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Evaluation of TCAS II Version 7.1 Using the FAA Fast-Time Encounter Generator Model

B.J. Chludzinski

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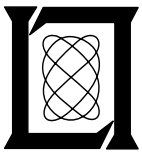
Lincoln Laboratory
MASSACHUSETTS INSTITUTE OF TECHNOLOGY
LEXINGTON, MASSACHUSETTS



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16. Abstract

This report documents the Lincoln Laboratory evaluation of the Traffic Alert and Collision Avoidance System II (TCAS II) logic version 7.1. TCAS II is an airborne collision avoidance system required since 30 December 1993 by the FAA on all air carrier aircraft with more than 30 passenger seats operating in the U.S. airspace. Version 7.1 was created to correct two potential safety problems in earlier versions. The first change focuses on the sense reversal logic. The second change focuses on avoiding "wrong way" responses to Vertical Speed Limit or "Adjust Vertical Speed, Adjust" RAs.

Lincoln Laboratory evaluated the logic by examining more than eight million simulated pairwise encounters, derived from actual tracks recorded in U.S. airspace. The main goals of the evaluation were: (1) to study the performance of the revised sense reversal logic for encounters where one pilot ignores the TCAS advisory; (2) to determine if the revised sense reversal logic has an adverse impact on encounters where both pilots follow the TCAS advisories; (3) to determine if the change from "Adjust Vertical Speed, Adjust" advisories to "Level Off, Level Off" advisories provides a safety benefit for TCAS.

Three sets of encounters were examined in order to fulfill these goals: encounters where both aircraft are TCAS-equipped and both pilots follow the advisories; encounters where both aircraft are TCAS-equipped and one pilot does not follow the advisory; and encounters where only one aircraft is TCAS-equipped. A detailed analysis followed by a summary is provided for each set of encounters. An overall summary is given at the end of the report.

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EXECUTIVE SUMMARY

This report documents the Lincoln Laboratory evaluation of the Traffic Alert and Collision Avoidance System II (TCAS) logic Version 7.1 for encounters designed to stress the performance limits of the CAS logic. These encounters were generated by the FAA William J. Hughes Technical Center (WJHTC) using their Fast Time Encounter Generator (FTEG) simulation.

BACKGROUND

TCAS II is an airborne collision avoidance system required since December 1993 by the Federal Aviation Administration (FAA) on all air carrier aircraft with more than 30 seats operating in the United States airspace. The FAA mandated TCAS II logic Version 6.04a by December 1994 to correct a potential safety problem in earlier versions of the TCAS II logic (6.02 and 6.04). Version 7 was a major revision to the 6.04a logic which was not mandated by the FAA. Version 7 provided enhancements to all major TCAS components (surveillance, Collision Avoidance System (CAS) logic, and displays/aurals). Version 7 is equivalent to the Airborne Collision Avoidance System II (ACAS II), the international version that has been mandated worldwide.

Historically, Lincoln Laboratory has been involved in the testing of the MITRE-developed "CAS logic," the logic that provides threat declaration and resolution. Lincoln Laboratory has collaborated with the FAA William J. Hughes Technical Center (WJHTC) to assess CAS logic performance via stress testing simulations designed to expose the performance limits of the CAS logic. A significant change to the sense reversal component of Version 7, known as CP112E, was proposed in 2004 in response to European observations of weaknesses in the sense reversal logic when one aircraft does not follow the TCAS advisory. In response to this proposal, the Lincoln Laboratory and WJHTC team was tasked to evaluate the revised CAS logic. This report covers only the Lincoln Laboratory evaluation.

It is difficult to design and validate improvements to the TCAS logic. The complex CAS logic has evolved over time. This logic can behave differently from encounter to encounter. In many cases a fix that resolves problems in one type of encounter will unexpectedly degrade the performance of the logic in other types of encounters. Stress testing of the logic is further complicated by the use of some simulated encounters that CAS cannot be expected to resolve (e.g., high vertical rate encounters in which the intruder maneuvers strongly just at the time that TCAS has selected a CAS advisory (see Methodology below)).

