

# SIMULATION OF TIME-ON-PROCEDURE (ToP) FOR EVALUATING AIRLINE PROCEDURES

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## Abstract

Airline Standard Operating Procedures (SOP) define the sequence of flight crew actions to handle the set of mission situations that can emerge in the execution of a commercial airline flight. Each SOP must be completed within an Allowable Operational Time Window (AOTW) to avoid a hazardous outcome. For dynamic plants (e.g. airliner) the Time on Procedure (ToP) and the AOTW are distributions that vary with the interactions between environment, plant, and operator actions. Making sure that new, or modified procedures, can be completed in a timely manner (i.e.  $ToP < AOTW$ ) is a critical step in verification of SOPs.

This paper describes a method to simulate the ToP distributions for SOPs based on analysis of aircraft flight data. The Monte Carlo (MC) simulation for ToP has a three-step process described as (1) generate the AOTW, (2) identify AOTW interval, (3) generate ToP. A case study analysis of the Take-off procedure is demonstrated resulting in a simulated ToP within 5% of the actual. The implications of these results for testing procedure design and limitations of this method are discussed.

## 1 Introduction

Airline flight deck operations are governed by airline Standard Operating Procedures (SOPs). These SOPs identify the flight crew actions in response to plausible situations that might emerge in the execution of a revenue-service airline flight.

By standardizing procedures, the airline can: (1) ensure safe and efficient operations that are in adherence to its overall operational philosophy and policies [1], [2], (2) enable crew members to be paired with other crew members with whom they may have never flown before [1], and (3) provide the basis for objective flight crew proficiency evaluation.

Each SOP must be performed within an Allowable Operational Time Window (AOTW) (Figure 1). The AOTW for a given flight is defined by the circumstances of the flight including; aircraft performance, atmospheric conditions (e.g. temperature, wind), air traffic navigation procedures and instructions, air traffic and other external factors that affect the flight trajectory and the flight operations. Due to the complex environment in which the procedure is performed, the AOTW is not a fixed time but a time distribution that can exhibit a large variance (Figure 1).

The time to complete the SOP actions is known as Time on Procedure (ToP). Like AOTW, the ToP is not a fixed number and can vary due to factors such as the availability of information to perform the next step, aircraft performance, individual technique, variability in attention and reaction times, and fatigue (Figure 1).

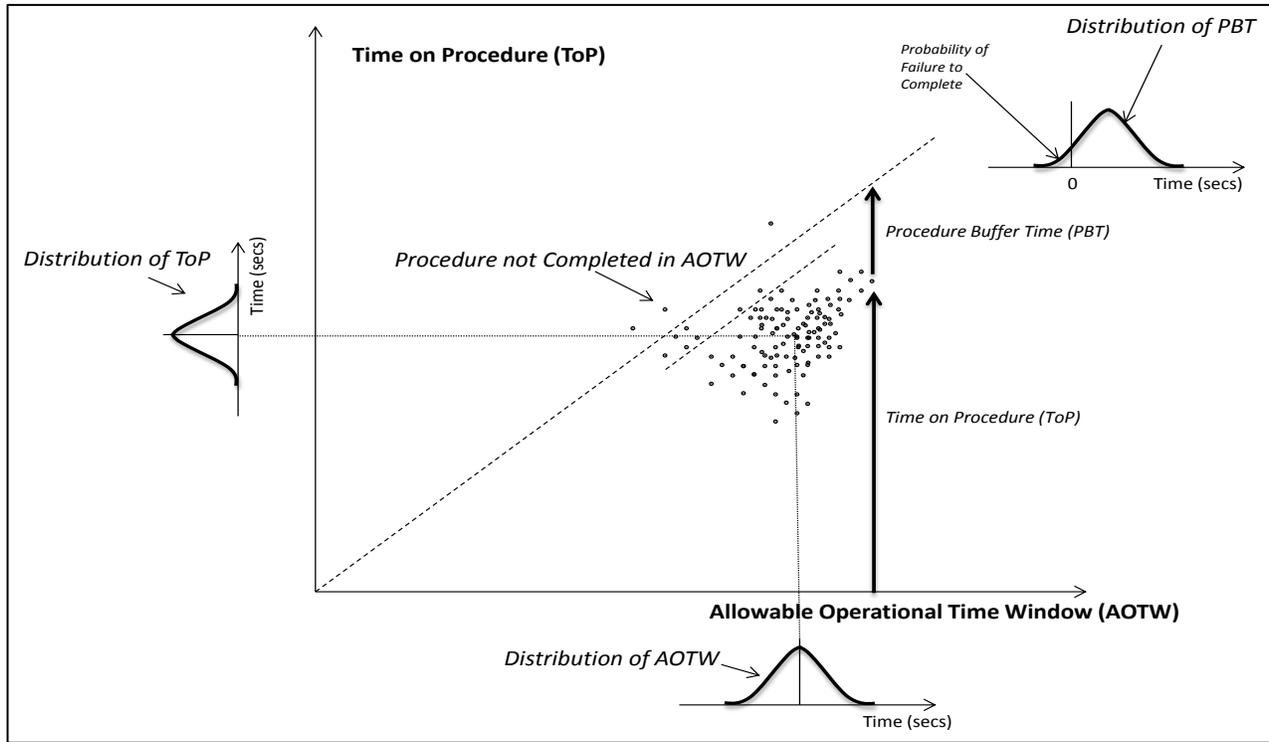
When the ToP is in excess of the AOTW it may be of no consequence, or it may place the aircraft in a potentially hazardous situation (e.g. flap overspeed, altitude deviation), or result in an inefficiency (e.g. extra leg in a Holding Pattern, extended along-track distance, go-around).

