benefits to the CDTI display (FAA, 2016; Cardosi, Lennertz, & Donohoe, 2015). Pilots used the display to:

- Call the aircraft ahead, above, or below them using the displayed call sign to inquire about ride quality.

- Make more informed requests of ATC. (Route changes and altitude requests have a greater chance of being approved when no conflicting traffic can be identified on the ADS-B-based CDTI.)
- Identify a path for emergency descent.
- See who might be ahead of them in Customs. (While this might appear to be trivial, it actually has both practical and operational implications. If a large aircraft is ahead, then the lines in customs will be longer. Long wait times in customs lines result in disgruntled passengers and contribute to increased chances of missed connections. Depending on the circumstances, crews might request an altitude with less headwind or increase their speed, attempting to arrive before the other aircraft.)

While most pilots found the CDTI easy to interpret and use, problems were noted with the location of the CDTI (off to the side). More research is required to determine the required display placement, whether it needs to be integrated with other flight deck displays, and to identify training requirements.

4.6.2 Interval Management (IM): En Route and Terminal Operations

IM is a flight deck-based tool to maintain relative spacing between aircraft. The goal of IM is to reduce the variation in inter-arrival spacing, thus enabling more capacity. To participate in IM, an aircraft must be equipped with ADS-B (IN and OUT) and must be within range of an aircraft equipped with ADS-B OUT. In IM, the flightcrew receives a clearance from ATC to commence IM operations and then follows speed guidance to maintain relative spacing with a leading aircraft. Unlike RTA, speed constraints in an arrival are considered guidelines; the actual speed of the aircraft can vary from the published speed constraints by ± 15% (Jackson, Howe-Veenstra, & Walker, 2019). IM is particularly useful in the terminal area, where relative spacing will allow for increased capacity compared to absolute spacing. Relative spacing also enables more flexibility for aircraft on arrival as they transition to the final approach (Bone & Mendolia, 2018). Operations based on relative spacing are seen by many as the key to maximizing arrival throughput (e.g., Stone, 2019, personal communication). When the ceiling and visibility do not allow for visual approaches, ADS-B IN and IM can increase capacity in the constrained terminal environment.

In IM operations, pilots will not be responsible for separation; their only responsibility will be to follow speed guidance from the avionics. Controllers are responsible for separation, however to achieve increased capacity, they may need to apply smaller buffers to the minimum separation standard than those applied today. In the future, it may be possible to reduce current separation standards for IM operations, further increasing capacity.

Much work—including research and development and operational trials—has examined the flight deck human factors associated with IM. Most recently, Bone and colleagues (Bone & Mendolia, 2018; Bone, & Penhallegon, 2019) have examined the information that should be presented on the flight deck to support IM. The original research prototype flight deck display was designed based on the RTCA Minimum Operational Performance Standards (MOPS) for IM. These Standards are being revised by RTCA SC-186/WG-4 based on recent research that showed that the information assumed to be needed by pilots to perform the operation successfully did not match actual measurements of pilot performance. This research indicated that while flightcrews preferred to have a progress indicator (graphical or numeric) shown on the flight deck (Bone & Mendolia, 2018), displaying only the speed to be followed was sufficient for performance (Bone, personal communication). Specifically, displaying the IM speed on the flight deck, and providing an indication when the speed has changed (e.g., brief flashing or reverse video) was sufficient to enable IM operations (Bone, personal communication).

Flight test evaluations of IM have focused on en route, arrival, and final approach phases of flight (Swieringa, Wilson, Baxley, Roper, Abbott, Levitt, & Scharl, 2017) and sought to examine both the spacing accuracy between aircraft and the frequency of speed commands issued to the flightcrew. Evaluations occurred in Seattle airspace over a period of 19 days and included a United Boeing 737, Honeywell Boeing 757, and a Honeywell Falcon-900. Crews had both speed guidance and speed conformance monitoring on a separate prototype flight deck display.

Aircraft engaged in IM crossed the “planned termination point” within two seconds of the goal—indicating that spacing was relatively accurate throughout the IM operation; however, there was some variability in performance, specifically related to aircraft deceleration. In some cases, when aircraft were required to decelerate on arrival, it became more challenging to maintain accurate spacing due to different deceleration rates between the leading and following aircraft. At the cross “final approach fix” the average spacing error was 6.24 seconds (Standard Deviation = 8.28 seconds); this did not meet the spacing goal, and may be partly due to differences between actual and forecast winds. In this flight trial, crews received 0.57 speed changes per minute (or, about one speed change every two minutes); speed reversals were also observed and impacted pilot acceptability of the operation. Qualitative data (Baxley, Swieringa, Wilson, Roper, Hubbs, Goess & Shay, 2017) further indicated that pilots thought IM required “large decelerations”, “too many speed changes” and required the aircraft to be “too fast when close on the final approach fix”. Pilots also reported high workload to enter the IM clearance and related information (e.g., winds), which may be reduced with CPDLC. Finally, pilots observed some mismatch between the IM operation and arrival and approach procedures, especially regarding the speed constraints and the nominal performance of the aircraft.

