

Designing Scenarios for Controller-in-the-Loop Air Traffic Simulations

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Well prepared traffic scenarios contribute greatly to the success of controller-in-the-loop simulations. This paper describes each stage in the design process of realistic scenarios based on real-world traffic, to be used in the Airspace Operations Laboratory for simulations within the Air Traffic Management Technology Demonstration 1 effort. The steps from the initial analysis of real-world traffic, to the editing of individual aircraft records in the scenario file, until the final testing of the scenarios before the simulation conduct, are all described. The iterative nature of the design process and the various efforts necessary to reach the required fidelity, as well as the applied design strategies, challenges, and tools used during this process are also discussed.

I. Introduction

Human-in-the-loop (HITL) simulations are an integral part of the Air Traffic Management (ATM) Technology Demonstration-1 (ATD-1).¹ ATD-1 is an effort to operationally demonstrate the feasibility of high throughput efficient arrival operations during peak traffic conditions, using NASA-developed technologies. The HITL simulations of this project help to assess the performance of the integrated software technologies and, to assess the performance of the human working with those systems.

The Airspace Operations Laboratory (AOL) has a long history in conducting controller-in-the-loop simulations using the Multi-Aircraft Control System (MACS) as its primary simulation environment.² The AOL recently conducted a series of HITL simulations in support of ATD-1.^{3, 4} In any successful HITL simulations of an ATM environment, a set of realistic traffic scenarios is required to provide the controllers with a detailed image of the real-world operations. Achieving a high realism of the modeled traffic, in terms of loads in sectors, loads on routes, carrier-aircraft type-equipage combinations, filed flight plans, traffic patterns, etc., enables the controllers and pilots to execute their tasks in the same way as they would in the real world. In general, if the realism of the simulation environment and the simulated traffic is high, researchers will be able to obtain a reasonable impression of how the operations might behave when the ATD-1 systems are transferred to, and tested in an operational setting.

In preceding ATD-1 HITL simulations the Airborne Spacing for Terminal Arrival Routes (ASTAR) -equipped Aircraft Simulator for Traffic Operations Research (ASTOR) simulator (Ref. 5), containing one of the ATD-1 technologies, was integrated into the simulation environment. The complexity of the scenario design process increased: flights operated by the ASTOR simulator needed strategic placement in the arrival sequence, and required careful coordination between two file formats: that of the MACS traffic scenarios, and a specific ASTOR scenario format. The two scenario files needed to interleave seamlessly when running the combined system in a HITL simulation. Because these early simulations focused on the integration of the ATD-1 systems, the scenarios design was less constrained initially. For example, not all the traffic types needed to be simulated, and flight initialization positions and routes were eligible for editing, as long as the general characteristics of the traffic were maintained.

Upcoming ATD-1 HITL simulations will investigate the system performance. An increased level of fidelity of the traffic scenarios is necessary to support this goal. The experiments will simulate more sectors and additional traffic, such as over-flights, departure traffic, satellite arrivals, and satellite departures. Also, a range of aircraft performance groups will be represented in the scenarios (i.e., jets, high- and low-performing turbo-prop aircraft and

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piston aircraft). The distributions of the traffic on the various routes, and the corresponding air carrier and aircraft type mixes must match those in the real world. The positions of the arrival aircraft need to match as close as possible to the positions from the recording of actual traffic. A thorough vetting process must then follow, one that includes lab tests, full scale simulation shakedowns and subject matter expert interviews. This helps to mitigate scenario artifacts, such as unrealistic aircraft routing, incorrect ownership, immediate conflicts upon simulation initialization, unrealistic speeds and altitudes, etc.

The next section of this document first informs about other existing scenario generation software and work on the development of traffic scenarios. To prepare the ground for the current work it then states objectives and gives an overview of the traffic scenario design process that was followed. In the end details of the airspace are presented. The section Scenario Design guides step-by-step through the individual scenario development stages. At first, insights of the data acquisition are laid out, followed by details of the main scenario editing. The section concludes with information on testing and validation. To explain the actual outcome of the scenario-building effort a variety of metrics for one of the scenarios are presented. The document ends with a conclusion highlighting the essential scenario building steps and insights gained during this process, discussing key problems that were encountered, and pointing out where room for improvement was found.

II. Background

A. Related work

Building traffic scenarios for fast- or real-time simulations have long been an integral part of the overall simulation process. It may take considerable amounts of time to construct traffic files that meet the needs of the simulation. Depending on the desired complexity of the traffic and airspace, and whether the simulation will be conducted in fast-time or real-time, scenarios may be compiled manually, partially automatically, or even completely automatically. Even with automatically-generated scenarios, often there is some degree of manual editing still required.^{6,7}

The AvScenario software is described as a tool which automates many scenario-building steps.⁶ It is able to automatically read a variety of existing flight data that, after import, can be modified in several ways. Using a graphical interface, routes as well as flight path start- and end points can be modified by simple drag and drop actions. It also provides direct text-editing features without the need for the user to employ other text-editor or spread-sheet software. The software also provides the functionality to easily modify adaptation data such as navaids, routes and other airspace features like special use airspace areas. An AvScenario traffic file can be exported in the generic extensible markup language (XML) format, or into specific simulator formats. For the latter, an explicit mapping of the individual scenario information elements is required.

In the AwSim trajectory simulation software scenarios provide typical information, such as latitude, longitude, altitude, and time to simulate flights as a population of 4-dimensional trajectories. Other parameters included are aircraft types, weights, and fuel burn values. AwSim uses an agent-based model employing Monte-Carlo algorithms to generate the 4-dimensional trajectories, and can work from live flight data feeds such as Aircraft Situation Display to Industry (ASDI).⁸

Other scenario-building software takes advantage of a genetic algorithm to modify real-world traffic by time-shifting the flights such that aircraft-to-aircraft encounters and conflicts are being generated.^{9,10} Also, European Air Navigation Service Providers and universities are employing fast-time and real-time simulations for their research, for which traffic scenarios are required: a software application called TRAFFIC MOdeller (TRAMO) was created to aid users in building traffic scenarios for usability studies.¹¹ It has manual editing capabilities and also provides batch processing functions to import traffic data from external sources, such as Reorganized ATC Mathematical Simulator (RAMS) or Total Airspace and Airport Modeler (TAAM). Similar to AwSim it also provides drag-and-drop editing of the flight trajectories. ATACs SkyView software can use real-world data to build traffic scenarios for controller training.¹²

B. Traffic Scenario Objective

The objective of the scenario design task was to create traffic scenarios that mirror real-world high-demand arrival flows under realistic wind conditions, for all airport flow configurations. Recordings of live traffic served as the basis for the scenarios, which were intended to be used for various simulations within the ATD-1 effort, thereby increasing the comparability of simulation results across the experiments conducted by the different research groups. The scenarios were first designed to support the requirements of the Controller Managed Spacing (CMS) ATD-1 (CA) experiment series. A critical goal was to develop traffic scenarios that captured the original characteristics of the live traffic recordings as best as possible, with as few differences from the live recording as possible.

C. Process Overview

The scenario design process that was used followed the development flow illustrated in Ref. 6, but can be broken down into three main steps. One, the scenario design preparation, which includes real-world traffic identification, acquisition and the preparation of the raw traffic data for output. Two, the main scenario design. This step includes initial scenario editing and cleanup, the main aircraft record set adjustment and, building the ASTOR scenarios. The third step includes scenario testing, validation and fine tuning. The three steps are described in the subsequent paragraphs in more detail.