The difference between the ToP and the AOTW is the Procedure Buffer Time (PBT) [3]. The percentage of the PBT distribution that is less than zero determines the Probability of Failure to Complete (PFtoC) the procedure on time (Figure 1).

A PFtoC for a procedure less than a design threshold (e.g. 0.05) could serve as a quantitative indication that the procedure is verified.

### 1.1 Computer Aided Design and Testing (CAD) Standard Operating Procedures

The SASOP tool is a CAD-like tool for Simulation and Analysis of Standard Operating Procedures (SASOP) [3]. The tool provides a means to test a procedure in the presence of stochasticity in AOTW and ToP. The SASOP tool, (Figure 2)



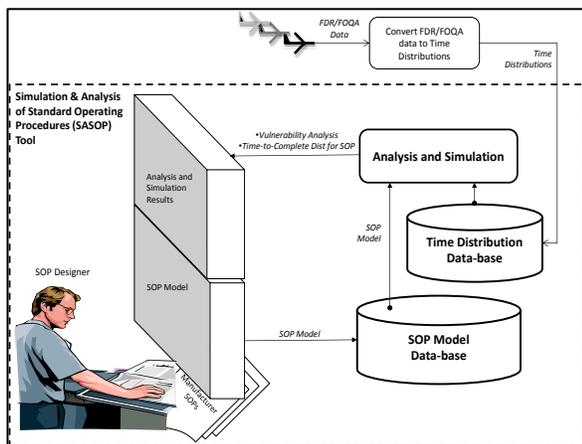
**FIGURE. 1: Scatter-plot of ToP and AOTW for a set of flights yield distributions for ToP relative to the AOTW. The difference between the AOTW and the ToP for a given flight is the Procedure Buffer Time (PBT).**

allows the designer to define the SOP using a simple graphic input. The SOP model is stored in the SOP data-base. Each SOP can be simulated using empirically derived data from the Time Distribution data-base. The data for the Time

Distribution data-base is derived from FDM and FOQA data. The results of the vulnerability analysis and simulation of the SOP are displayed on the SASOP GUI.

A previous paper describes how to calculate the AOTW distribution [3]. This paper describes a three-step method for simulating the ToP distribution using a Monte Carlo (MC) simulation. This simulation can be used for verification of a new or modified procedure.

This paper is organized as follows: Section 2 provides an overview of SOPs and SOP testing. Section 3 describes how to process the data for the MC simulation, describes the MC simulation for ToP, and proposes a method for evaluating the simulation results. Section 4 demonstrates the method for the takeoff procedure for a four-engined jet aircraft. Section 5 discusses implications and limitation of the method.



