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An Analysis of the Speed Commands from an Interval Management Algorithm during the ATD-1 Flight Test

Christine Watters
Louisiana State University, New Orleans, Louisiana

Sara R. Wilson and Kurt A. Swieringa
Langley Research Center, Hampton, Virginia

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National Aeronautics and
Space Administration

Langley Research Center
Hampton, Virginia 23681-2199

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Abbreviations and Acronyms

ABP	Achieve-by Point
ASG	Assigned Spacing Goal
ATD-1	Air Traffic Management Technology Demonstration – 1
FAA	Federal Aviation Administration
FAF	Final Approach Fix
FL	Flight Level
IM	Interval Management
KBFI	Boeing Field / King Country International Airport
KMWH	Grant County International Airport
KSEA	Seattle-Tacoma International Airport
Max	Maximum
Med	Median
Min	Minimum
NASA	National Aeronautics and Space Administration
nmi	Nautical Mile
Ownship	Aircraft conducting an IM operation
PTP	Planned Termination Point
SD	Standard Deviation
STAR	Standard Terminal Arrival Route
Target	Aircraft the IM aircraft is assigned to follow

1 Introduction

Air traffic demand is predicted to increase over the next 20 years, with commercial aviation revenue passenger miles growing on average 1.8% annually [1]. As the number of commercial flights increases, arrival operations into high-density airports, especially during periods of peak traffic flow or inclement weather, often experience significant inefficiencies due to the use of miles-in-trail procedures and step-down descents. Use of these current procedures contributes to reduced airport throughput, increased controller workload, increased arrival delay, and increased fuel burn, emissions, and noise. Although advanced arrival procedures are available, they are underutilized due to the lack of supporting technologies.

The National Aeronautics and Space Administration's (NASA's) Air Traffic Management Technology Demonstration – 1 (ATD-1) integrated advanced ground-based and airborne scheduling and spacing technologies to enable efficient arrival operations in the terminal airspace during high levels of traffic density [2]. The ATD-1 integrated system consists of three technologies: the Traffic Management Advisor with Terminal Metering (TMA-TM) provides terminal air traffic controllers with a deconflicted arrival schedule, Controller Managed Spacing (CMS) provides terminal air traffic controllers with decision support tools to help them meet the schedule calculated by TMA-TM, and Interval Management (IM) provides flight crews with flight-deck automation that enables them to achieve or maintain a precise spacing interval behind the preceding aircraft.

ATD-1 conducted simulations that investigated the integrated use of these technologies in order to operationally demonstrate an arrival management concept that uses performance-based navigation and to accelerate the transfer of NASA scheduling and spacing prototypes to the Federal Aviation Administration (FAA). Both TMA-TM and CMS were evaluated at the FAA's William J. Hughes Technical Center in 2015 and transferred to the FAA [3]. NASA contracted with Boeing, with Honeywell and United Airlines as subcontractors, to build and flight test an IM avionics prototype [4-6]. This paper describes the speed behavior of the IM avionics prototype, focusing on the speed command rate and the number of speed increases.

2 Flight Test

The goals of the ATD-1 Avionics Phase 2 flight test were to develop an IM avionics prototype, integrate that prototype into two test aircraft, and conduct validation flight tests. IM system performance was evaluated during three phases of flight: en route, arrival, and final approach. Quantitative data were collected from each aircraft and qualitative data were collected from the subject pilots via post-run and end-of-day questionnaires, as well as daily group debrief sessions. The results of the flight test are being used to assess the performance of the IM avionics prototype.

2.1 IM Operations

IM is an airborne spacing concept which consists of avionics and procedures used by air traffic controllers and flight crews to precisely manage inter-aircraft spacing. IM operations are defined by their IM clearance type which is determined by attributes related to an Assigned Spacing Goal (ASG). The ASG is the desired spacing interval between an aircraft conducting IM operations (Ownship) and the lead (Target) aircraft and can be given as either a time or distance. The IM operation is said to be in the maintain stage if the aircraft is maintaining the ASG until the Planned Termination Point (PTP) and in the achieve stage if the aircraft's goal is to achieve the ASG by the Achieve-by Point (ABP). When in the maintain stage, the Ownship uses a state-based speed control law to either capture the ASG or maintain it within a ten second tolerance, or the distance-based equivalent. When in the achieve stage, the Ownship uses a trajectory-based speed control law to achieve the ASG by the ABP. The Ownship and target aircraft are required to be in-trail during the maintain stage, but can be on merging routes during the achieve stage.

The achieve and maintain stages are combined into four IM clearances that were flown during the ATD-1 flight test [5]:

- The *Maintain* clearance is used when the Ownship and Target aircraft are following a common route and the controller wants the Ownship to maintain the current in-trail spacing as determined by the IM avionics. The algorithm determines speeds that will continuously maintain the in-trail spacing within ten seconds, or the equivalent distance, until the PTP. This clearance was intended for tactical use, when the Ownship is at the spacing interval desired by air traffic controllers.
- The *Capture* clearance is used when the Ownship and Target aircraft are on a common route and the controller wants the IM aircraft to achieve the ASG quickly and then maintain it until the PTP. The algorithm determines speeds that will correct the initial spacing error, and then maintain the spacing interval within ten seconds of the ASG. This clearance is intended for use when the spacing interval between the Ownship and Target aircraft is close to the ASG, which can either be determined by the air traffic controllers or derived from the schedule calculated by TMA-TM.
- The *Cross* clearance is used when the controller wants the Ownship to achieve the ASG at the ABP, and then maintain it until the PTP. The achieve stage is used to correct the initial spacing error by the ABP, and then the algorithm transitions to the maintain stage until termination. This clearance is meant for strategic use, with the ASG derived from the schedule calculated by TMA-TM. Furthermore, this clearance allows the Ownship and Target aircraft to be on different routes prior to the ABP.
- The *Final Approach Spacing* clearance is used when the final controller wants to use IM to control the rate of compression or overtake with a preceding arrival on final. This clearance is designed to improve the spacing accuracy at a point near the Final Approach Fix (FAF). The ASG can either be determined by air traffic controllers or derived from the schedule calculated by TMA-TM.

All of the IM operations can have an ASG that is either time- or distance-based; however, the expectation is that the ASG will be time-based for most operations. Distance based ASGs should not be used during the maintain stage if the aircraft is descending or decelerating, and so they were only used for certain operations in this flight test.

2.2 Air Space Design

This flight test took place in Seattle en route (ZSE) and Moses Lake terminal (KMWH) airspace. Three aircraft departed from Boeing Field (KBFI) and Seattle-Tacoma International Airport (KSEA). Two Standard Terminal Arrival Routes (STARs) were developed by Boeing and Jeppensen for this flight test and are shown in Figure 1 (red lines). The SUBDY1 and UPBOB1 arrivals provide a continuous route to runway 32R by connecting to the published Area Navigation and Required Navigation Performance Z approaches. The SUBDY1 arrival routes started at either ZIRAN or JELVO with a medium altitude merge at NALTE. The SUBDY1 and UPBOB1 arrival routes both merged at ZAVYO, which was the FAF. En route operations started at ZIRAN and ended at SINGG (blue line in Figure 1). The straight-in and merging routes used for the Final Approach Spacing operations are shown by the purple lines in Figure 1.