In the terminal environment, crews received about 1.5 speed changes per minute (Bone & Mendolia, 2018); however, some speed reversals were observed (e.g., guidance to increase speed after the flightcrew had configured the aircraft for landing); these can impact the flightcrews’ trust in the operation.

Based on this body of research, future research could examine the compatibility of IM speeds on final with a stabilized approach, and how to refine the algorithms to reduce speed reversals at lower altitudes (which would increase pilot acceptability). Given the impact of workload and the potential to increase head-down time at a busy phase of flight (cf. Oseguera-Lohr, Lohr, Abbott & Eischeid, 2002), future flight trials should include the simplified speed guidance display, that is, including minimum speed only. Finally, consideration should be given to the degree to which the target aircraft’s procedure must be constrained to yield successful IM operations and the amount of tolerable uncertainty in wind conditions.

It should be noted that in 2015, Airbus expressed doubt that the avionics required for IM would be cost-effective. Airbus submitted a position paper to RTCA (Airbus, 2015) that stated that the current FMS functionality was sufficient to achieve Dynamic 4D-Trajectory operations (see also Airbus, 2009). This assumes sufficient a level of ground (ATC) automation that has yet to be implemented.

The NextGen Advisory Committee (2016) recommended that –"after the [research] is complete and prior to the FAA's final investment decision…[FAA and industry] review …the results, including the cost and benefits …to determine the final status of future recommendation on IM development and implementation" (p. 15).

5. 'There's an App for That' and Other Additional Capabilities:

It is impossible to predict applications that could be developed between now and the implementation of Dynamic TBO. Manufacturers and operators continue to explore possible uses of the EFB, in part, because it is not subject to the same level of certification as the FMS. For example, GE Aviation is making its "Connected FMS" software development kit, which securely pairs an EFB to the FMS, available to app developers. Connected FMS is advertised to 'reduce both pilot workload and human error' [3] by allowing pilots to optimize a flight plan and load the desired route into the FMS as a route request for downlink to ATC. The ground system would then process the route request and send up a loadable clearance.

5.1 D-Taxi

A gate-to-gate (as opposed to a runway-to-runway) implementation of Dynamic TBO would include D-Taxi operations. These are aircraft taxi instructions issued via CPDLC. Because surface operations are time-critical, several issues regarding feasibility and safety will need to be explored in addition to the usual flight deck issues associated with information/display requirements and procedures. Extensive human factors research will be required to address these issues before implementation can be considered. Eurocontrol plans to implement D-Taxi before the U.S. and FAA can benefit from their experience and lessons learned with continued involvement in the relevant ICAO and RTCA/EUROCAE working groups.

5.2 Extended Projected Profile (EPP)

ADS-C will be required for another capability assumed for Dynamic TBO: the EPP. The ATN-B2 standard defines the EPP trajectory that can be sent via ADS-C from an aircraft to ground automation (RTCA, 2016) The EPP trajectory message contains a representation of the reference trajectory from an

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[3] See https://youtu.be/DYBCt-If4i4

aircraft's FMS. However, the EPP only provides a representation of the active reference trajectory within the FMS based on the current active flight plan. Furthermore, the EPP is only valid for the current clearance when it is in a coupled path guidance mode (i.e., coupled LNAV and VNAV; Bronsvoort, McDonald, Torres, Hochwarth, Boucquey, Paglione, Young & Vilaplana (2016) as in Guerreiro & Underwood (2018)).

The only FMS that can currently output an EPP is the Thales/GE FMS on the Airbus A320/330/340 starting with Standard (version) S8T6[4]. EPP can be added to the existing FANS 1/A standard with a software-only update. This functionality could be used to downlink speed reports or RTA time windows to ATC in the descent (separately from EPP).

Recall that when an aircraft passes abeam a waypoint in excess of a specified parameter (as defined by the avionics), the FMS is unlikely to sequence the active waypoint. This means that the flightcrew will need to sequence the waypoint or else ADS-C reports, CPDLC position reports, and the EPP will contain incorrect information. Additionally, pilots need to be aware that unnamed waypoints (i.e., pilot or company-defined waypoints) need to be reported in a specified format. Some aircraft operators use the ARINC 424 latitude/longitude format and some aircraft use arbitrary names (e.g., those created by an air carrier) for latitude/longitude waypoints that would not be able to be processed by the ground system in an EPP. In the near term, this can cause problems for pilots and controllers communicating about a route (present, future or requested).