**FIGURE 2: Computer Aided Design and Testing (CAD) of Standard Operational Procedures (SOP)**

## 2 Designing and Testing SOPs

Standard Operating Procedures (SOPs) specify [1], [2]:

- (1) what task to perform
- (2) when to perform the task (timing and sequence)
- (3) what actions are required to perform the task
- (4) who conducts the task (i.e. pilot-flying (PF) or pilot-monitoring (PM)), and
- (5) what feedback to provide (i.e., call-outs)

The Federal Aviation Administration (FAA) Advisory Circular AC 120-71B “Standard Operating Procedures and Pilot Monitoring Duties for Flight Deck Crewmembers” provides guidelines on the background, basic concepts, and philosophy of SOPs [4]. To meet these guidelines, SOPs must be carefully designed to maintain appropriate workload by ensuring the sequential execution of actions and by ensuring the correct information is available before it is required in the procedure [2].

For example, during a segment of the takeoff procedure, between aircraft rotation (i.e. nose-up) and the first flap retraction airspeed, the flight crew must accomplish the following tasks in the exact sequence to establish the required aircraft state before the next task can be performed: (1) climb at the required pitch angle, (2) maintain the required airspeed, (3) raise the landing gear, (4) engage the autopilot, (5) select the NAV mode on the autopilot, (6) reduce thrust, and (7) set a new airspeed target on the autopilot Mode Control Panel (MCP).

Several accidents have identified the need to design procedures such that they can be completed within the allowable operational time window (AOTW). This is especially true when the AOTW exhibits significant variance [5] [6] and/or when the ToP exhibits significant variance [5] [7] [8].

Most often, procedures are designed by the aircraft manufacturer with primary, if not exclusive, attention to intended use of aircraft systems and the engineering requirements. The procedures are then adapted by the airlines to reflect company philosophy, policy, and the type and location of operations. The modified procedures are vetted by a team of experts with human factors, aircraft systems, and operations knowledge. Following the review process, the procedures can be validated empirically by testing them against the behavior of

regular pilots [1, page 51]. The test takes place in a flight simulator using a sample of the target population of pilots to serve as subjects for the test. Due to the complexity of the operating environment, even a well-funded test with 20 flight crews, may not be able to cover all the plausible scenarios that can occur that constrain the design of a procedure.

The ability to test the procedures on desk-top simulation could assist in the procedure verification process by identifying situations in which the procedure may not complete in a timely manner (i.e.: ToP > AOTW).

## 3 Monte Carlo Simulation of ToP

This section describes the use of Flight Data Monitoring (FDM), or its equivalent Flight Operational Quality Assurance (FOQA) data to derive the ToP distribution.

### 3.1 Data Preparation for the MC Simulation

This section describes the engineering analysis process for creating the data for the Monte Carlo simulation described in section 3.2. There are four steps:

- 1- Data collection and organization
- 2- Cluster analysis - scatter plot ToP vs. AOTW
- 3- Creation of the inverse function for ToP and for AOTW
- 4- Simulation of the AOTW and ToP

#### Step1: Collect Data and Organization

This step consists of the gathering of FDM data and relevant timestamps, and of the grouping of segments’ time durations.

FDM or FOQA data can provide a time-stamp for each event. The time stamp is the time the event occurred. For example, the time that the aircraft achieves the  $V_1$  decision to take off speed.

Calculating the ToP or the AOTW Distributions is done by calculating duration between two Critical Events (i.e. Segments). The method is the same for both the AOTW and the ToP distributions. For example, the ToP for Segment  $x$ , flight  $i$ , or ToP ( $x_i$ ) is the difference between the

time stamps for sequential critical events in that flight.

$$\text{ToP}(x_i) = t@Critical\ Poi(i,2) - t@Critical\ Point(i,1)$$

Where:  
*i* is the flight index

The distribution for ToP for each Segment, across all flights is the aggregation of these flights. The  $AOTW(x_i)$  and  $ToP(x_i)$  for flight *i* can be plotted on X-Y graph as shown in Figure 1.