The overall process relied on two main software applications: the Trajectory-Based Route Analysis and Control (TRAC) tool, and the Multi Aircraft Control System (MACS), both developed at NASA Ames. TRAC is an air traffic visualization, graphical design and analysis software that supports the iterative design of next generation (NextGen) air traffic management concepts.^{7, 13} It provides an airspace graphical user interface onto which default and custom airspace adaptation data, simulation data, and other analysis features can be overlaid using individually controllable layers. Several tools and functions provide extensive data manipulation and analysis capabilities. TRAC supports data sources from MACS and other research tools. It is able to load, visualize and filter raw data from live traffic recordings, and output the relevant data from the identified periods of interest in a format that can be understood by the MACS software.

MACS provides an environment for rapid prototyping, human-in-the-loop air traffic simulations, and evaluation of the current and future air/ground operations.² It is the simulation platform used for the ATD-1 HITL studies. It includes a powerful scenario editor that provides a synchronized graphical (Scenario Editor) and tabular (AC Table Editor) representation of the traffic scenario. While users can edit all elements necessary to simulate a flight directly in the table, they can also modify aspects of an aircraft trajectory (e.g., initialization position) by drag-and-drop actions in the graphical interface. The scenario editor provides several automated functions, such as ‘auto-update’ which re-computes the value of one flight parameter based on the modified value of another. For example, the target waypoint (i.e., the next downstream waypoint) is linked to, and updated depending on, the initialization point of a flight: if the initialization point changes, the target waypoint can update automatically. The scenario editor also provides an error-checking functionality. It typically checks against aircraft performance values and rules for route definition. Additional scenario editor tools include: trajectory manipulation functions (i.e., functions to quickly alter altitude, initialization time and initialization position), load graphs (e.g., indicating the predicted traffic count in sectors) and conflict highlighting tools (for identifying aircraft-to-aircraft or aircraft-to-weather encounters).

Traffic scenarios for ATD-1 were designed to simulate operations at and around Phoenix International Airport (KPHX), because it shares characteristics of likely ATD-1 demonstration sites, including established RNAV OPDs. After an examination of live traffic recordings, several peak arrival demand periods were identified based on their peak terminal area entry rates. They reflect different times of the year and times of the day, and exhibit different arrival-fix distributions. In the end, the two maximum arrival rushes were selected, which included traffic pushes from over three of the four arrival directions. In one case the arrival rush occurs during an east-flow airport configuration, whereas in the other case the arrival rush occurs during a west-flow airport configuration.

Each traffic scenario is comprised of four main aircraft groups: the first group contains flights that are members of an identified peak arrival rush (subsequently referred to as arrivals). The second group of aircraft includes additional arrival flights that arrive after the members of the peak period (subsequently referred to as extended arrivals). These aircraft served to ensure that Center and Terminal Radar Approach Control (TRACON) Feeder and Center controllers still have traffic in their sectors when the last flights of the arrival peak are approaching their landing runway. The third group of aircraft consisted of the departures leaving KPHX. Only departures leaving from the inbound runway were selected and included into the traffic scenarios. Lastly, the fourth group of aircraft included the over-flight traffic. These are flights departing and landing from airports other than KPHX. Any over-flight aircraft not interacting with the traffic in the test sectors was removed from the scenario, to minimize the amount of traffic the ghost controllers had to interact with.

D. Airspace and Routes

Figure 1 shows the test airspace including the test sectors with radio frequency and altitude strata labels, as well as the routes including the waypoints with altitude and speed restrictions. The simulation’s test airspace was comprised of three high-altitude sectors (37, 50, 93) and five low-altitude sectors (43, 39, 38, 46, 42) from Albuquerque Center (ZAB), four high-altitude sectors (40, 60, 36) one low-altitude sector (35) from Los Angeles Center (ZLA), and four Phoenix TRACON (P50) sectors; two feeder sectors (206-Apache, 212-Santan) and two final sectors (205-Freeway, 204-Verde). Additionally, the simulation was supported by several confederate ghost

rushes. However, when working from cm_sim data, a call-sign alone cannot be used to reference a unique flight because, as happens on occasion in the real-world, an arriving flight can re-use its same call-sign when it departs from the same airport. For these reasons, several levels of filtering were needed to properly identify the four main aircraft groups. The initial filtering by call-sign, for the west-flow data set, left a subset of 155 a/c (out of 4542 a/c overall). Further filtering by flight type (arrival traffic only) resulted in a subset of 79 a/c. Filtering by arrival runway reduced the number of aircraft in the set to 75 a/c. In order to filter out the remaining irrelevant aircraft, a manual search was necessary: flights with subsequent call-signs (e.g., AWE9 vs. AWE94) or duplicate call-signs (AMF2863_557 vs. AMF2863_559) were identified in the list of aircraft and, where appropriate, un-selected.

The Data Set Flight Table (accessible via the aircraft tab of the Data Set Properties window) displays the filtered traffic data in a tabular fashion (Fig. 3). With

the arrivals properly filtered, a time slider (found in the visualization tab), which allows the user to play out, fast forward, or rewind the traffic, was then moved to the point in time where the first aircraft of the

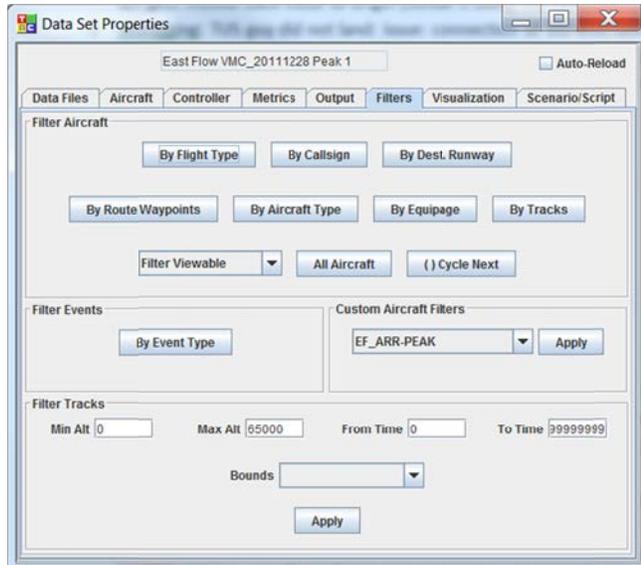


Figure 2. TRAC Filter tab in the Properties window of a data set.

callsign	entryTimeSeconds	entryToDeleteTimeSeconds	type	atcType	destinationAirportName	landingRunwayName	route
ASH2727	226	33184657	CRJ9	CRJ9	PHX	PHX08	.WOTRO_MAIERS..
ASH2762	1142	33186339	CRJ9	CRJ9	PHX	PHX08	.WOTRO_MAIERS..
ASH2769	973	33185700	CRJ9	CRJ9	PHX	PHX07R	.BLH_GEELAS..
ASH2788	0	33183218	CRJ2	CRJ2	PHX	PHX08	.BLH_ARLIN3..
ASH2816	1269	33186640	CRJ9	CRJ9	PHX	PHX07R	.BLH_GEELAS..
ASH2840	2519	33189450	DH8B	DH8B	PHX	PHX07R	.MOHAK_ARLIN3..
ASH2842	0	33183919	CRJ9	CRJ9	PHX	PHX08	.WOTRO_MAIERS..
ASH2852	2566	33189573	DH8B	DH8B	PHX	PHX08	.INW_JESSE1..
ASH2853	0	33183571	DH8B	DH8B	PHX	PHX07L	.MOHAK_ARLIN3..
ASQ4656	0	33184318	E45X	E45X	PHX	PHX07R	.JCT_J86_ELP_J50_SSO_KOOLY4..
AWE119	432	33184919	B752	B752	PHX	PHX07R	.BLH_GEELAS..
AWE125	1067	33186024	B752	B752	PHX	PHX07R	.BLH_GEELAS..
AWE12	0	33183317	A320	A320	PHX	PHX08	.WOTRO_MAIERS..
AWE158	564	33185296	A319	A319	PHX	PHX08	.WOTRO_MAIERS..
AWE183	1142	33186203	A320	A320	PHX	PHX07R	.BLH_GEELAS..
AWE195	0	33185268	A321	A321	PHX	PHX08	.GCK_J96_CIM_ZUN_EAGUL5..
AWE231	1274	33186424	A320	A320	PHX	PHX07R	.BLH_GEELAS..
AWE250	0	33183467	A321	A321	PHX	PHX07R	.BLH_GEELAS..
AWE265	0	33185573	A319	A319	PHX	PHX08	.LBL_FTJ_J244_ZUN_EAGUL5..