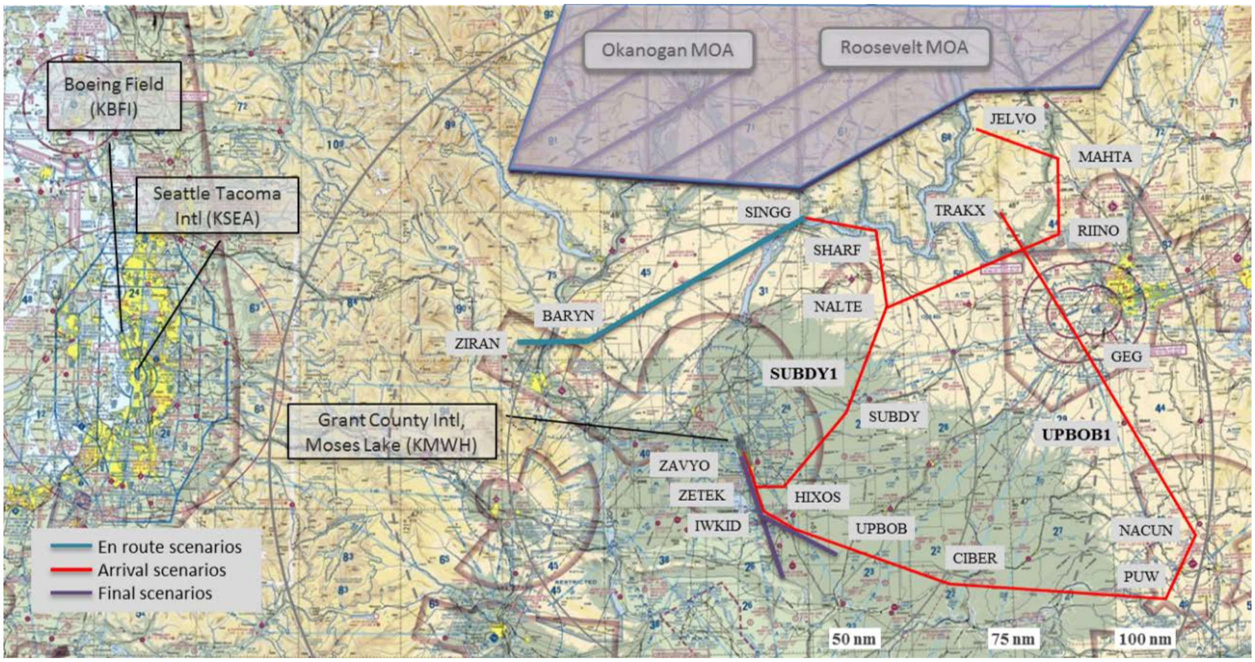


Figure 1. Flight Test Airspace

The three aircraft that participated in this flight test are pictured in Figure 2. A Honeywell Dassault Falcon 900 (center) was used as the lead aircraft during a majority of the en route and arrival scenarios. A Honeywell Boeing-757 (B-757) (pictured on the left) and a United Boeing-737 (B-737) (pictured on the right) were equipped with the IM avionics prototype.

Figure 2. Flight Test Aircraft and Team

2.3 Test Matrix

The flight test was designed to investigate the performance of the IM avionics prototype during three phases of flight: en route, arrival, and final approach. The scenarios were developed to allow for the examination of the following independent variables [4]:

- IM clearance type: Cross, Capture, Maintain, or Final Approach Spacing
- Initial spacing error
- ASG units: time- or distance-based operations
- ABP location: *Cross-Merge* where the ABP was the merge point, NALTE, or *Cross-FAF* where the ABP was the FAF, ZAVYO (only applicable for Cross clearance)
- Lead aircraft delay (only applicable for arrival operations)
- Aircraft route geometry (only applicable for the Final Approach Spacing clearance)

The lead aircraft delay is not discussed in this paper; however, reference [6] contains a comprehensive description. The test plan called for 124 data points, which included two replicates of each test condition. In order to minimize the impact of schedule constraints and potential weather during execution of the flight test, each replicate of the scenarios was prioritized and the run order was randomized within priority level. Tactical decisions made during the flight test and software anomalies resulted in 144 data points. Table 1 shows the test matrix for the final data points collected.

Table 1. Flight Test Scenarios Flown

Scenario	IM Clearance Type	Time- or Distance-based Operations	N
En Route	Maintain	Time Distance	4 3
	Capture	Time Distance	2 2
Arrival	Maintain	Time	18
	Capture	Time	32
	Cross-Merge	Time	27
	Cross-FAF	Time Distance	41 7
Final Approach	Final Approach Spacing	Time Distance	5 3

Of the 144 successful data points, 125 were arrival scenarios. The main objective of the flight test was to evaluate the IM performance for time-based arrival scenarios, resulting in this type of scenario having the most runs (n = 118). There were seven distance-based arrival scenarios, all of which were Cross-FAF operations. The comprehensive breakdown of the flights in this paper is also separated by route and stage of flight. The IM operations in the arrival scenarios started at Flight Level (FL) 350 or FL230 and ended at the FAF. For the arrival operations, the Capture and Maintain clearance types used a state-based speed control law for the entire route and were only flown on the SUBDY1 arrival. The Cross-Merge clearance types began at ZIRAN or JELVO and used a trajectory-based speed control law until reaching NALTE where the spacing algorithm switched to a state-based speed control law until the PTP. The Cross-FAF operations were also flown on the SUBDY1 arrival using a trajectory-based speed control law the entire time. The Cross-FAF operation was unique in that it was the only operation to be flown on the UPBOB1 route and the only arrival operation to have an ASG given in distance.

Then en route scenarios consisted of four types: Capture and Maintain clearances each with time- and distance-based ASGs. Of the eleven runs, six were time-based and five were distance-based. The final approach scenarios were categorized into four types. The flights had either a straight-in approach or a merging approach and were either time-based or distance-based.

3 Flight Test Results

Over the nineteen-day flight test, 144 data points were collected and used to evaluate the performance of the IM avionics prototype. To see an in-depth analysis of the achieved spacing error and flight crew questionnaire responses see [5] and [4], respectively. Analysis done in [4] states that the flight crews found the IM speeds to be operationally acceptable overall; however, the high number of speed commands was frequently commented on by the pilots in both the post-run and end-of-day questionnaires. The results in this paper will focus on speed command behavior, in particular the frequency and location of IM speed commands. Frequent speed commands and speed reversals can increase a crew's workload and cause them to lose trust in the system. Consequently, it is important to minimize the number and magnitude of speed commands while meeting the desired spacing precision.

3.1 Speed Increases

During the arrival and final approach phases of fight, an aircraft's airspeed is often monotonically decreasing. Therefore, almost all speed increases seen in this flight test are the result of the algorithm achieving or maintaining the spacing goal. Pilots will likely find frequent speed increases or speed increases close to the FAF undesirable during arrival operations, particularly when they are in the process of configuring their aircraft for landing. The location and frequency of speed commands are examined in order to characterize the speed behavior of the IM avionics prototype.

3.1.1 Number of Speed Increases Per Minute

The number of speed increases per minute of flight time is shown in Table 2. The duration of an IM operation is an important factor when determining frequency of speed increases since each phase of the flight is expected to last a different amount of time. The en route and final approach scenarios were much shorter than the arrival scenarios, and even between runs on the same route and with the same clearance type there is variability between the time and distance of the run. In addition, the IM operation was not started at the exact same location for each run due to scenario setup challenges, resulting in some runs being shorter or longer both time-wise and distance-wise than others.

For the en route scenarios, the Capture clearance type had a higher number of speed increases per minute than the Maintain clearance type. One reason for this may be speed increases that occur as the ASG is captured. The number of speed increases is a less important factor when determining IM performance during en route operations because the aircraft are not decreasing speed in preparation for landing at an airport.

The arrival scenarios had different results from the en route scenarios by clearance types. For the arrival scenarios, the Maintain clearance type averaged the most speed increases with 0.34 per minute. The Maintain clearance type used the state-based speed control law and was always flown on the SUBDY1 arrival, JELVO transition (JELVO.SUBDY1). The other operations on the JELVO.SUBDY1 route consistently had a lower number of speed increases when compared to the same operations on different routes. This is especially obvious for the Capture clearance type, which had a similar number of speed increases regardless of route with 0.19 and 0.23 speed increases per minute on the JELVO.SUBDY1 and ZIRAN.SUBDY1 arrivals, respectively.

When considering the operations that used the trajectory-based speed control law (Cross operations) on the SUBDY1 arrival, the routes starting at ZIRAN had more speed increases per minute than those starting at JELVO. This is seen by comparing the Cross-FAF operations on JELVO.SUBDY1 and ZIRAN.SUBDY1 as well as the Cross-Merge operations on the portions of the SUBDY1 arrival from JELVO to NALTE and from ZIRAN to NALTE. The UPBOB1 arrival also used the trajectory-based speed control law and showed comparable speed increases per minute to the JELVO.SUBDY1 route.