**Step 2: Cluster Analysis - Scatter Plot ToP vs. AOTW**

**a. Clusters Identification:**

The next process with the scatter plot is to identify the cluster forming the dataset. The clusters analysis uses K mean clustering and the number of clusters is determined by visualization supported by the *Calinski-Harabz* criterion:  $\left(\frac{SS_B}{SS_W} \times \frac{(N-k)}{(k-1)}\right)$ , where  $SS_W$  is the overall within cluster variance, and  $SS_B$  is the overall between-cluster variance.

The greater the value of the *Calinski-Harabz* criterion ratio, the more cohesive the clusters (low within-cluster variance) and, the more distinct/separate the individual clusters (high between-cluster variance) [9].

**b. Identification of the AOTW Intervals and Conditional Probabilities:**

To accurately generate procedure timings, it is necessary to frame the dataset into sections. In doing so, intervals of the AOTW were defined and slicing the AOTW helps with the formulation of conditional probabilities statements. This will become clearer in the case-study demonstration.

**c. Calculation of conditional probabilities.**

Grouping of the data into clusters and AOTW intervals sets the framework for the definition of conditional probabilities expressed in terms of “for a given AOTW, what is the probability that the dataset falls under a specific cluster of ToP?”.

**Step 3: Definition of the inverse function for the Cluster ToP and for the Overall AOTW**

At this step, each cluster is isolated and the ToP distributions is analyzed to build an inverse function ( $ToP\_ClusterX^{-1}$ ). As well, the overall AOTW distribution is analyzed and a corresponding

inverse function ( $AOTW^{-1}$ ) is also defined. With the inverse functions defined, it is possible to generate random numbers that trace back those specific distributions. The end goal of this operation is to accurately generate AOTWs for a specific procedure and subsequently simulate a ToP. The details of the simulation are discussed in the next sub-section.

**3.2 Monte Carlo Simulation of AOTW and ToP**

This section describes the algorithm of the Monte Carlo Simulation for the ToP. The input to the simulation is the Overall AOTW and Cluster ToP inverse functions, in addition to the conditional Probabilities rules. The output of the simulation is the Overall ToP distribution.

The algorithm for the ToP simulation is to perform the following algorithm in a Monte Carlo Simulation as follows:

- i. Generate AOTW random number (to determine which cluster is used)
- ii. Check what AOTW interval the result above falls under
- iii. Generate ToP random number instance using the conditional probabilities.

The pseudo code for the simulation is as follows:

```

=====
For i from 1 to Big Number do
    (AOTW-1) = Overall AOTW_Inverse
    If: AOTW-1 is in AOTW1
        Then Generate Random Number
        Case: Random Number <= X
            ToP_Cluster1,
        Case: x < Random Number <= Y
            ToP = ToP_Cluster2-1,
        Case: y < Random Number <= Z
            ToP = ToP_Cluster3-1,
        Else ToP = ToP_Cluster4-1,
        End Case
    Elseif: AOTW-1 is in AOTW2
        Then Generate Random Number
        [same structure for all AOTW intervals]
    End If
End For

```

The starting point is the generation of a random timing for the AOTW. This is performed by drawing from the AOTW data previously captured in the dataset via the inverse function  $AOTW^{-1}$ . Next is checking where that instance of AOTW falls within the predefined AOTW intervals. This will inform the conditional probabilities that are implemented through a “Case” and “If-Then-Else” like statements.

### 3.3 Method for Evaluation of Simulated Results

Testing of the simulation results is performed via the comparison of the simulated results versus the actual data using the following, and to illustrate, the AOTW is taken as example.

- (1) the 5th percentile

$$5th \% \text{ tile } AOTW(x) = \mu AOTW + Z_{0.05} * \sigma AOTW$$

- (2) The 95th percentile:

$$95th \% \text{ tile } AOTW(x) = \mu AOTW + Z_{0.95} * \sigma AOTW$$

- (3) The median:

$$Median AOTW(x) = \{(n + 1) / 2\}^{th} \text{ Value}$$

- (4) The mean:

$$Mean AOTW(x) = \frac{\sum_i^n AOTW(x)}{n}$$

Where:  $i$  is the flight index,  $n$  is the number of total recorded flights, and  $x$  is the procedure segment

## 4 Case Study: Flap Retraction in Takeoff Procedure

This section describes an application of the process described in section 3.1. to model and test the ToP Monte Carlo Simulation described in sections 3.2. The results are evaluated by the method in section 3.3.