Figure 3. The TRAC Data Set Flight Table allows saving the information of the filtered flights in the TRAC or MACS scenario format. Note: only eight of 45 columns are shown.

respective arrival rush was just outside of the respective TRACON meter fix. A link between the time slider and the flight table keeps the data in the table synchronized with the aircraft present at the selected and later times. For example, assume that a flight enters the playback (visualizing the first track-hit for that aircraft in the cm_sim file) at 1:00 a.m. If the time-slider is set to 00:00 a.m. the initialization time in the flight table will be set to 3600 seconds. But when the time-slider, for example, is set to 01:30 a.m. the initialization time in the flight table will be set to zero and its initialization position in the flight table will be set to the current position of the aircraft, opposed to the position where the aircraft first entered the replay. This ‘snap shot’ of the arrival traffic (their locations, their altitude, their flight plans, etc.), was exported as a MACS traffic scenario file. This process was repeated for the other main aircraft groups, with extra care taken to ensure that the time- slider was set to/kept at the same time that was chosen for the arrivals. This guaranteed that initialization positions of all the aircraft were in correct relation to each other.

The exported traffic files contained mostly information that was available in the cm_sim data, with specific columns for departure and destination airports, aircraft type, the filed route, altitude, initial latitude and longitude coordinates, the initialization time of the aircraft, etc. Where possible, other values were computed by TRAC using certain assumptions. For example, indicated airspeed (IAS) was computed assuming a no-wind environment and applying the International Standard Atmosphere (ISA) model. Some fields were set to a default values for all flights.

For example, a column for setting whether an aircraft was in Vertical Navigation (VNAV) was set to TRUE. Some fields however, cannot be assumed, such as an aircraft's altitude target, and were either set to zero or 'NOT_SET'. These exported files were then opened in the MACS scenario editor (Fig. 4), for further editing and manipulation.

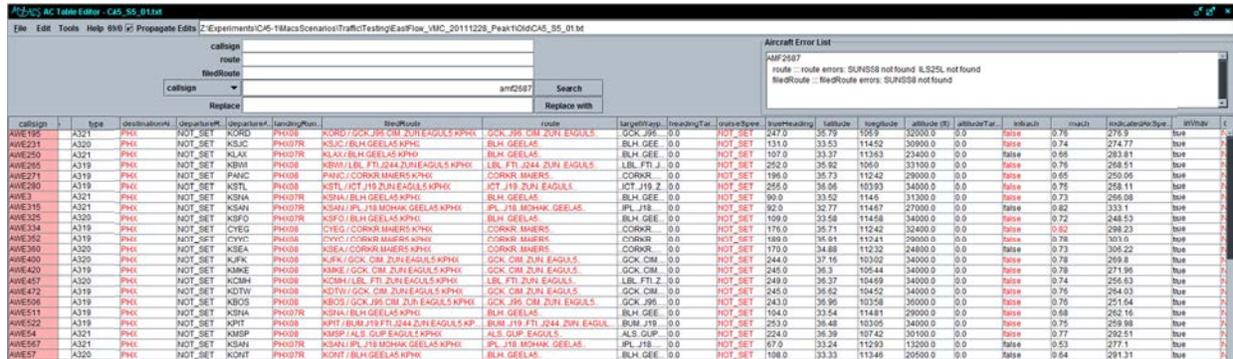


Figure 4. The MACS AC Table editor provides a spread-sheet style interface to the scenario content. Each flight is represented by one row. Cells in red were flagged by the automated error checking feature. Note: only 20 of 60 columns are shown.

B. Main Scenario Design

The next section describes the scenario editing actions that mature the raw traffic scenario to a state at which it can be taken to a distributed simulation environment in the lab for testing and validation.

Before any scenario edits were applied a general decision had to be made, to which degree the raw traffic information in the scenario can be modified, and still meets the goal of capturing the original characteristics of the live traffic recordings as best as possible, while applying the least amount of changes. The *cm_sim* data contains the recordings of live *controlled* traffic. Therefore, the various values for each flight in the raw traffic scenario represent the control actions of the controllers (delay vectors, temporary altitudes), but it is unknown exactly what the clearances were and why they were given. It was agreed, that the focus should not be on trying to edit the scenarios attempting to capture those control actions. On the contrary, the goal was rather to study the control actions of the test subjects, to answer the question how they would control the traffic. The implication of this decision for scenario development was that route, altitude and speed edits were accepted, where necessary, under the premise to stay as close as reasonably possible to the original values.

1. Route Edits

In MACS scenario files two route fields need to be defined. The data in the <filedRoute> column describes the route the ATC host system has available upon simulation initialization. The data in the <route> column describes what the FMS on the flight deck side knows; this is the routing the aircraft is ultimately flying. Those two route entries needed to be validated for accuracy so that MACS can parse them. The values were checked for correct syntax and any offending route tokens.

The arrival and extended-arrival aircraft were assigned a nominal arrival route. In general, this meant that flights were assigned the appropriate route for the aircraft type category and equipage (i.e., jet/turbo, capable of flying area navigation (RNAV) routes), and were routed to the landing runway closest to the direction they came from. Traffic on the approach to KPHX from the north-west were assigned to either the MAIER5 (RNAV) or COYOT2 (non-RNAV) STAR, while arrival traffic from the north-east were assigned either the EAGUL5 (RNAV) or JESSE1 (non-RNAV) STAR. All aircraft from the north were assigned to the 26/08 runway. Arrivals approaching KPHX from the south-west were routed via either the GEELA6 (RNAV) or ARLIN3 (non-RNAV) STAR, and arrival aircraft from the south-east were assigned either the KOOLY4 (RNAV) or SUNSS7 (non-RNAV) STAR, all of which were assigned the 25L/07R runway.

Figure 5 and Fig. 6 use AMF2687 as an example. Besides listing any error for a flight record in the aircraft error list (cf. Fig. 4) MACS also provides details on detected errors when the mouse is hovered over a field that is highlighted in red font.

Three delimiters are used to describe a route. A “.” indicates that the next item is a fix. The “/” means that the next item is not a normal fix but a named collection of fixes (or a part of that name). A defined name could be STARs, standard instrument departure (SID) routes, jet routes, etc. Their definitions are saved in MACS airspace adaptation files. The “/” is what is used as a convention to separate out the departure airport from the rest of the flight plan. The objective for the current design process is to have the <filedRoute> represent as much as possible the full pre-departure filed flight plan. The <route> column represents a truncation of the <filedRoute> including only route tokens that the aircraft will actually pass during the simulation.

The black box in Fig. 6 shows the errors that were found for the <filedRoute>. In this case MACS does not know about the jet route J92 and about the STAR SUNSS7. MACS also does not accept duplicate entries. To fix those errors, first all entries for J92 were deleted. In this case the deletion of J92 did not impact the aircraft route, because the next downstream point from its initialization location is the fix TUS (cf. Fig 5). If the offending route tokens are downstream from the initialization position, and if their deletion impacts how the flight traverses the test sectors, then one attempt to fix the route is to replace them with the individual waypoints that comprise the named token. For example, if a flight is filed to use J72 entering at ABQ and exiting at BLD (i.e., ..ABQ.J72.BLD..) and if J72 happens to be unknown to MACS then it could be replaced with (some of) its waypoints (i.e., ..ABQ..LORAT..GUP..PGS..BLD (cf. Fig. 7).