6. Training

Training will be a critical issue in the implementation of TBO on the flight deck. As the procedures for advanced concepts are developed, the roles and responsibilities of pilots and controllers will need to be clearly defined, particularly with respect to any operations involving designated spacing goals assigned to pilots. Pilots interviewed noted that the time air carriers give to training is severely limited, with concentration on emergency procedures and little or no time spent on normal procedures. For example, training for CPDLC DCL and en route could have consisted solely of a bulletin or other self-study (such as computer-based training [CBT]; see Lennertz & Cardosi, 2015 for a sampling of air carrier training types for CPDLC). As the communication avionics may need to be upgraded for Dynamic TBO, so too will the training pilots receive on CPDLC. Pilots interviewed noted that in today's CPDLC operations, pilots are typically handed a bulletin and, in reality, learn CPDLC "on the line" (i.e., in actual revenue operations, from their co-pilots and trial and error). As the clearances communicated via CPDLC become increasingly complex, so will the processes needed to construct a clearance request, load the received clearance, correctly review and close out any discontinuities, and know when clarification from ATC is required. This will require a higher level of training than pilots now receive from their companies on CPDLC.

Pilots interviewed by Holder (2013) regarded such self-study as "ineffective" (p.15). While airlines routinely try to minimize training time to minimize costs, training for each NextGen application will need to be appropriate for the complexity of the operation and equipment required. For example, operations

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[4] S8T6 stands for Single Aisle (Narrow Body) Standard 8 Twin Aisle (Wide Body/Long Haul) Standard 6.

such as CAVS and IM will likely require simulator training. Such training is not only necessary to prevent pilot error in execution of the procedure, but to increase pilot acceptance of optional procedures designed to increase capacity.

A demonstrated example of the importance of training in the acceptance of a NextGen application was seen with In-Trail Procedure (ITP). ITP is one of the ADS-B applications in the NextGen program. It increases opportunities for aircraft in oceanic airspace to climb or descend to an optimal flight level through the use of ADS-B technology. The use of ITP is intended to allow aircraft to fly at more fuel-efficient altitudes more often (reducing both fuel use and emissions) and increase passenger comfort and cabin safety by vacating turbulent altitudes. The Volpe Center discussed ITP with pilots and controllers in 2013 to determine why pilots and controllers were not using the procedure. Follow-up discussions were conducted in 2016 after changes were made to the training given to pilots and air traffic controllers (Cardosi & Lennertz, 2016).

In the 2013 discussions with pilots, the most common negative comment was that pilots were apprehensive about requesting an ITP due to the lack of hands-on training for the procedure. The pilots who liked having the equipment and procedure available to them had received hands-on, interactive training; all of these pilots were either Line Check Airmen (LCAs) or pilots who had trained with an LCA. Most of the line pilots, however, had received only a CBT module (a PowerPoint-type presentation with narration). This training covered the intent and mechanics of the ITP, explained the conditions under which an ITP could be requested, and how to use the equipment to see if a climb or descent could be requested. If the ITP conditions were met, the “ITP view” on the ADS-B display of traffic would show the pilot the words to use to communicate the ITP request via CPDLC. This tutorial did not include any opportunity to interact with a mock-up of the system. Several pilots stated that they did not feel that the CBT alone was sufficient training for a reduced-separation maneuver.

Interestingly, one of the reasons pilots stated that they were reluctant to use the ADS-B traffic display was because they thought that it was connected to the FMC. These pilots said they were more likely to use the display after understanding that it is not connected to the FMC. In 2016, after pilots received training that included the opportunity to interact with the display, pilots were comfortable using the display options and cited several ways in which they used the display on a routine basis to increase efficiency and avoid turbulence.

Another training issue that came to light in this study was that in order to contact the aircraft directly or to refer to the aircraft to ATC, pilots need to translate the displayed aircraft flight ID to the call sign used over voice. Some of these translations are likely to be familiar to pilots (such as UAL for United and AAL for American). Others, such as AZA for Alitalia, DLH for Lufthansa, AAR for Asiana, and QFA for Qantas, are less likely to be familiar. It would be helpful for pilots to have a way to match the three-letter identifier in the aircraft flight ID to the call sign prefix used over voice. This could as simple as a list of carriers that they are likely to encounter during their flight in a newsletter article, or this information could be placed on their iPads in a ready reference location.