Speed increases are particularly problematic for the Final Approach Spacing clearance, since it is conducted when pilots are configuring their aircraft for landing. While the arrival scenarios included a final approach segment, the entire Final Approach Spacing clearance was conducted when the Ownship and Target aircraft were either on their final approach course or on a vector toward their final approach course. The final approach results in Table 2 must be carefully interpreted since even though the magnitude of the numbers indicates few speed increases, the length of time of the operations is relatively short. Minimizing the number of speed increases during this phase is important for the workload of the crew and to ensure that they are able to manage their aircraft’s energy to achieve the stabilized approach criteria required for landing.

Table 2. Speed Increases Per Minute

Scenario	Route	Stage	IM Clearance Type	Time- or Distance-based Operations	N	Mean	SD	Min	Med	Max
En Route	ZIRAN.BARYN.SINGG	Maintain	Maintain	Time	4	0.13	0.01	0.12	0.13	0.13
				Distance	3	0.00	0.00	0.00	0.00	0.00
			Capture	Time	2	0.23	0.10	0.17	0.23	0.30
				Distance	2	0.33	0.00	0.33	0.33	0.33
Arrival	JELVO.SUBDY1	Maintain	Maintain	Time	18	0.34	0.13	0.16	0.33	0.58
			Capture	Time	26	0.19	0.10	0.06	0.17	0.43
		Achieve	Cross-FAF	Time	18	0.17	0.08	0.05	0.15	0.32
				Distance	5	0.22	0.08	0.14	0.25	0.30
	ZIRAN.SUBDY1	Maintain	Capture	Time	6	0.23	0.05	0.18	0.24	0.27
		Achieve	Cross-FAF	Time	3	0.30	0.11	0.19	0.31	0.41
				Distance	2	0.26	0.13	0.17	0.26	0.36
	SUBDY1 (NALTE to ZAVYO)	Maintain	Cross-Merge	Time	27	0.25	0.13	0.07	0.23	0.57
	JELVO.SUBDY1 (JELVO to NALTE)	Achieve	Cross-Merge	Time	6	0.21	0.12	0.12	0.16	0.40
	ZIRAN.SUBDY1 (ZIRAN to NALTE)	Achieve	Cross-Merge	Time	20	0.34	0.26	0.11	0.25	0.87
	TRAKX.UPBOB1	Achieve	Cross-FAF	Time	20	0.17	0.05	0.07	0.17	0.26
Final Approach	Merge	Achieve	Final Approach Spacing	Time	1	0.96	N/A	0.96	0.96	0.96
				Distance	1	0.59	N/A	0.59	0.59	0.59
	Straight-in	Achieve	Final Approach Spacing	Time	4	0.30	0.06	0.25	0.28	0.39
				Distance	2	0.35	0.30	0.14	0.35	0.56

3.1.2 Distance-to-go for Speed Increases

The arrival portion of the flight begins the initial decent of the aircraft and ends at the FAF. While some speed increases might be needed to meet the desired spacing performance, the goal is to have a very limited number of speed increases with the majority occurring well before final approach. Table 3 shows the percentage of speed increases that ensued during increments of each operation. Distance-to-go is given as nautical miles (nmi) to the PTP, or in the cases of the Cross-Merge flights using the trajectory-based speed control law, distance-to-go to the ABP (NALTE). The distance from NALTE to ZAVYO was approximately 56 nmi, ZIRAN to NALTE approximately 93 nmi, and JELVO to NALTE approximately 68 nmi.

Figures 3 to 7 show maps of where the speed commands occurred on the route. The waypoints are indicated by grey dots with their names appearing above them. In Figures 3-6 which depict the routes for the arrival scenarios, the ZIRAN.SUBDY1 route is comprised of the red and purple lines with the red line depicting the portion of the ZIRAN.SUBDY1 route starting at ZIRAN and going to NALTE, and the purple line is from NALTE onward. Cross-FAF, Cross-Merge and Capture operations were flown on this route. The Capture operation using the maintain stage of the spacing algorithm and the Cross-FAF operation using the achieve stage were flown on the ZIRAN.SUBDY1 route. The Cross-Merge operation was flown starting with the achieve stage (red line) and switching to the maintain stage at NALTE (purple line). The blue and purple lines mark the JELVO.SUBDY1 route with the JELVO to NALTE portion in blue. The Capture and Maintain operations were in the maintain stage and the Cross-FAF operation was in the achieve stage for the entirety of this route. The Cross-Merge operation was in the achieve stage from JELVO to NALTE (blue line) and, as in the ZIRAN.SUBDY1 route, switched to the maintain stage after NALTE (purple line). The green line shows the TRAKX.UPBOB1 route which was only flown using the Cross-FAF clearance type. In Figure 7, the yellow line connects ZIRAN to BARYN to SINGG which was the path flown during the en route scenarios. Blue markers indicate one speed command occurred in that area, green dots indicate between two and nine speed commands with the number appearing inside the dot, and yellow dots indicate ten or more speed commands occurred in that area.

The majority of speed increases occurred with less than 50 nmi to go to the PTP. The last 50 nmi of the SUBDY1 route starting at ZIRAN includes over 75% of the speed increases on that route. The JELVO.SUBDY1 arrival has over 60% of the increases happening within 50 nmi of the PTP. The distance-versus time-based operations did not have an operationally significant impact on the location of the speed increases. Figure 3 shows speed increases throughout the JELVO.SUBDY1 route for Maintain and Capture operations. Both clearance types had a higher number of speed increases just prior to NALTE and the PTP. The difference between the maps shown in Figures 3 (a) and (b) compared to the maps shown in Figures 3 (c) and (d) indicate that the state-based speed control law used by the Capture and Maintain operations resulted in more speed increases throughout the flight than the trajectory-based speed control law used by the Cross-FAF operations. However, the similarity between the maps shown in Figures 3 (a) and (b) for the Capture and Maintain operations indicate that the clearance type does not influence the number of speed increases required, rather the route itself determines where they will occur.

The NALTE to ZAVYO route segment was only approximately 56 nmi, forcing the vast amount of speed increases to occur with less than 50 nmi to go. Table 3 shows that only 11% of the increases on this route with the Cross-Merge clearance occurred more than 50 nmi from the PTP, a short span around NALTE. NATLE was the ABP for all Cross-Merge operations, meaning this area was where the IM operation switched from a trajectory-based speed control law to a state-based speed control law. This could have contributed to the relatively high number of speed increases in this area. The Cross-Merge maps in Figure 5 provide more evidence of this, showing speed commands at NALTE for all three breakdowns.

The location of speed increases that occurred on the UPBOB1 arrival was fairly consistent based on distance-to-go (see Figure 6). This is unique compared to the other Cross-FAF time-based operations for which most of the speed increases occurred near the end of the flight. Since only one IM clearance type was flown on the UPBOB1 arrival, the cause of this difference cannot be determined, but the winds, pilot technique, speed control law, or interactions between these may be contributing factors.

For the en route scenarios, maps of the speed increases are shown in Figure 7. The en route path was very short and straight in comparison to the arrival routes, which should be considered when interpreting the results. The en route paths also had constant speeds and altitudes, whereas the arrival routes were descending with procedural speed changes.