For arrival aircraft the adapted arrival routes begin in the high-altitude test sectors. Therefore, if a route token is unknown and has to be deleted, the route of a flight through the test sectors would change very little, if at all. Figure 8 shows an example. COA1707 is filed to fly KIAH./JCT.J86.ELP.J50.SSO.KOOLY4.KPHX. Assume J50 is not known to MACS. If deleted, as it was done for COA1708, it would only bypass the waypoint ALIBY, and enter the test sector 90 just a bit north of where it would have originally. Again, the waypoints of an unknown route, ALIBY in this case, can also be entered specifically into the filed route.



Figure 5. A graphical representation of the filed route for AMF2687.

filedRoute	route
MMHO./XHMO.J92.VYLLA.J92.TUS.SUNSS7.KPHX	..XHMO..J92..VYLLA..J92..TUS..SUNSS7..
<div style="border: 1px solid black; background-color: black; color: white; padding: 2px; display: inline-block;"> J92 not found J92 not found SUNSS7 not found J92 is duplicated </div>	
MMHO./..VYLLA..TUS.SUNSS8.KPHX	..TUS.SUNSS8.FINAP.ILS25L

Figure 6. The MACS error feedback feature provides pointers on which route elements are erroneous.

If MACS reports an error about duplicate entries, as shown in the example of AMF2687, the one entry that is closest to the origin airport was deleted, as it most likely does not affect how the aircraft is actually flying through the test sectors; the graphical representation of the <filedRoute> in the Scenario Editor provides an easy way to verify the route. In the example J92 is unknown to MACS and so all J92 tokens were deleted.

The last token that is labeled as an error in the example above is the STAR SUNSS7, because the MACS adaptation listed this STAR under a custom name (SUNSS8), which was a modified STAR in support of ATD-1. In other cases STARs may get flagged as error because they were not adapted (for example for airports other than KPHX), or the actual published routes were updated and received different name since the recording date of the cm_sim data. Because AMF2687 is initialized close to TUS and flies straight towards it (cf. Fig. 5), the fix VYLLA (behind of the aircraft initialization position) is removed from the <route> entry. Individual cells or entire columns can be set to be auto-update depending on the entries in other columns. The <targetWaypoint> column was set to

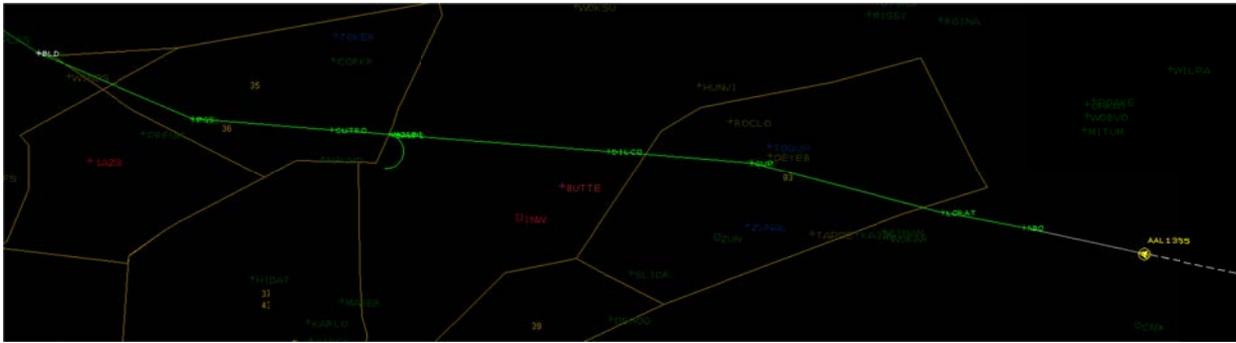


Figure 7. Jet route J72 connects the nav aids and fixes ..ABQ..LORAT..GUP..PGS..BLD



Figure 8. The lateral impact on a flight path when omitting a route element. COA1707 and COA1708 have identical filed routes except that for COA1708 after the nav aids ELP the jet-route J50 was omitted.

auto-update, with a dependency linking it to the <route> column. Therefore, the update of the <route> for AMF2687 automatically triggered the correct waypoint name to be entered into the respective <targetWaypoint> cell.

2. Initialization Point and Altitude Edits

To provide the desired realism for the upcoming ATD-1 simulations, a key aspect of the scenario design was to closely match real-world traffic situations. Because the ATD-1 project is focusing on arrival operations, the initial flight state of the arrival traffic to KPHX in the scenarios needed to model the respective flight state of the raw traffic as close as possible. Therefore, the initialization latitude and longitude values, and initialization times of the flights of the peak arrival rush and the additional arrivals were kept constant in the scenarios, even if the initialization position of the flights were off-route. Because the flights were initialized in VNAV, they generally were back on their route quickly. Some aircraft were exempt from this constraint. Those special cases are explained in section III.B.4.

Retaining the actual initialization positions for over-flight traffic was less critical, as long as the interactions with the traffic streams in the test sectors were not altered significantly. The initialization positions of the over-flight traffic were adjusted to align with the respective filed route.

The altitudes of the arrivals and extended arrivals were kept constant also, with few exceptions. Values were modified if they did not comply with the direction of flight or if they needed to be rounded to the nearest flight level. Because the cruise altitude and target altitude fields were set to auto-update, they were modified when the respective altitude value was edited. The cruise altitude of some flights, especially those not in cruise upon scenario initialization, was verified by bringing up the respective trajectory profile in TRAC. For flights in cruise, before top of descent (TOD), all three altitude values matched. For flights in descent the altitude target, that is, the altitude to which the aircraft will climb or descend after initialization, was set to the first downstream altitude restriction. For all flights but the departures value in the start point name column was auto-updated based on the values in the latitude and longitude column. For the departures the start point name was set to the name of the respective departure runway; the latitude and longitude values were filled in automatically. Exceptions were flights that

departed KPHX but were airborne already. The altitude values for the departures that were still at KPHX at their initialization was set to the runway altitude, and their altitude target was set to their cruise altitude.

The initialization points of over-flight traffic were eligible to be modified. Over-flights were moved onto their filed route using an automated function. For some aircraft the flight path would change significantly. In order to avoid that, an additional (published) waypoint before the initialization position was inserted into the filedRoute. After moving the flight onto its filed route it remained close to its original initialization position.

3. Speed Edits

The next scenario building step was to update or correct the speed values of the flights. The decision making process on which speeds needed to be set to which value is depicted in the flow chart in Fig. 9. The IAS and the Mach number are directly linked to each other; editing one value in MACS will set the other one to be auto-updated. The <inMach> column indicates if a flight is flying mach speeds upon initialization. The AC Table editor will set the cells in this column to true if the aircraft is higher than 29000 ft.

For flights in cruise a typical cruise mach numbers or, if lower than 29000 ft, a typical cruise IAS was used (often internet lookup). Both the speed target, which is the speed to which the aircraft will accelerate/decelerate after initialization, and the cruise speed values were set to the same value for aircraft that are initialized before their top of descend (TOD). Descending flights would get assigned a typical cruise mach number if they were higher than 29000 ft. If they passed that altitude already they would get assigned a typical cruise IAS, unless they are already past a waypoint with a speed restriction. In that case, the flight would get assigned the IAS of that restriction; the speed target value was set to the next downstream speed restriction. Departures that are still on the ground at KPHX got assigned an IAS of zero. The IAS of KPHX departures that were initialized airborne and are in their climb phase was set to their climb speed (the <climbSpeed> column was set to auto update). Their speed target value was set to their cruise speed value.