7. Next Steps: Summary of Recommendations

7.1 Recommendations on General Programmatic Issues

1. The FAA should publish a detailed TBO Concept of Operations from an operator's perspective to support cost/benefit analysis and operator investment decisions.
2. Continued leadership and strong participation in RTCA/EUROCAE joint working groups and relevant ICAO panels and working groups are needed in order to foster global harmonization for TBO capabilities. Proactive global harmonization is needed to address phraseology for time- and trajectory-based clearances.
3. Decision support tools intended for use in TBO by ATC and the flight deck need to be developed and tested in tandem in light of a concept of operations that defines how they will interact.
4. A systems approach should be taken to: decide what functions should be performed by which actor; define exactly what capabilities are to be included in TBO; determine what information is needed by whom, when it is needed, and in what format it should be presented.
5. FAA Certification should determine what TBO functions should be performed by the FMS and what could be performed safely by an EFB.
6. Programmatic decisions should be based on objective results of assessments whenever possible.
7. System performance (including objective and subjective measures of performance of pilots, controllers, and dispatch, and feedback from operators) should be monitored on a routine basis in an environment with a strong safety culture where errors can be self-reported without the fear of punishment for honest mistakes as new capabilities are implemented.
8. FAA should utilize independent human factors support to assist the FAA in identifying and remedying problems prior to implementation and to identifying solutions to problems as they arise.
9. Prior to implementation, operational testing and evaluation of complex systems or procedures that are to be required for TBO is essential to helping to ensure that the system or procedure function as intended and do not induce pilot errors.

7.2 Research Considerations for Flight Deck Capabilities that are Assumed for TBO

1. Flight deck human factors research should continue to examine the feasibility of using the current message set (i.e., FANS 1/A) for Dynamic TBO.
2. Progressing toward loadable complex clearances for Dynamic TBO will require substantial operational research with a strong human factors component. Extensive testing and trial operations will be needed to identify and resolve technical issues that could result in pilot error,

unnecessary increase in pilot workload, and loss of pilot and controller trust and confidence in the system.

3. The FAA should support the development of voice phraseology to support complex clearances in addition to the CPDLC message set.
4. Research should be conducted to explore the feasibility of using RTAs as a sequencing tool, particularly on descent.
5. Research is needed to determine the placement for the flight deck display required for CAVS operations, whether the display should be stand-alone or integrated with other flight deck displays, and to identify training requirements.
6. Research should examine the compatibility of IM speeds on final with a stabilized approach, how to refine the algorithms to reduce speed reversals (and increase pilot acceptability), and the need to include similar information (e.g., winds) at low altitudes across aircraft. Future work should also consider the degree to which the target aircraft's procedure must be constrained to yield successful IM operations. Furthermore, the amount of tolerable uncertainty in wind conditions and delay allocation should be quantified in order to understand the limits of the robustness of the current methodology.
7. The implications of 'pushing' winds and other information to the aircraft on pilot workload and potential errors should be investigated.
8. Extensive human factors research will be required to address information/display requirements and procedures associated with D-Taxi before implementation can be considered. FAA can benefit from the experiences with implementation of D-Taxi in Europe and associated lessons learned with continued involvement in the relevant ICAO and RTCA/EUROCAE working groups.

7.3 Issues to be Considered with the Implementation of TBO

1. The effects of FMS variances on the pilots who may have to transition from one variant to another within their fleet should be investigated.
2. For each specific advanced flight deck capability, potential variability and interactions of operating procedures that can affect the trajectory of the aircraft need to be understood and communicated to the flightcrew.
3. The FAA should continue to engage in operational testing and human factors assessments of new equipment and new procedures for TBO.
4. The clearances intended for use in TBO will need to be tested by all users (air and ground) in tandem in the environment in which they are to be used. This should include testing in a variety of FMSs to ensure that the clearances can be supported by the avionics and are usable by pilots.
5. As the communication avionics may need to be upgraded for Dynamic TBO, so too will the training pilots receive on CPDLC.
6. Coordination between the TBO Program Office and the Data Comm Program Office will help to ensure that CPDLC requirements for TBO can be supported by the avionics and message set.
7. Procedures for the clearance negotiation (voice and CPDLC) and the transmission of complex clearances via CPDLC need to be designed to help prevent pilot errors. Research is needed to

understand the best uses CPDLC for clearance negotiation and the delivery of complex clearances to support the implementation of advanced NextGen concepts.