This case study was based on the takeoff procedure data for 1042 flights for a 4 engine jet aircraft operated in Europe.

The takeoff procedure is one of the more complex procedures performed by commercial airline pilots. The aircraft must be transitioned from a ground vehicle to an air vehicle (i.e. rotate and

retract landing gear), and then from a high lift (and high drag) air vehicle to moderate lift (and lower drag) air vehicle (i.e. retract takeoff flaps). All of this must be conducted in close proximity to terrain and obstacles, while following air traffic control navigation procedures and instructions, in the presence of air traffic, and while managing the aircraft systems.

The segment with the flap retraction from 24° to 18° is explained in Figure 3. When the aircraft achieves the  $V_{F18}$  speed, or flap retraction speed, (e.g. 126 knots), the Pilot Flying (PF) requests “Flaps 18” The Pilot Monitoring (PM) checks for the correct speed and the retracts the flaps by moving the Flap Handle from the 24° degree detent to the 18° detent.

When the flaps have retracted to 18° the PM confirms “FLAPS 18” and the PF checks the flap position indicator and confirms “CHECKED”

The PF checks the altitude, and sets the new speed on the MCP. The new speed is confirmed by the PM.

### 4.1 Data Preparation

#### Step 1: Data Collection and Organization

Data on takeoff procedure of a 4 engines jet aircraft provided timestamps information for flaps retraction from 24° to 18° during takeoff. The two critical points delimiting the AOTW are the schedule’s Flap Retraction Speed from 24° to 18°

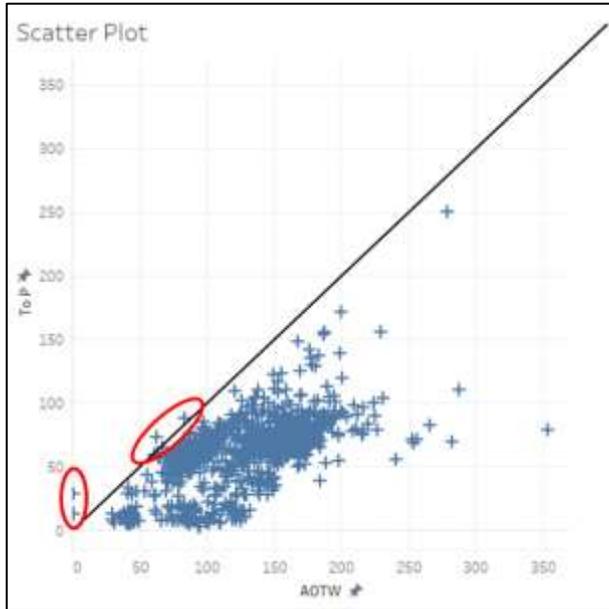
57. SPEED ACHIEVES  $V_{F18}$ (e.g. 126 knots)
58. PF sees  $V_{F18}$  (e.g. 126kts) on PFD
59. PF orders “FLAPS 18”
60. PM silently checks  $V_{F18}$  (e.g. 126 kts) on the PFD
61. PM selects flaps lever to 18°
62. PM monitors flaps transition on flaps position indicator
63. PM confirms “FLAPS 18”
64. PF checks flaps position 18° on flaps position indicator
65. PF confirms “CHECKED”

**FIGURE 3: Flap retraction portion of Takeoff SOP**

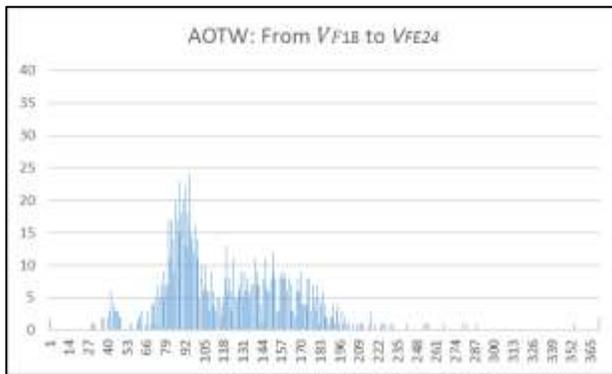
( $V_{F18}$ ) and the Maximum Flap Extended speed for flaps 24 ( $V_{FE24}$ ) which defines the maximum speed at which flaps can be operated at  $24^\circ$  without incurring structural damage. The ToP for this segment is defined by the same lower bound i.e.:  $V_{F18}$ , but the upper bound of the time interval is defined as the instant at which the flaps reach the  $18^\circ$  position.