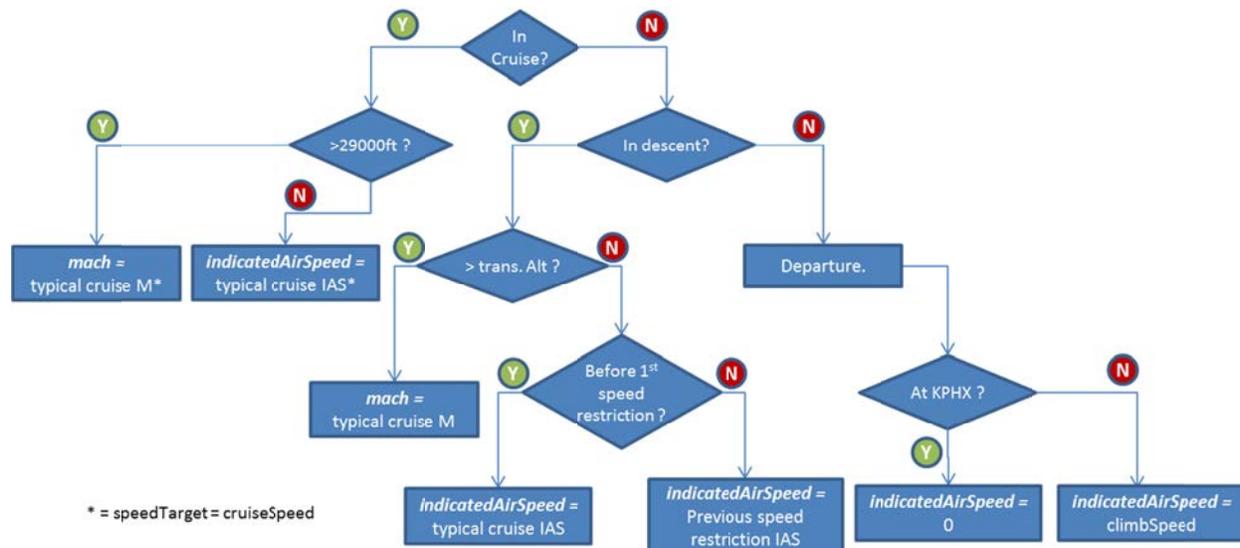


Figure 9. Decision tree for assigning the indicated air speed and mach values

Later in the scenario design process the speeds were updated using a different speed assignment strategy. MACS supports the use of cost index (CI). It is used for various trajectory computations. The CI is a factor that indicates the balance between speed and fuel efficiency. A CI of 999 gives speeds as fast as possible without consideration of fuel, while a CI of zero gives maximum efficiency.

The CI in MACS is used in the scenario editor to compute the cruise, descent and climb speeds. Together with the altitude all other altitude and speed values were updated automatically and the manual lookup of typical speeds and altitudes was rendered obsolete; using the CI all values were computed by MACS. The approach speed and landing speed values were kept at 140 kts and 120 kts, respectively. The MACS auto-fix function was applied if those values were flagged as error. Before setting a CI value however, the auto update references of the various columns had to be verified. The diagram in Fig. 10 is explaining the selected auto update dependencies. A CI of 100 is commonly used by the airlines. Setting the CI to this value provided typical speed values.

4. Moving initialization positions into ZLA

Cm_sim data is recorded for each Air Route Traffic Control Center (ARTCC). Because KPHX is on the west side of ZAB (cf. Fig. 1) the first traffic state data available is just before the Center boundary. This meant that traffic was initialized inside the ZLA test sectors and/or just outside the ZAB high-altitude test sectors leaving little to no time for the controllers to condition those flights before they enter their airspace or, before they needed to be handed

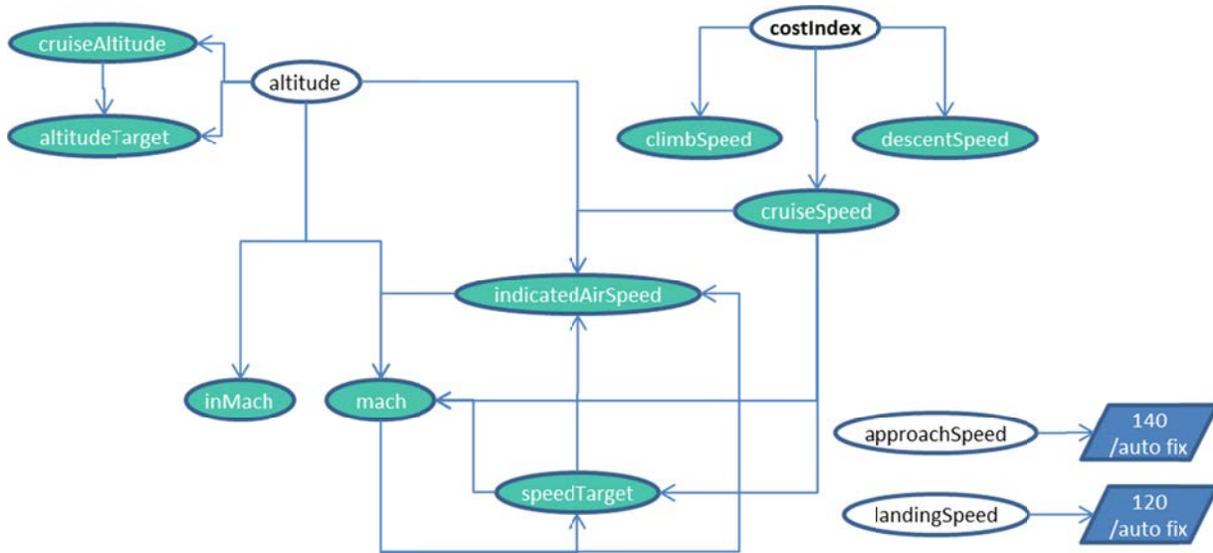


Figure 10. Auto update dependencies of the MACS AC Table Editor set during current scenario development process.

off to the next sector. Consequently traffic entering ZAB airspace from the west was backed up into ZLA airspace. The cm_sim files from ZLA for the respective traffic days were used to obtain the flight plan and state information for the various flights that needed adjustment.

Because CIDs are re-issued in every Center, it was not possible to use a call-sign-CID combination to create a unique identifier to find exact matches for the flights of the ZAB and ZLA cm_sim data files. TRAC was used to parse out of the ZLA cm_sim file flights with matching call-signs. In a second step MS Excel was used to lineup the flights using the origin and destination airport information. The flight plans from the ZLA cm_sim file were then copied over the corresponding flight plans in the existing traffic scenario files which were created based on the ZAB cm_sim files. The filed route and route entries were checked again for errors and updated as described above.

Next, the flights entering ZAB from the west with an initialization time greater than zero were moved along their filed route (using the Move Aircraft function in MACS) towards their origin airport into ZLA airspace. The goal of this scenario editing step was to do this in such a way that the resulting traffic situations resemble the original situation from the ZAB cm_sim file as close as possible. This meant that, if the traffic was not controlled by controllers, the aircraft should be at the same simulation time at their original initialization positions. For example, assume a flight was moved back a distance along its filed route that equates to 500 seconds of flying time. The aircraft now needs to be initialized 500 seconds earlier in order for it to be at its original initialization position at the original simulation time.

After the flights were moved, their start point name and latitude and longitude coordinates were updated accordingly. Also the altitude, altitude target and possibly the cruise altitude were updated if an aircraft was backed up to a position before its top of climb (TOC). Those altitude values were checked if they comply with the direction of flight, up- and downstream restrictions, and whether or not they needed rounding. In a second step, the initialization times of the aircraft were reduced such that the flights arrived at their original initialization positions at the same simulation time.