Table 3. Percentage of Speed Increases Occurring by Distance-to-go for Arrival Scenarios

Route	Stage	IM Clearance Type	Time- or Distance-based Operations	N	Percentage of Speed Increases by Distance-to-go			
					[0,25]	(25,50]	(50,75]	>75
JELVO.SUBDY1	Maintain	Maintain	Time	18	31%	13%	24%	32%
		Capture	Time	26	33%	16%	34%	17%
	Achieve	Cross-FAF	Time	18	50%	32%	14%	5%
			Distance	5	70%	5%	0%	25%
	Total for JELVO.SUBDY1.RR32R			67	36%	28%	17%	20%
ZIRAN.SUBDY1	Maintain	Capture	Time	6	39%	33%	28%	0%
	Achieve	Cross-FAF	Time	3	43%	50%	7%	0%
			Distance	2	40%	20%	30%	10%
	Total for ZIRAN.SUBDY1.RR32R			11	42%	36%	14%	9%
SUBDY1 (NALTE to ZAVYO)	Maintain	Cross-Merge	Time	27	49%	41%	11%	0%
JELVO.SUBDY1 (JELVO to NALTE)	Achieve	Cross-Merge	Time	6	50%	50%	0%	0%
ZIRAN.SUBDY1 (ZIRAN to NALTE)	Achieve	Cross-Merge	Time	20	51%	44%	6%	0%
TRAKX.UPBOB1	Achieve	Cross-FAF	Time	20	33%	23%	29%	16%

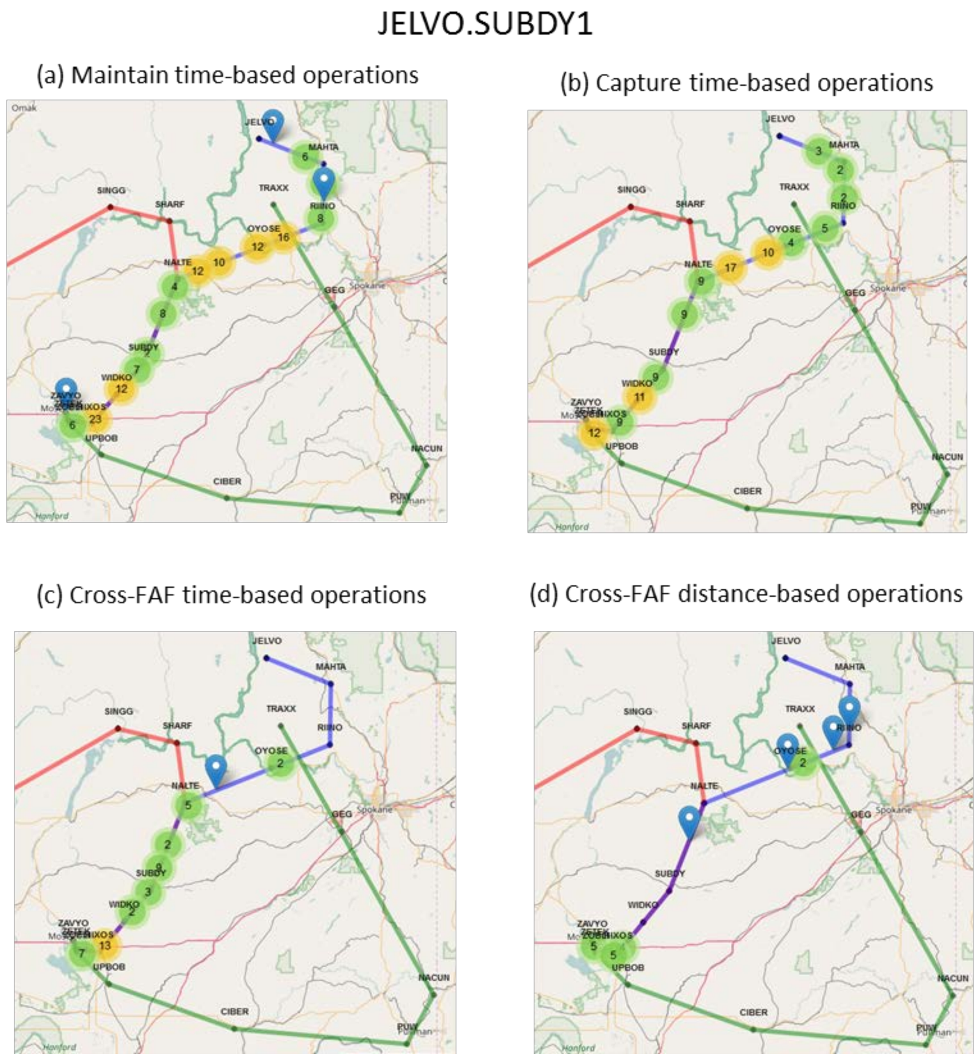


Figure 3. Maps of speed increases during arrival scenarios for JELVO.SUBDY1 route: (a) Maintain time-based operations, (b) Capture time-based operations, (c) Cross-FAF time-based operations, and (d) Cross-FAF distance-based operations.

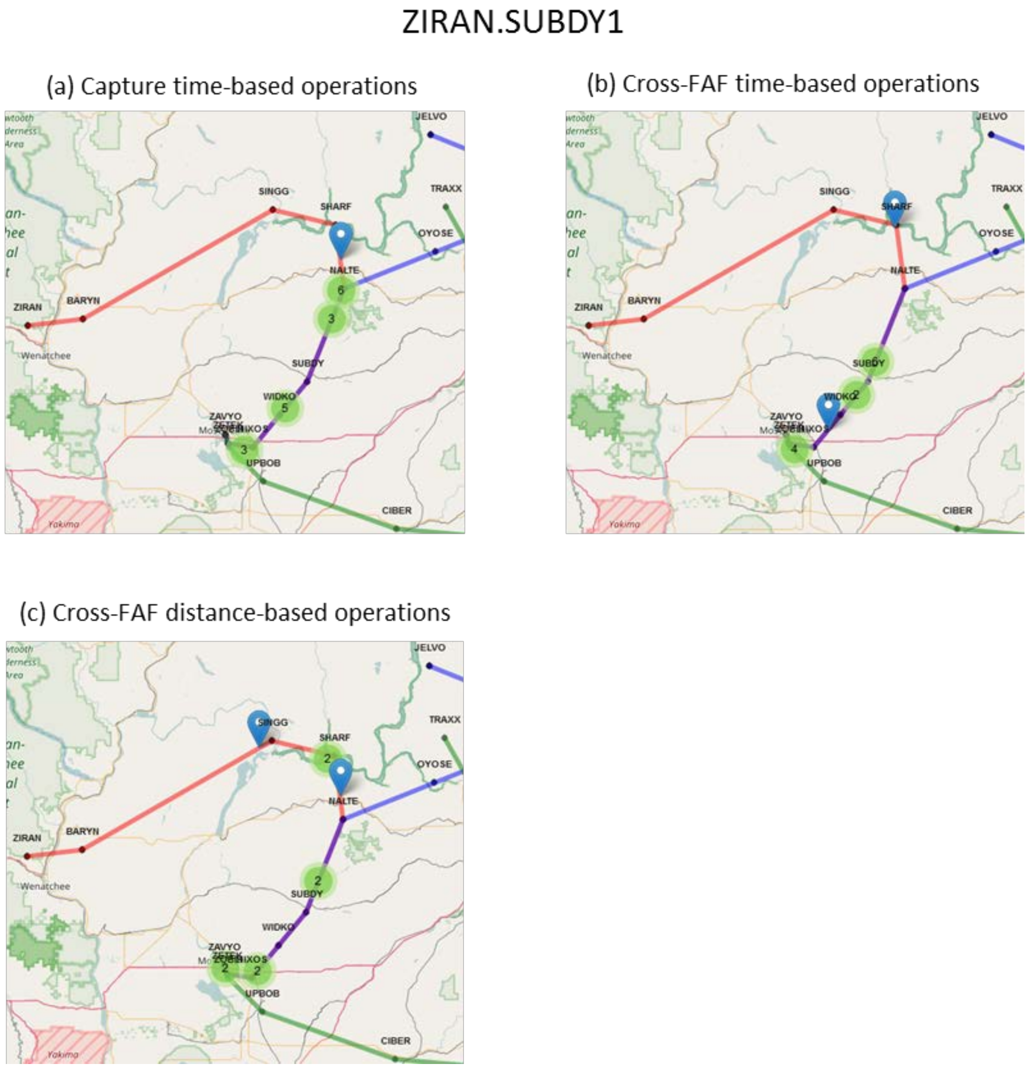
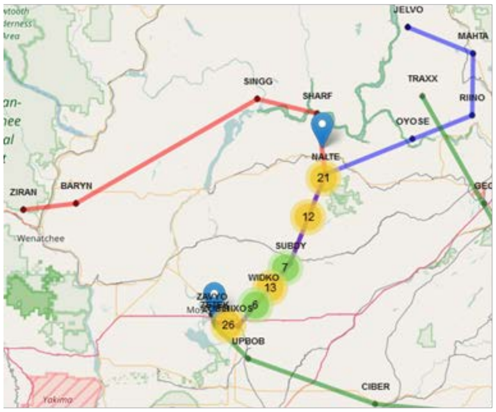


Figure 4. Map of speed increases during arrival scenarios for ZIRAN.SUBDY1 route: (a) Capture time-based operations, (b) Cross-FAF time-based operations, and (c) Cross-FAF distance-based operations.