Figures 4 and 5 show the AOTW and ToP in a frequency distribution. Both distributions exhibit multiple modes.

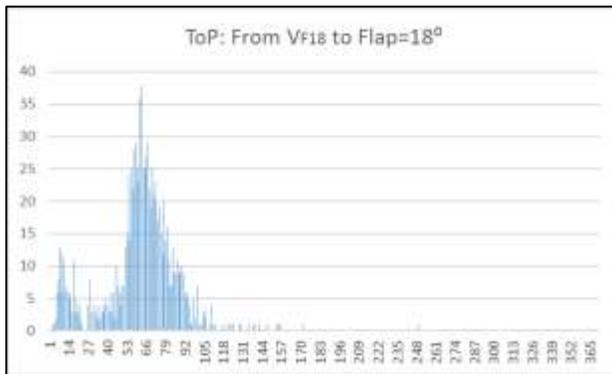
The X-Y scatter plot for each AOTW and Top is shown in Figure 6. The diagonal line crossing the plot identifies the region, up and left from the line, in which the ToP exceeds the AOTW (i.e.  $AOTW \leq ToP$ ). Also, consistent with the histograms in Figures 3 and 4, the scatter plot shows clusters of AOTW and ToP pairs.



**FIGURE 6: Scatter plot of AOTW and ToP pairs (in sec.)**



**FIGURE 4: AOTW distribution (in sec.) from aircraft data**



**FIGURE 5: ToP distribution (in sec.) from aircraft data**

**Step 2: Cluster Analysis**

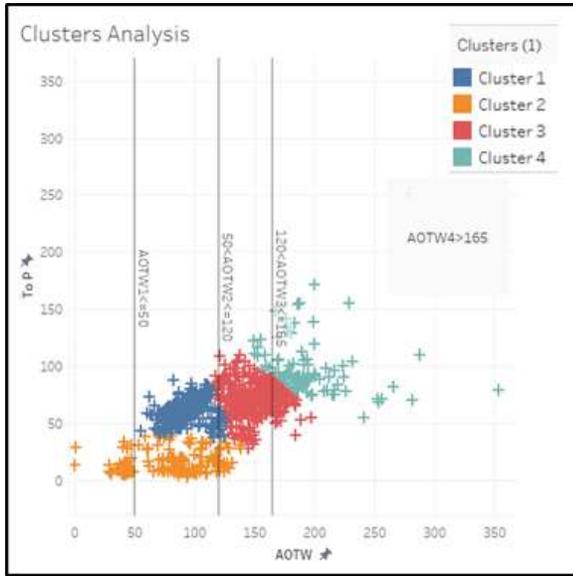
**a. Clusters Identification**

The clusters analysis was performed using the *Tableau Software* tool. Four clusters were identified per the K-means cluster method explained in section 3.2.a.

The clusters are color-coded in the Figure 7.

**b. Identification of the AOTW intervals and conditional probabilities:**

In addition to the clusters grouping, the case-study dataset was sliced into four intervals demarcated by AOTW limits (figure 7). The first interval is defined by  $AOTW \leq 50$ , and titled AOTW1. The second interval was defined by AOTW2 such as  $AOTW = 50 < AOTW2 \leq AOTW = 120$ , and the third interval:  $AOTW = 120 < AOTW3 \leq AOTW = 165$ , whereas the final interval included all AOTW where  $AOTW4 > AOTW = 165$ .



**FIGURE 7: K-Means clusters of AOTW and ToP pairs.**

**c. Calculation of the Conditional Probabilities**

Once the clusters and the AOTW intervals are defined, the conditional probabilities are calculated. Table 1 below shows a summary of the results.