Caution had to be used to not back up a flight over a distance that corresponds to a flying time greater than the initialization time. With Zero being the earliest possible initialization time, this would result in the aircraft being at the reference point at a different time. If an aircraft was off-route initially, moving an aircraft along its filed route will put the aircraft back onto it. This means that not all original initialization positions as imported from the ZAB cm_sim raw data were maintained. Other traffic that entered the simulation close to the test sectors was backed up from the original initialization locations, too. The same strategy as described above was applied.

5. Sector Assignments

In a last step of the main scenario editing sector ownerships were assigned to the flights. Two columns in the scenarios that is, <ctasSectorId> and <acSectorId>, define the sector assignments. <ctasSectorId> indicates the sector that has track control of the aircraft when it gets initialized. <acSectorId> indicates the pseudo pilot station linked to this sector, that will have ownership of the aircraft. The <acSectorId> was set to be auto-updated by the <ctasSectorId>. Initially, all aircraft were assigned to the Ghost High sector. Then, using the map view of the Scenario Editor the aircraft inside and just outside of the test sectors were selected and assigned to the respective sector number if their altitude was less than the Ghost High floor altitude. Cross-checks of the altitude values against the sector floor indicated flights that had to be assigned to the Ghost Low sector. Lastly, flights assigned to the Ghost High sector with altitudes lower than the sector floor altitude were assigned to the Ghost Low sector. Any flights that have one of the P50 satellite airports as their destination were assigned to the Satellite Ghost controller. Any departures out of KPHX or out of any of the satellite airports were assigned to the Departure ghost controller.

6. ASTOR Scenario Design

The AOL has the capabilities to simulate eight high-fidelity single pilot stations. The ASTOR simulator stations from NASA Langley were integrated with the MACS simulation environment. Flights operated by the ASTOR simulator needed strategic placement in the arrival sequence, and required careful coordination between two file formats: that of the MACS traffic scenarios, and the specific ASTOR scenario format.

As a first step candidate ASTOR flights were identified in the east- and west-flow MACS scenarios. Because the ASTOR aircraft performance model that is recommended for HITL studies emulates the characteristics of a Boeing B757-200 (B752) aircraft, flights using this aircraft type were primary ASTOR candidates. Other aircraft types of the same weight class (e.g., A321, B738, etc.) were also emulated reasonably well using the B752 performance model. Additionally, other constraints had to be met: candidates had to land within one hour of simulation time and needed to be initialized before their TOD.

In the east- and west-flow traffic scenario two KPHX arrivals were B752 aircraft. Several other ASTOR candidate flights in each scenario were identified complying with the aforementioned constraints. Table 1 lists the flights that were ultimately selected as ASTORs.

In the next scenario editing step key aircraft values from the eight ASTOR flights in each MACS scenario were copied to the respective ASTOR scenario file. Those values included call-sign, latitude, longitude, true heading, mach number, altitude, origin, destination, cruise altitude, climb Speed, descent speed, cost index, aircraft type, filed route, target waypoint, and beacon code. Before copying those values, however, the aircraft type of the six additional ASTOR candidates in MACS were set to be B752 aircraft to account for the B752 aircraft model used for the ASTOR simulators. The weight was set to a common cruise weight of 194000 lbs. As a result the speed values of those flights were updated automatically (cells were set to auto-update). The mach values of all ASTOR candidates were rounded to have two digit decimals.

East-flow		
<callsign>	<filedRoute>	<acType>
AWE119	PKOA./FOOTS..FICKY..SXC..TRM..BLH.GEELA6.KPHX	B752
AWE125	PHNL./EDSEL..ELKEY..LAX..TRM..BLH.GEELA6.KPHX	B752
AWE3	KLAX./TRM.J169.BLH.GEELA6.KPHX	A321
AWE158	KLAS./PRFUM.MAIER5.KPHX	A319
AWE271	PANC./WINEN..CORKR.MAIER5.KPHX	A319
AWE54	KMCI./ALS..GUP.EAGUL5.KPHX	A321
BSK610	KCID./RSK.J161.ZUN.EAGUL5.KPHX	B738
AWE265	KBWI./LBL..WILPA..ZUN.EAGUL5.KPHX	A319
West-flow		
DAL2021	KDTW./GCK..CIM..ZUN.EAGUL5.KPHX	B752
N610G	PHNL./EDSEL..ELKEY..LAX.J96.YCDIL.J50.BLH.GEELA6.KPHX	B752
AWE500	KLAX./TRM.J169.BLH.GEELA6.KPHX	A320
AWE197	KSAN./IPL.J18.MOHAK.GEELA6.KPHX	A321
AWE152	KGEG./WINEN..CORKR.MAIER5.KPHX	A321
AWE34	KPDX./WINEN..CORKR.MAIER5.KPHX	A321
AWE191	KPHL./LBL.J19.FTI.J244.ZUN.EAGUL5.KPHX	A321
UPS2876	KSDF./CIM..ZUN.EAGUL5.KPHX	B763

Table 1. ASTOR flights selected for east- and west flow configuration.

Figure 11 shows an example snippet of an ASTOR scenario file. The entries from line 1-23 define database references (routes and airspace), wind file references and define values that are needed to interact with MACS (e.g., the name of the MACS scenario bundle). Lines 26-54 show the entries that define the current and future state of one ASTOR flight, where line 27 defines the initialization state of the flight. Line 33 references the name of a company route (KLASKPHX01) that determines which route the aircraft will actually fly. Some default company routes are provided by the ASTOR system, but in order to retain the original routing from the MACS scenario, custom routes were added.

Some ASTOR flights had an original initialization time greater than zero. To have all ASTOR stations initialize at the same time and, in order to avoid a long wait time for pseudo pilots the respective ASTOR aircraft in MACS were backed up along their filed route the appropriate amount and their initialization times were set to 120 seconds (cf. to Footnote ††). The initialization latitude, longitude and time values were then copied from MACS back to the ASTOR scenarios.

When running the scenario in a human-in-the-loop mode together with MACS, the ASTOR and MACS traffic scenarios get initialized and launched at the same time and play in parallel. To avoid having duplicate flights with the same call-signs on top of each other, the first letter of the call-signs of the ASTOR flights in the MACS scenarios were replaced with an 'X' (e.g., AWE158 → XWE158). Additionally the <entryTimeSeconds> were set to a very high value (e.g., 55555) to move the aircraft out of the simulation, but to keep them as “dummies” in the traffic files for future scenario edits.

C. Scenario Testing and Validation

Before testing the scenarios in a distributed lab configuration the individual scenario files for arrivals, extended arrivals, departures and over-flights were merged into one single traffic scenario file. After the merge a built in MACS scenario editor function was used to probe for any aircraft that are in conflict upon initialization which would leave the controllers no chance to prevent it. After this scenario editing step the scenarios were in a state ready to be tested in lab sessions and simulation shakedowns to gain further controller feedback.

Several lab check-out sessions with researchers only, multiple full-day simulation shakedowns with retired controllers and pseudo pilots, and a full-day meeting with subject matter experts (SME) (i.e., two recently retired P50 controllers) provided valuable insights into the operations of P50 and uncovered a number of issues. Before applying further changes and fine-tuning the scenarios a change control procedure was put into place that kept track of the modifications in the MACS and ASTOR traffic files.