Cross-Merge

(a) SUBDY1 (NALTE to ZAVYO)



(b) JELVO.SUBDY1 (JELVO to NALTE)

(c) ZIRAN.SUBDY1 (ZIRAN to NALTE)

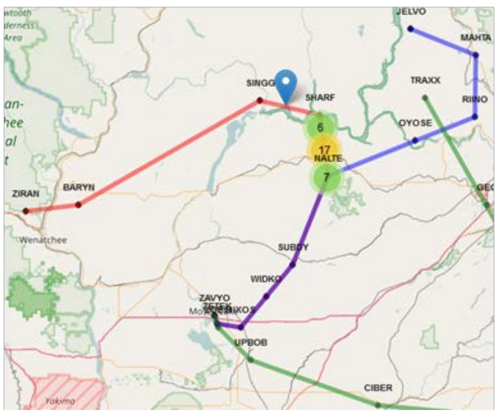


Figure 5. Map of speed increases during arrival scenarios for Cross-Merge operations: (a) SUBDY1 (NALTE to ZAVYO), (b) JELVO.SUBDY1 (JELVO to NALTE), and (c) ZIRAN.SUBDY1 (ZIRAN to NALTE)

TRAKX..UPBOB1

Figure 6. Map of speed increases during arrival scenarios for UPBOB1 route with Cross-FAF time-based operations

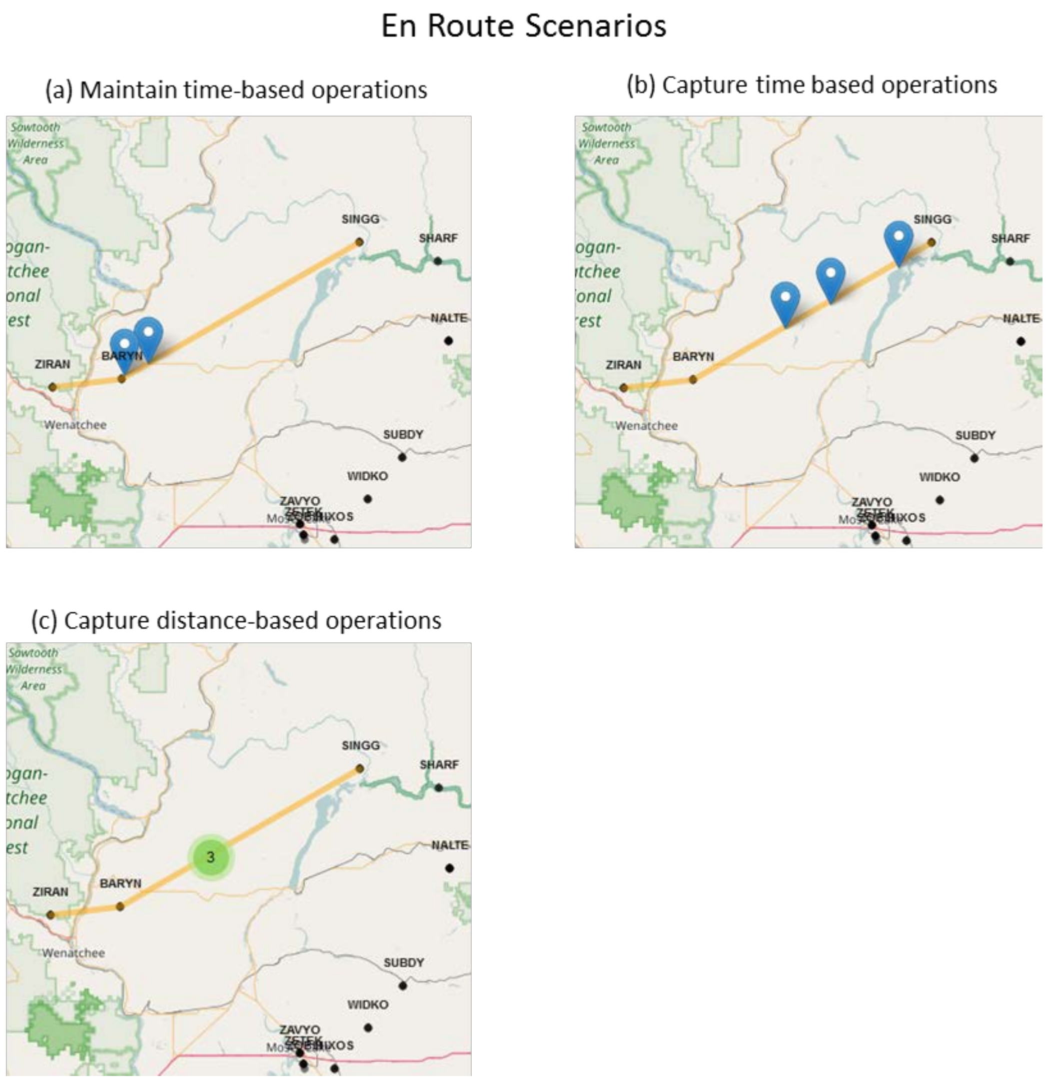


Figure 7. Map of speed increases for en route scenarios: (a) Maintain time-based operations, (b) Capture time-based operations, and (c) Capture distance-based operations

3.2 Speed Commands

Providing speed commands is key to IM, but too many weaken the viability of using these operations. Too many speed commands negatively contribute to the workload of the flight crew; however, determining the optimal set of speed commands is complicated. There is no finite number of speed commands or speed commands per minute defined as an acceptable standard. Therefore, all inferences in the following sections are comparisons between groups and not a definitive statement on performance of IM operations in terms of speed commands.

3.2.1 Number of Speed Commands Per Minute

Summary statistics for the number of speed commands per minute are shown in Table 4. These numbers are greater when compared to Table 2 since the speed increases are a subset of all speed commands. This is most notable for the arrival and final approach scenarios where speed decreases are frequent.

For the arrival scenarios, the Maintain clearance type once again had the most speed commands per minute with one given every 75 seconds on average. The same observation that was made for the speed increases can also be made here, with the high number of speed commands per minute related to the clearance type but not the route. This is seen by comparing the other clearance types on the JELVO.SUBDY1 arrival to their counterparts on the ZIRAN.SUBDY1 arrival as there was no consistency on which route had more speed commands per minute. The Capture operation saw a slightly higher number of speed commands per minute on the ZIRAN.SUBDY1 arrival, but the Cross-FAF maximum number of speed commands per minute occurred on the JELVO.SUBDY1 arrival. Just as with the speed increases, the UPBOB1 arrival had the fewest number of speed commands per minute. This can likely be attributed both to how straight the route is and the nature of the Cross-FAF operation. Further examination is required to determine the exact cause of the difference.

For the SUBDY1 routes, operations using a trajectory-based speed control law had the fewest number of speed commands, and operations using a state-based speed control law had the highest number of speed commands per minute when starting at JELVO. The opposite is seen when looking at operations beginning at ZIRAN.

The time- and distance-based Cross-FAF operations had a similar number of speed commands per minute on the ZIRAN.SUBDY1 arrival, both of which were greater than the number of speed commands per minute for the Capture operation on that route. However, on the JELVO.SUBDY1 arrival, the time-based Cross-FAF operation had a fewer number of speed commands per minute than distance-based Cross-FAF, time-based Maintain, and time-based Capture operations. By comparison, the distance-based Cross-FAF operations starting at JELVO had a speed command rate greater than one speed command every minute and a half, which is very close to the maximum speed command rate observed during the flight test scenarios. This indicates that no clear difference between time- and distance-based operations was observed.