**Step 3: Definition of the inverse function for ToP and for AOTW**

Each cluster was isolated and the ToP inverse

**TABLE 1: Conditional probabilities for clusters**

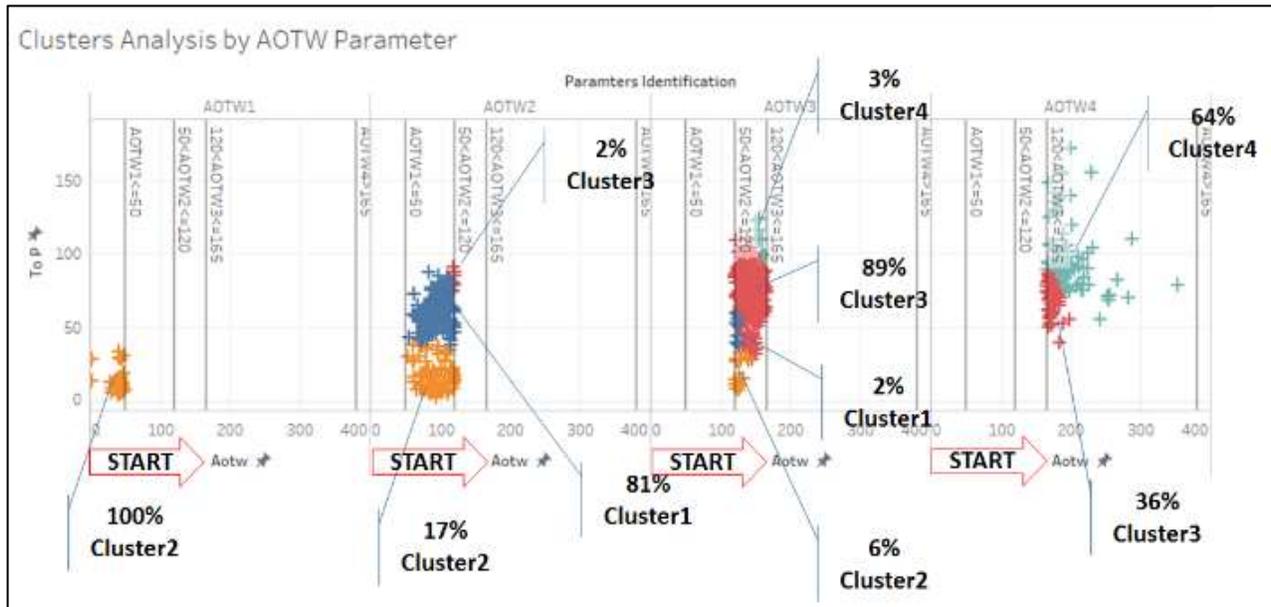
	Cluster1	Cluster2	Cluster3	Cluster4	Total Obs
<b>AOTW1</b>					
Count	0	37	0	0	37
Percent	0%	100%	0%	0%	100%
<b>AOTW2</b>					
Count	432	93	8	0	533
Percent	81%	17%	2%	0%	100%
<b>AOTW3</b>					
Count	7	19	273	9	308
Percent	2%	6%	89%	3%	100%
<b>AOTW4</b>					
Count	0	0	58	104	162
Percent	0%	0%	36%	64%	100%

To clarify further, Figure 8 below displays 4 repetitive frames where only one AOTW interval is isolated to show its content of clusters. This visual shows for example that if the AOTW is part of interval AOTW2 (i.e.:  $50 < AOTW \leq 120$ ), there is a 2% chance that the ToP is in Cluster 3, a 17% chance it is in Cluster 2, and an 81% chance it is in Cluster 1. This structure is implemented in the simulation.