Several important changes were applied to the scenarios after the shakedowns and SME feedback. It was decided to simulate the P50 operations with the north-western Military Operations Area (MOA) around Luke Air Force Base active. This means that the filed route and route entries for all flights crossing that area had to be changed so that this area was not penetrated. Controllers also explained other special use airspace (SUA's) regions around KPHX that had to be taken into consideration. The cm_sim traffic data does not include any information whether or not a SUA area was active or not. The only indicator was if flights were penetrating those regions or not; the reason however were unknown. For the scenario design process and the simulation conduct the following was decided: re-route flights that cross main SUA areas that are active almost all the time. Keep the routing of flights that cross other SUA areas the same. They were considered inactive. Flights that initialize inside a SUA area were considered to have special permission to penetrate that area; no control action to move the flight out of that area was necessary by the

```

1 #_ScenarioInitFile_: CA5-1_ScenarioInitFile
2
3 00:00:00.00>NAVDATABASE CA5_15Nov-10Jan-2013
4 00:00:00.00>NAVDATABASEFILE CE11_nav_database
5 00:00:00.00>NAVDATABASEINIT KPHX_Rwy07R08_database_initialization
6
7 # Winds
8 00:00:00.00>WINDPREDICTED ZAB_20110430_10Z_East_Forecast
9 00:00:00.00>WINDTRUTH ZAB_20110430_07Z_East_Truth
10
11 # MACS items
12 #00:00:00.00>MACSDATABASE PHX
13 #00:00:00.00>MACSEXPERIMENT CA5-1
14 00:00:00.00>MACSCONFIG CA5-1
15 00:00:00.00>MACSBUNDLE Bundles/Datacollection/20130715_Datacollection_Run01_E1.scena:
16 00:00:00.00>MACSMANAGER
17 00:00:00.00>MACSCONTROLLER 8
18
19 # Misc Stuff
20 00:00:00.00>LOG2FILE
21
22 #####
23 01:30:00.00>QUIT
24 #####
25
26 # NASA4
27 00:02:00.00>CRE AWE158 NASA_CMF, 35.827816, -114.61484, 124T, 29000, 0.76
28 00:02:00.00>AWE158 ASSIGN ASTOR4
29 00:02:00.00>AWE158 FPLACTYPE A319/Q
30 00:02:00.00>AWE158 RATE_OF_CLIMB 0
31 00:02:00.00>AWE158 GROSSWT 194000
32 00:02:00.00>AWE158 ZEROFUELWT 170000
33 00:02:00.00>AWE158 COROUTE KLASKPHX01 PRFUM
34 00:02:00.00>AWE158 ORIG KLAS
35 00:02:00.00>AWE158 DEST KPHX
36 00:02:00.00>AWE158 XPDR 1484
37 00:02:00.00>AWE158 DIALDNALT 3400
38 00:02:00.00>AWE158 MCPALT 29000
39 00:02:00.00>AWE158 CRZALT 29000
40 00:02:00.00>AWE158 CLBSPD 279
41 00:02:00.00>AWE158 DESSPD 0.76
42 00:02:00.00>AWE158 PILOTMODEL NORMAL PDS_MANUAL VIA_SPD_WINDOW
43 00:02:00.00>AWE158 COSTINDEX 100
44 00:02:00.00>AWE158 FCCPITCHMODE VNAV
45 00:02:00.00>AWE158 FCCROLLMODE LNAV
46 00:02:00.00>AWE158 EQUIPAGECONFIG EquipageConfig_PIRAT
47 00:02:00.00>AWE158 ENABLEPDSDISPLAYS TRUE
48 00:02:00.00>AWE158 ENABLEPDSMCDUBUTTON TRUE
49 00:02:00.00>AWE158 AOPCONFIG AOP_MANAGED
50 00:02:00.00>AWE158 TCASCONFIG TCAS_for_PIRAT
51 00:02:00.00>AWE158 ADSBCONFIG ADSB_PIRAT
52 00:02:00.00>AWE158 PDSCONFIG PDS_for_PIRAT
53 00:02:00.00>AWE158 RADICONFIG Radio_Default
54 00:02:00.00>AWE158 FFLROUTE KLAS./PRFUM.MAIERS.KPHX

```

Figure 11. Snippet of a ASTOR scenario file.

test subjects. Figure 12 shows the test sector outlines in black and the SUA areas that were considered active with a grey shading. Other SUAs are outlined in red.

KPHX SMEs also pointed out the routing that Group C (Table 2) aircraft typically get assigned.¹⁵ Usually they are handled by the satellite arrival sectors who issue control vectors via specific waypoints and do not use any of the RNAV or non-RNAV routes. The routes of the Group C aircraft in the scenarios were checked for correct routing and were adjusted if necessary. Furthermore, the SMEs pointed out that certain aircraft types that were used in the traffic scenarios were not able to fly RNAV operations. Those aircraft types were simply replaced with similar performing types that are RNAV capable. For example, CRJ2 aircraft were replaced with CRJ9 aircraft.

Group	Aircraft type
Group A	Turbojets (except EA50, C25A/B, E50P, and C500-C551 series aircraft)
Group B	Turboprops (except C208, DHC6&7, P46T and T34T and BE99), EA50, C25A/B, E50P, and C500-C551 series.
Group C	All other aircraft and C208, DHC6&7, P46T, T34T and BE99.

Table 2. Aircraft groups as defined in the Albuquerque ARTCC and Phoenix TRACON Letter of Agreement

Initial shakedown revealed that the initial choice of north/south Ghost Controller split did not work very well. The flight data blocks from the aircraft in in ownership of the ghost controllers would clutter their scope too much. The Ghost High/Low sector split was set up instead. The sector ownerships of the affected aircraft were updated accordingly. Other flights were pointed out by the controllers that suddenly popped up in the sectors. When looking at those flights more closely it became clear that they were mostly departures from satellite airports that climb through the floor of the sectors and should get handed off from the Ghost Low controller.



Figure 12. Restricted airspace regions around KPHX.

7. Little gotchas with big impact

Throughout the main scenario design process and during testing several small errors and problems occurred that affected just a few aircraft but had a larger impact on the whole system; other flights were impacted and therefore controller workload. While some of the errors could be fixed or workarounds could be found by edits in the scenario file itself others would require software changes. In this section two examples are described.

During tests it was noticed that a few arriving flights would descent to their first altitude restriction well ahead of the respective waypoint. Once the flights passed it, they would climb back up to the cruise altitude until descending again. Other flights with a cruise altitude lower than the first altitude restriction would climb to meet this restriction opposed to staying level until intercepting the vertical path downstream (target altitude and cruise altitude were set to the same value as the (current) altitude). In both situations the solution that prevented this behavior was to set the <inVnav> fields in the AC Table Editor to false and have the aircraft fly in flight level change (FLCH) mode. Pseudo pilots were briefed to switch the flight mode for those aircraft back to VNAV at the appropriate times.

Tests also revealed that aircraft that land into the Albuquerque International Sunport Airport would descent, but then get stuck at a very low altitude (about 1600 ft). The flights would not get deleted from the simulation and kept flying indefinitely. Debugging showed that the MACS software confused the destination airport, listed in FAA format (i.e., ABQ), with the Very High Frequency Omni-directional Radio-range (VOR) of the same name. A software update allowed MACS to recognize airport names following the ICAO naming convention. The filed route, route, departure and destination airport entries were updated accordingly. An automated function in MACS assisted with those edits.

D. Scenario versions

In preparation for the most recent CA experiment several data collection and training scenarios were created by using the two original east- and west-flow scenarios as templates. Besides the two original scenarios three additional data collection versions per airport flow configuration needed to be generated to be simulated in four wind environments per arrival direction. To minimize learning effects the call-signs for each flight for each version were modified. TRAC provides an automated function that generates new call-signs for a loaded data set. The function will retain the airline portion of the call-sign, as well as the length of the number string while keeping the first digit the same.