The en route scenarios are again showing outcomes opposite to those in the arrival scenario. Here, the Capture clearance type had more speed commands per minute than the Maintain clearance type. For the Maintain clearance, the distance-based operations had a greater number of speed commands per minute than the time-based operations, while the Capture time-based operations had slightly more than the distance-based Capture operations. However, it is important to note that these observations are based on a small number of data points and relatively short en route operations.

For the final approach spacing operations, the merge geometry had the highest speed command rate. The operation using a time-based spacing goal had on average one speed command every 42 seconds while the distance-based operation had a speed command on average every 61 seconds. These results should not be compared to the en route and arrival scenarios since more speed decreases are expected during final approach and these operations lasted the shortest amount of time.

Table 4. Speed Commands Per Minute

Scenario	Route	Stage	IM Clearance Type	Time- or Distance-based Operations	N	Mean	SD	Min	Med	Max
En Route	ZIRAN..SINGG	Maintain	Maintain	Time	4	0.21	0.08	0.10	0.23	0.27
				Distance	3	0.47	0.30	0.14	0.53	0.74
			Capture	Time	2	0.55	0.08	0.50	0.55	0.61
				Distance	2	0.52	0.04	0.49	0.52	0.55
Arrival	JELVO.SUBDY1	Maintain	Maintain	Time	18	0.80	0.23	0.47	0.74	1.23
			Capture	Time	26	0.53	0.17	0.32	0.49	0.97
		Achieve	Cross-FAF	Time	18	0.45	0.19	0.15	0.43	0.95
				Distance	5	0.73	0.23	0.40	0.80	0.99
	ZIRAN.SUBDY1	Maintain	Capture	Time	6	0.56	0.21	0.27	0.54	0.82
		Achieve	Cross-FAF	Time	3	0.67	0.18	0.56	0.57	0.88
				Distance	2	0.69	0.18	0.56	0.69	0.82
	SUBDY1 (NALTE to ZAVYO)	Maintain	Cross-Merge	Time	27	0.65	0.20	0.31	0.65	0.99
	JELVO.SUBDY1 (JELVO to NALTE)	Achieve	Cross-Merge	Time	6	0.58	0.19	0.36	0.57	0.80
	ZIRAN.SUBDY1 (ZIRAN to NALTE)	Achieve	Cross-Merge	Time	20	0.67	0.38	0.11	0.53	1.73
	TRAKX.UPBOB1	Achieve	Cross-FAF	Time	20	0.43	0.08	0.28	0.42	0.61
Final Approach	Merge	Achieve	Final Approach Spacing	Time	1	1.44	N/A	1.44	1.44	1.44
				Distance	1	0.98	N/A	0.98	0.98	0.98
	Straight In	Achieve	Final Approach Spacing	Time	4	0.73	0.14	0.56	0.74	0.88
				Distance	2	0.61	0.46	0.29	0.61	0.94

3.2.2 Distance-to-go for Speed Commands

The flight crew workload changes significantly over the course of the flight, making the location of the speed commands an important variable in determining if the number of speed commands is problematic. More speed commands are acceptable during the beginning of the flight than during the final approach phase. Table 5 shows the percentage of speed commands that occurred during each portion of the flight for each operation. The flights are cut into fourths based on their distance-to-go to the PTP or ABP (ABP was only used for the Achieve stage of Cross-Merge operations). Figures 8 to 12 show where on the route the speed commands occurred for each operation.

For all operations types, the last 25% of the route tended to have more speed commands than the earlier route segments. For the ZIRAN.SUBDY1 route, more than 40% of the speed commands occurred during this period during the Cross-FAF and Cross-Merge operations. The relatively steady pattern of the number of speed commands occurring per quadrant across all the operations on the ZIRAN.SUBDY1 route suggests that there were characteristics associated with this route or the speed control laws that caused an increase in the number of speed commands. Some possibilities include increased control law gains near the ABP for the trajectory-based speed control law, variability in how the procedural deceleration segment prior to the FAF was flown, and a large turn just prior to the FAF.

The SUBDY1 route staring at JELVO had speed commands occurring more uniformly throughout the route, although the majority still occurred after the halfway point which is slightly before NALTE. Unlike in the ZIRAN transition, flights on the JELVO transition needed speed commands at the beginning of the flight. That the Cross-FAF operation had fewer speed commands in the beginning of the flight than the Capture and Maintain is inherent to the nature of the speed control law.

Figure 12 shows very few speed commands during the en route scenarios and most of the speed commands occurred early in the operations. The en route scenarios flew a relatively straight path with a constant altitude and speed, leading to the Maintain and Capture operations having an easier time maintaining their ASG. Most of the speed commands occurred near the slight turn at BARYN near the beginning of the operation.

Table 5. Percentage of Speed Commands Occurring by Distance-to-go for Arrival Scenarios

Route	Stage	IM Clearance Type	Time- or Distance-based Operations	N	Percentage of Speed Commands by Distance-to-go			
					[0,25]	**(25,50]**	**(50,75]**	**>75**
JELVO.SUBDY1	Maintain	Maintain	Time	18	31%	25%	18%	27%
		Capture	Time	26	31%	32%	20%	17%
	Achieve	Cross-FAF	Time	18	46%	30%	12%	13%
			Distance	5	58%	20%	8%	14%
	Total for all JELVO. SUBDY1 Runs			67	36%	28%	17%	20%
ZIRAN.SUBDY1	Maintain	Capture	Time	6	36%	38%	15%	12%
	Achieve	Cross-FAF	Time	3	42%	45%	13%	0%
			Distance	2	54%	19%	15%	12%
	Total for all ZIRAN.SUBDY1 Runs			11	42%	36%	14%	9%
SUBDY1 (NALTE to ZAVYO)	Maintain	Cross-Merge	Time	27	49%	41%	11%	0%
JELVO.SUBDY1 (JELVO to NALTE)	Achieve	Cross-Merge	Time	6	50%	50%	0%	0%
ZIRAN.SUBDY1 (ZIRAN to NALTE)	Achieve	Cross-Merge	Time	20	51%	44%	6%	0%
TRAKX.UPBOB1	Achieve	Cross-FAF	Time	20	33%	23%	29%	16%