Refer to 3.2. Monte Carlo Simulation of the AOTW and ToP for more details. Next, is Step 3.

function defined. Figure 8 shows an example ToP for Cluster 1

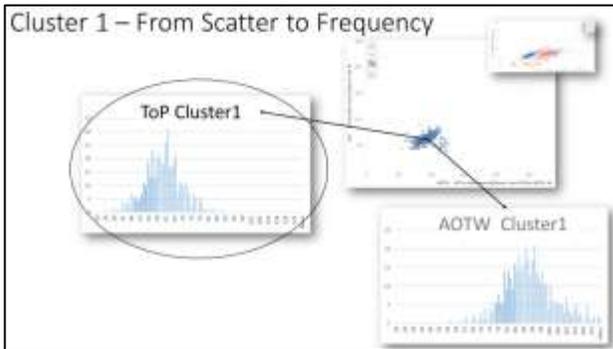
The ToP from cluster 1 was isolated and an inverse function was defined. To explain, in Figure



**FIGURE 8: AOTW intervals for isolated clusters of AOTW and ToP pairs**

8 on the right, the value ToP=66 sec., recorded a frequency of 31. The inverse function enables to answer the reverse question i.e. given 31 occurrences, what is the ToP?

In this same manner, an inverse function for the overall AOTW (no cluster specified) was defined.

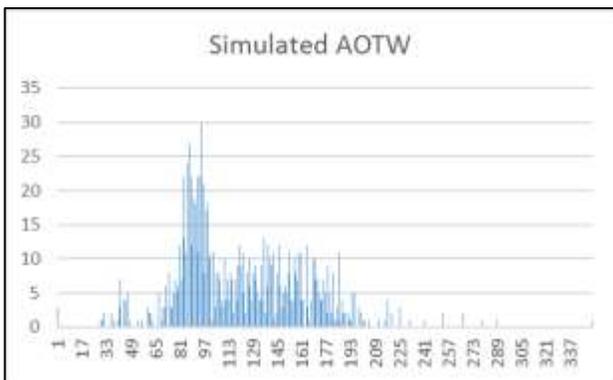


**FIGURE 9: ToP of Cluster 1 for inverse function generation**

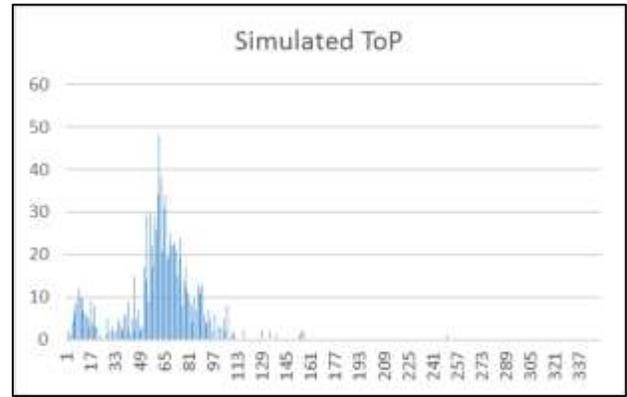
For this case-study, the inverse function was coded in Microsoft Excel Visual BASIC for Applications (VBA).

#### 4.2 Monte Carlo Simulation Results

Coding of simulation was done in VBA. The pseudo code detailed in section 3.2. was implemented and the results of the simulation are displayed in Figures 9 & 10.



**FIGURE 10: Simulated AOTW**



**FIGURE 11: Simulated ToP**

#### 4.3 Monte Carlo Simulation Evaluation

A side-by-side comparison of the distributions displayed in Table 2 above shows accuracy with the range (5%-tile and 95%-tile). Also, the median and mean are within 2%. Calculations were performed in Microsoft Excel.

**TABLE 2: Comparison of actual vs. simulated results**

Measure	AOTW			ToP		
	Actual	Sim	% Diff	Actual	Sim	% Diff
5th %-tile	69.5	70	1%	10.5	11	5%
95th %-tile	187.9	185	-2%	94.25	94	0%
Median	111	112	1%	63.3	63	0%
Mean	122.2	120.2	-2%	61.5	61.8	0%

## 5 Conclusions and Future Work

This paper describes a method for creating a Monte Carlo Simulation of Time on Procedure (ToP) for a given procedure. The ToP simulation, based on aircraft data (e.g. Flight Data Monitoring or Flight Operational Quality Assurance), can be used to test new or modified Standard Operating Procedure (SOPs) while considering the variance in the Allowable Operational Time Window (AOTW) and in the ToP.

This paper demonstrates the application of a method for the flap retraction segment of the takeoff procedure. Failure to complete the flap

retraction prior to reaching the maximum speed for the flap setting results in a “flap overspeed” condition which requires maintenance at the termination of the flight (i.e.: disruption to the airline service and additional costs).

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