For controller training, scenarios with a reduced traffic load were needed initially. One third of each traffic group was deleted from the two original scenarios. The call-signs were randomized four times for each arrival direction to generate versions for the four wind sets. Finally, in order to further minimize learning effects a small random value was added to the initialization times of the arrival and extended-arrival flights which caused the scenario to play out slightly different. Later in the controller training, the same traffic loads as in the data collection runs were simulated. To generate scenario versions for those later training runs the two original data collection scenarios were used, and the randomized call-signs from the thinned training scenarios were applied. Additionally, new flight initialization times were generated the same way as described above.

Finally, the controllers were supposed to work at least once one of the data collection scenarios to possibly uncover any last scenario problems. To reduce learning effects the call-signs for each flight were randomized once more. All scenario versions were subject to the change control procedure.

The first data collection runs showed that controllers were getting increasingly better in controlling the traffic, and consequently their workload was getting lower. To counteract this trend it was decided to insert additional flights into the arrival rush period of the scenarios. For the east-flow scenarios six additional flights were added, for the west-flow scenarios five additional flights were added. All added flights were duplicates of jet aircraft on the RNAV routes. The remaining runs were sufficient to fill a complete data collection matrix with each of the eight scenario versions simulated once.

IV. Results

This section uses the east-flow traffic scenario to describe example results of the scenario design effort. The scenario building effort required approximately three months to complete, spanning the time from when the traffic days were chosen until simulation conduct. At times, several people worked separately on the traffic files, helping to finish the scenarios in time.

The east-flow scenario (without the additional six flights introduced later on) contained 338 flights. Figure 14-A shows the ratio between the four different flight categories, arrival peak members (ARR), extended arrivals (ARR-EXT), departures (DEP) and over-flights (OVR). The chart in Fig. 14-B shows all aircraft types of the 69 flights in the arrival rush. The most frequently used types are Boeing B737, Airbus A320, and Airbus A319, and Bombardier CRJ9 aircraft.

Figure 15 shows the lateral positions of the peak arrival and extended-arrival flights at the start of the traffic scenario in blue, with the respective original traffic at the correlating point in time of the raw cm_sim data file in red. It shows a near perfect alignment of the raw and simulated traffic in ZAB. The initialization positions of these arrival flights, with few exceptions, have not been altered. On the contrary, arrival flights from ZLA have been backed up along their routes to avoid having flights pop up inside the ZLA test sectors. Therefore, those flights do not lineup initially.

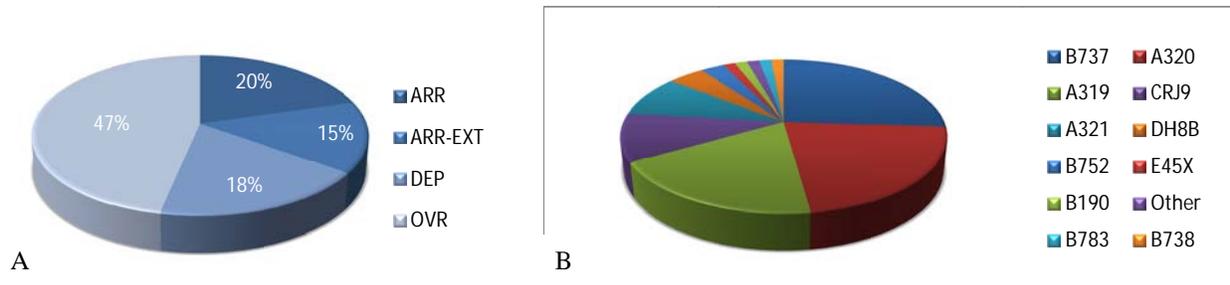


Figure 13. Selected metrics for the east-flow traffic scenario. A) Ratios of arrivals, extended arrivals, departures and over-flights. B) Aircraft types of the 69 aircraft comprising the arrival push

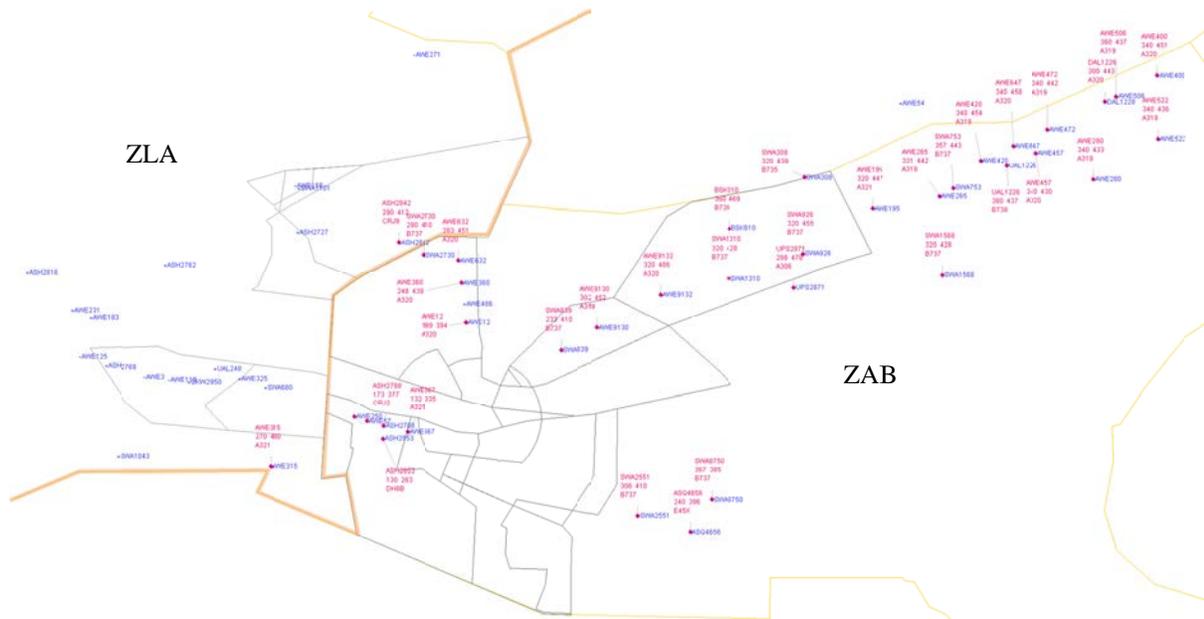


Figure 15. Deviation in lateral aircraft initialization position between the east flow cm_sim raw traffic (in red) and the scenario traffic (in blue). The time stamp at which the traffic was sampled from the ZAB cm_sim raw traffic file was 9:30:02 UTC (cm_sim) which correlated to 120sec simulation time in the traffic scenario.

V. Conclusion

Two base traffic scenarios, including several versions for controller training and for different wind conditions, have been created. The design process was greatly characterized by manual scenario modifications, although the MACS' built-in scenario editor provided a wide array of automated editing functions, such as error checking, auto propagation, aircraft conflict indication, flight position alteration, etc. The complexity of the scenarios was relatively high due to the variety of traffic types included and the restricted ability to modify aircraft initialization positions and routing.

The scenarios were used during the most recent CA HITL simulation and are expected to be used, as-is, during the upcoming simulations. The traffic files serve as a core template for other HITL studies of the ATD-1 effort, but are expected to be modified only minimally in order to allow direct comparison of simulation results as much as possible.

The experiences gained during the scenario design process helped to identify further possibilities to improve the MACS scenario editor. For example, scenario building would be much easier if the editor could know the airspace and route adaptation (STAR-transitions, STARs, approaches, SIDs) that is used during the simulation. Also MS Excel-like multi-layer filtering functions would be a very powerful addition to MACS' AC Table Editor.

In addition, it became obvious that an early in-depth familiarization with the airspace and its operations is essential. Specifically, understanding published operating procedures and letters of agreement, studying maps and recorded traffic, is crucial. Discussions with subject matter experts familiar with the selected site are invaluable and should be performed early. Actual field visits can and should complement the pool of information consisting of the sources just mentioned.

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