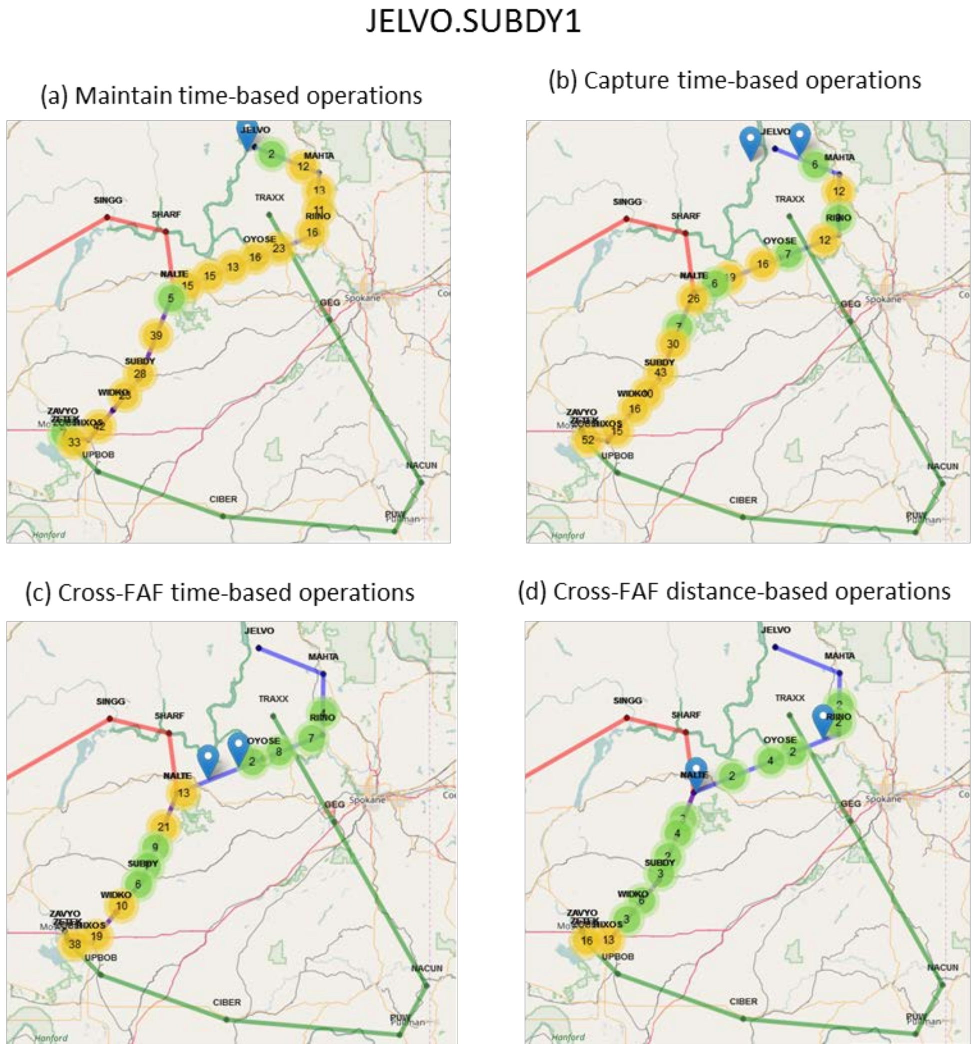


Figure 8. Maps of speed commands during arrival scenarios for SUBDY JELVO route: (a) Maintain time-based operations, (b) Capture time-based operations, (c) Cross-FAF time-based operations, and (d) Cross-FAF distance-based operations.

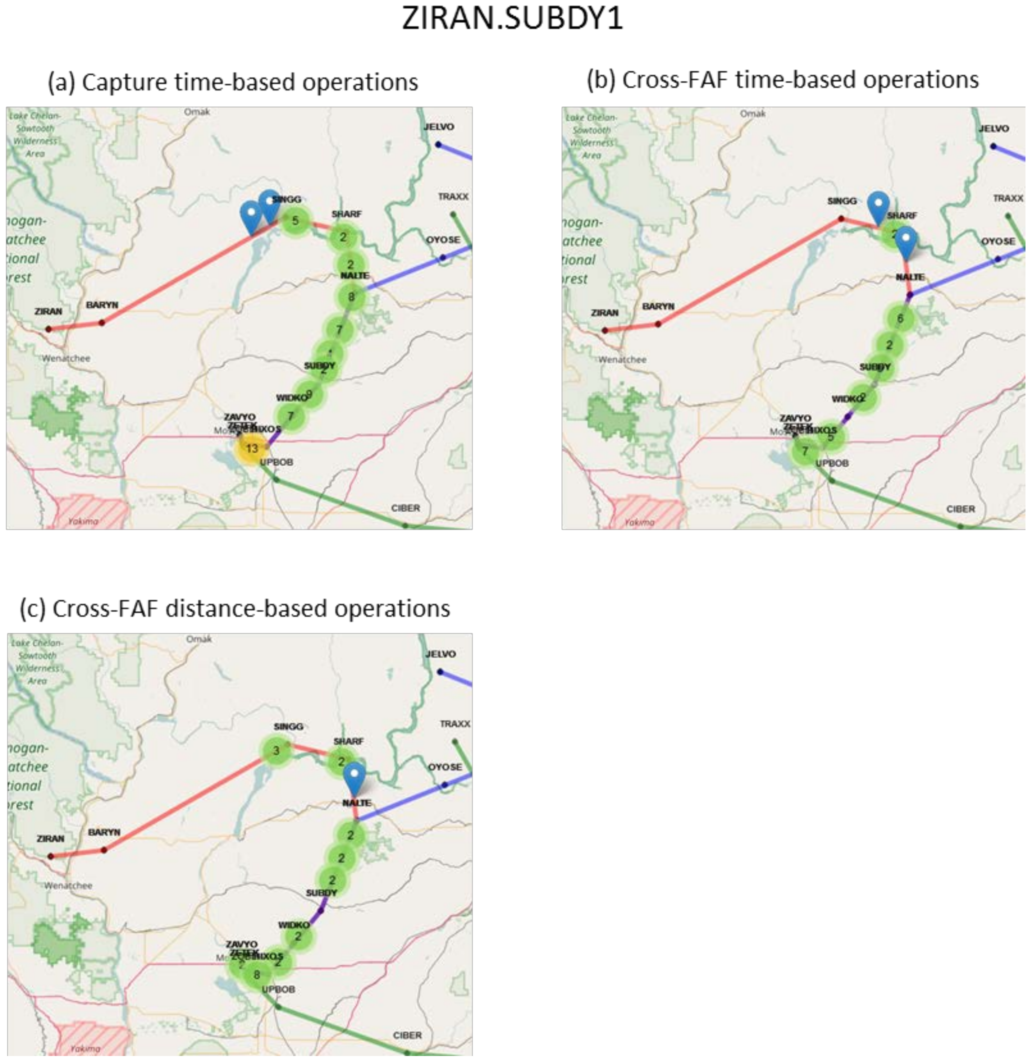


Figure 9. Maps of speed commands during arrival scenarios for SUBDY1.ZIRAN route: (a) Capture time-based operations, (b) Cross-FAF time-based operations and (c) Cross-FAF distance-based operations.