8. The FAA should continue to participate when RTCA SC-214/EUROCAE WG-78 reconvenes to revise the standards for Baseline 2 as these messages will applicable to Dynamic TBO.
9. During operational trials of TBO and post-implementation, operations must be continually monitored with feedback from the operators to identify what works well, what is problematic, and to identify any unanticipated consequences. Particular attention should be paid to human performance aspects, both positive and negative.
10. As the procedures for advanced concepts are developed, the roles and responsibilities of pilots and controllers will need to be clearly defined, particularly with respect to any operations involving pilot designated spacing goals assigned to pilots.

7.4 Development of a TBO Human Factors Roadmap

The FAA should develop a TBO Human Factors Roadmap that identifies specific capabilities and when they are expected to be available. This roadmap would be a ‘living document’ that is updated on a regular basis. For each capability, the roadmap should identify:

a. Known flight deck human factors issues associated with the capability;
b. Identification of any potential certification issues;
c. Recommendations for flight deck procedures and training (or identification of the need to develop procedures and training recommendations);
d. Identified research needs associated with those capabilities – this would include analysis and monitoring of implementation of capabilities (e.g., Established on Required Navigation Performance, “EoR”) to identify sources of pilot error and ways to mitigate those errors as well as identification of laboratory research and Human-In-The-Loop Simulations (HITLs);
e. Status of the research (planned, in progress, completed), the results of completed research and next steps;
f. Results of performance monitoring efforts, including feedback from the operators to identify what works well, what is problematic, and to identify any unanticipated consequences; and
g. Lessons learned from implementation of the incremental phases of TBO.

In addition, the roadmap should track global progress on the:

a) Development of phraseology (voice and CPDLC) needed to support complex clearances for TBO; and
b) Development of phraseology and procedures to support clearance negotiation.

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9. Appendix

Pilot-identified 'Work Around' for RTA

The following is an excerpt from a post on the Professional Pilots Rumor Network.[5] Here, a pilot lays out the details of a complex 'workaround' for RTA on descent.

The trick is to:		
	Main Step	***Additional Tips***
1.	Go to the LEGS page and enter the IAS that ATC want you to maintain from the RTA waypoint.	
2.	Go to the PERF LIMITS page and enter a limit on the MIN descent speed. The lower limit of IAS on descent should be equal to the speed ATC require you to maintain from the RTA waypoint (usually 250 kt). If the FMC should choose a higher descent speed than that for descent, that is fine as slowing down prior to arriving at a waypoint is handled very well by the FMC. It's when it has to speed up prior to a waypoint that it gets into trouble. i.e if you want to maintain 250 kt IAS from the chosen waypoint, and the descent speed chosen by the FMC prior to arriving at that waypoint is 265 kt, the descent profile will be fine.	*However if the FMC chooses a descent speed of 220 kt to make good the arrival time at that waypoint, the descent path from that waypoint onwards will still be based on a descent speed of 220 kt!* *Remember a speed entered in the LEGS page is actually an AT or BELOW speed. The FMC has chosen a speed BELOW 250 kt. Once you have passed the waypoint you would then have to enter 250 kt in the descent page and execute. This might put you high or low on the new descent path and you may have to put on thrust to accelerate and/or regain the new descent path. (I have seen descent speeds lower than 250 kt cause a descent path to be steeper than that built on a 250 kt descent.)* *The fact that you have put a lower limit on the DESCENT speed forces the FMC to calculate a lower CRUISE speed than it would have otherwise chosen to make up for the higher descent speed. Remember too that it will NEVER choose a speed (Mach) less than that which equates to the best Holding Speed (IAS)*

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[5] See: https://www.pprune.org/tech-log/263558-rta-arrival-manager-tool.html.

The trick is to:		
	Main Step	***Additional Tips***
3.	If the minimum speed (best holding speed) will not be slow enough to make good the required time of arrival, a CDU scratch pad message "UNABLE RTA" will appear. However this is only true for the current cruise altitude entered in the CRZ page. Remember for a given IAS your TAS decreases with decreasing altitude! With one CDU on the RTA page, the other goes to the CRZ page and enters a lower cruise altitude. Notice the effect this has on the waypoint ETA. It will be getting closer. Keep entering a lower and lower cruise altitude until the FMC indicates it can now make the required arrival time. You might have been cruising at F350 and the required level might be F300 or F250. You then simply have to request descent to that level.	
4.	If descent is required, do so in (Flight) Level Change or equivalent so that the descent is made using idle thrust and the TAS reduces as quickly as is possible. Make sure the MCP target speed is IAS (not Mach) and that the IAS is set to the best holding speed (found on the HOLDING page).	*Remember too the effect of wind at the new level. You might be descending out of a jet stream. A decreasing tailwind will have a profound effect on the resulting ground speed. Descending out of a headwind will obviously have the opposite affect and may cancel the reduction in TAS.*

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