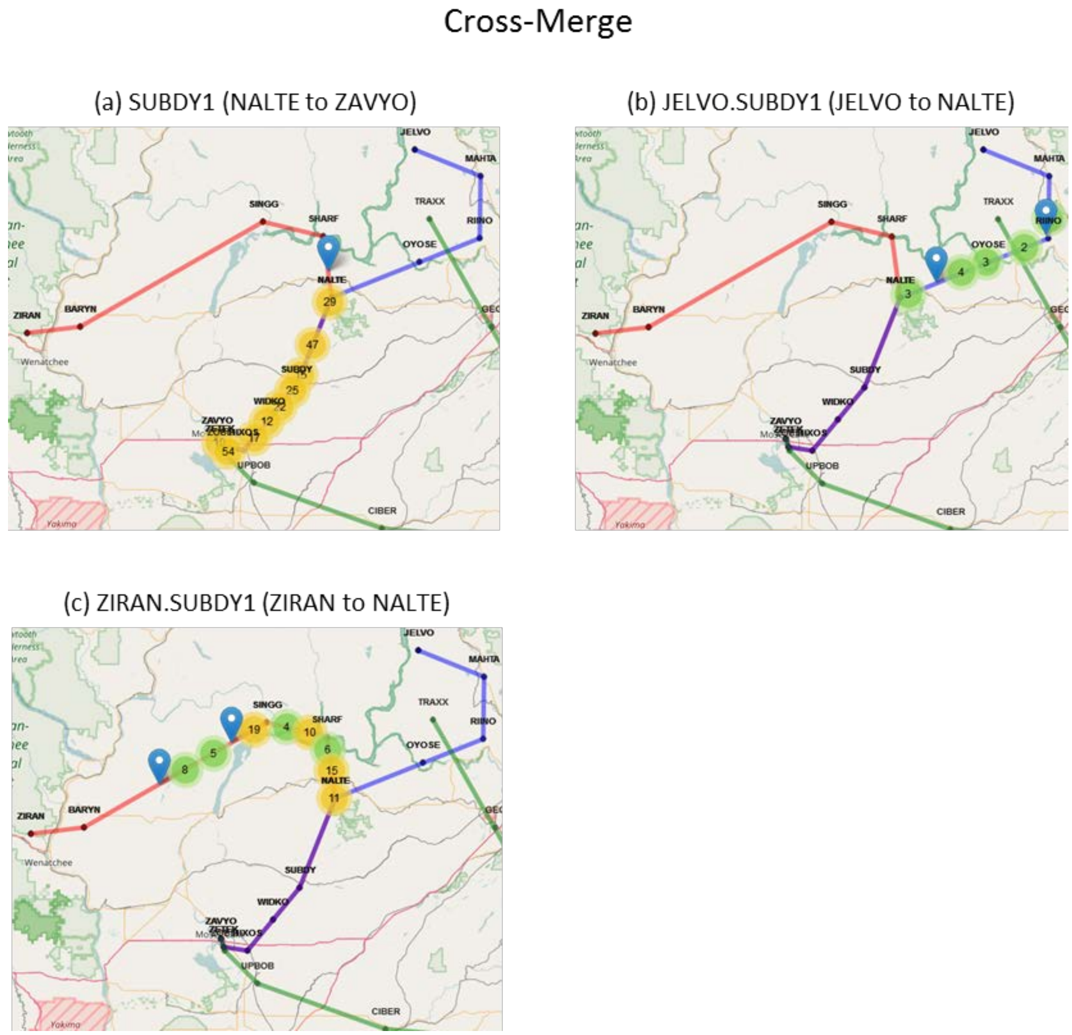


Figure 10. Maps of speed commands during arrival scenarios for Cross-Merge operations: (a) SUBDY1 (NALTE to ZAVYO), (b) JELVO.SUBDY1 (JELVO to NALTE), and (c) ZIRAN.SUBDY1 (ZIRAN to NALTE)

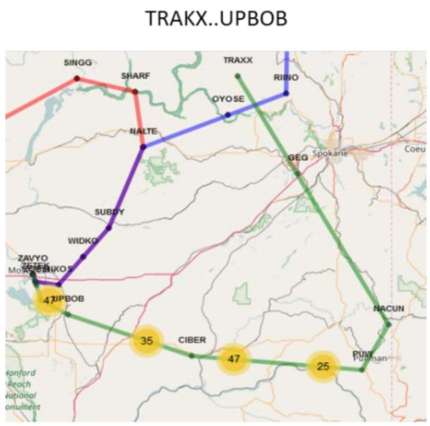


Figure 11. Map of speed commands for Cross-FAF time-based operations on the UPBOB1 Route

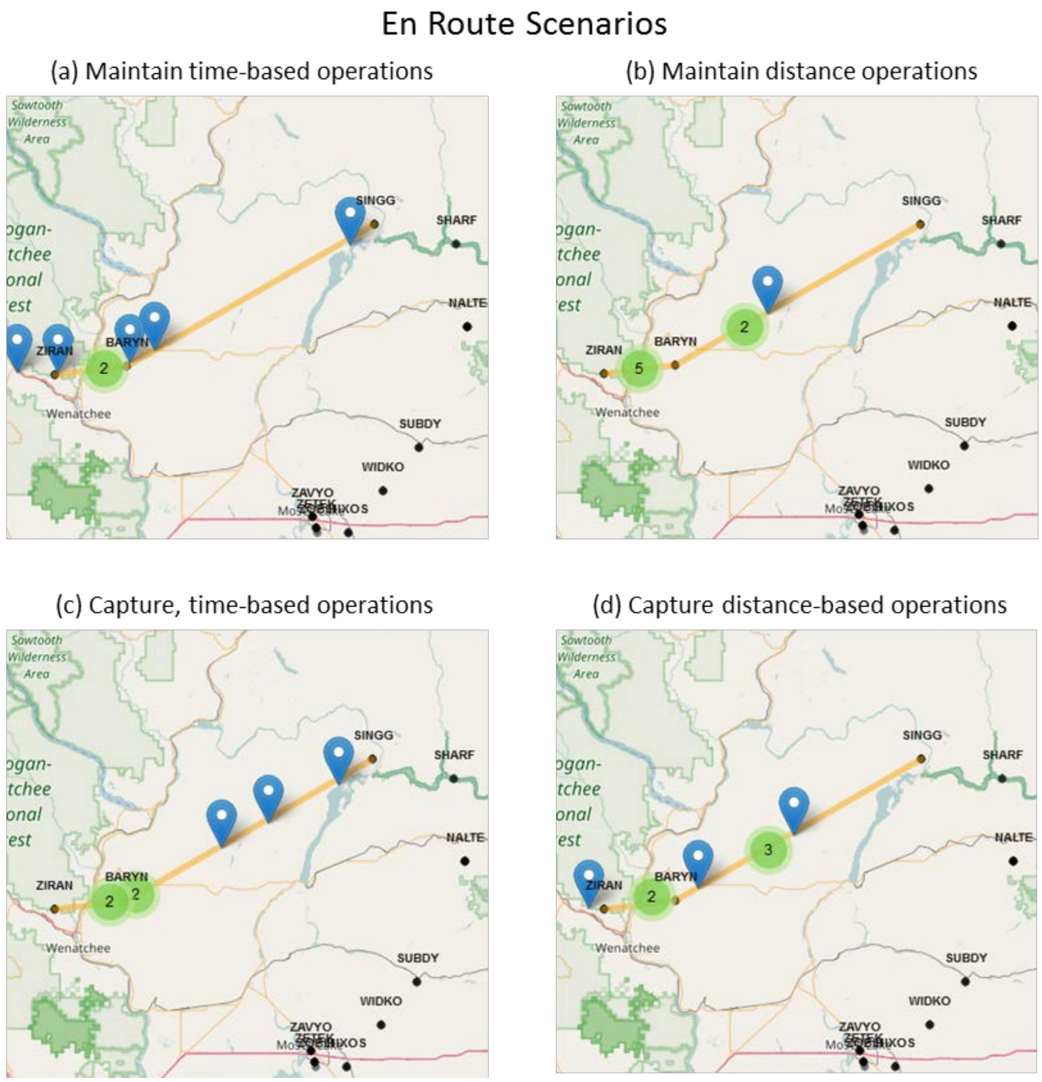


Figure 12. Maps of speed commands for en route scenarios: (a) Maintain time-based operations, (b) Maintain distance-based operations, (c) Capture time-based operations, and (d) Capture distance-based operations

4 Discussion

The examination of both the number of speed increases per minute and the number of speed commands per minute demonstrated that the clearance type was the biggest factor in determining the frequency of speed commands. The inherent nature of the clearance types determined how often an adjustment of speed needed to be made. Some clearance types required a stricter observance to the ASG, resulting in a greater number of both speed increases and speed commands in general.

Other than dictating the speed control law, the clearance type had no clear effect on where the speed increases or speed commands occurred. The location of the speed command was determined by both the route itself and the speed control law being used for the IM operation. One possible reason the route affected the location of the speed commands was the difference in curvature of the paths. The JELVO.SUBDY1 route, being both the curviest and the shortest of the arrival routes saw many more speed commands throughout the entire route than its straighter arrival counterparts. The trajectory-based speed control law needed fewer speed commands to adjust to the path than those on the state-based speed control law.

The one element that did not seem to be an indicator of frequency or location of speed commands was the units for the ASG. The number and location of the speed commands and increases differed from time-based to distance-based operations of the same clearance and on the same route but there was no clear pattern between them. This is an expected result since the speed control laws used for distance-based and time-based operations are similar.

The work in this paper indicates that there is not one clear factor that could be investigated further to reduce unnecessary speed commands. That the maximum number of speed commands or increases per minute for each route occurred with a different operation type shows that variables need to be considered together to determine speed commands. The clearance type or route alone does not determine how many or where speed commands will occur.

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14. ABSTRACT
NASA's first Air Traffic Management Technology Demonstration (ATD-1) successfully completed a nineteen-day flight test under a NASA contract with Boeing, with Honeywell and United Airlines as sub-contractors. An Interval Management (IM) avionics prototype was built based on international IM standards, integrated into two test aircraft, and then flown in real-world conditions to determine if the goals of improving aircraft efficiency and airport throughput during high-density arrival operations could be met. This paper describes the speed behavior of the IM avionics prototype, focusing on the speed command rate and the number of speed increases.

15. SUBJECT TERMS
ATD-1; Interval Management; Aviation; Flight test

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