This report describes findings based on the analysis of FTEG encounters only. A separate report will describe the Lincoln Laboratory analysis of encounters based on a United States airspace model carried out in parallel with the stress-testing study.

METHODOLOGY

The data analyzed by Lincoln Laboratory were generated by the WJHTC simulation program known as the Fast Time Encounter Generator (FTEG). Approximately 8.4 million pair-wise

encounters were simulated by the WJHTC. The aircraft parameters (e.g., vertical speed, acceleration rates, and vertical separation at planned closest point of approach (CPA)) used by FTEG were designed to include and extend somewhat beyond the typical values seen in the U.S. airspace. The maneuvers of the aircraft were timed to generate worst case situations for TCAS in order to be able to determine the performance limits of TCAS.

Note, this attempt to stress the logic leads to a significant difference between the FTEG and other types of safety simulations whose encounters are derived solely from airspace models. With the FTEG, some number of encounters can be expected to fail, and the goal is to understand and assess those failures rather than to produce a single safety metric. With the more standard safety studies, one would not be attempting to cause TCAS failures, and the goal would be to produce a realistic estimate of risk in a particular airspace.

Programs that were developed during previous logic evaluation efforts at Lincoln Laboratory were modified to operate with the output generated by FTEG after adding CP112E to the Version 7 logic. The performance metric used in all of the analysis programs is the vertical separation between the two simulation aircraft at CPA. Encounters with less than 100 feet of separation at CPA are defined as near midair collisions (NMACs). These encounters are considered failures of the CAS logic. If the planned encounter, i.e., what would have happened if TCAS were not present on the two aircraft, is also an NMAC, the failure is categorized as an unresolved NMAC. If the planned encounter is not an NMAC and the encounter with TCAS is an NMAC, the failure is categorized as an induced NMAC, meaning TCAS caused a failure where one did not previously exist.

CP112E was eventually expanded to include changes to the sense reversal logic for encounters in which reversal RAs are issued and followed appropriately, yet result in smaller vertical separation than if the reversal were not issued. This was sometimes referred to as inappropriate reversal RAs in coordinated encounters. These encounters had not been observed operationally; this revision was based on encounters observed in simulations only.

While the analysis of CP112E was underway, a second revision to the CAS logic was proposed. This revision, known as CP115, changes all corrective vertical speed limit (VSL) RAs to VSL0 RAs. The previous aural “Adjust Vertical Speed, Adjust” (AVSA) is replaced by “Level Off, Level Off” (LOLO). This was followed by CP116, which proposed removing a corrective annunciation and “green arc on weakening” when an advisory weakens solely due to an extreme altitude condition. TCAS Version 7.1 is defined as the addition of these three change proposals to TCAS Version 7.

The analysis in this report is focused on encounters with different outcomes for Version 7 and Version 7.1. These encounters were sorted into “new Saves” (Version 7.1 did not have an NMAC where Version 7 did have an NMAC) and “new NMACs” (Version 7.1 had an NMAC where Version 7 did not have an NMAC). The new NMACs are sorted into groups by encounter class, NMAC type (unresolved or induced), initial aircraft vertical rates, and the sequence of RAs generated by the two aircraft. One representative encounter, termed a Representative NMAC, is selected from each NMAC group for in depth examination. Similarly the new Saves are sorted into groups by encounter class, initial aircraft vertical rates, and the sequences of RAs generated by the two aircraft. One representative encounter, termed a Representative Save, is selected from each Save group for in-depth analysis.

EVALUATION GOALS

The evaluation of Version 7.1 was designed to answer three questions. First, "does CP112E significantly improve the sense reversal logic for encounters where one pilot ignores the TCAS resolution advisory (RA)?" Second, "does CP112E have any adverse impact on encounters where both pilots follow the TCAS advisory?" Third, "does the change from AVSA to LOLO associated with CP115 provide a safety benefit for TCAS?"

RESULTS

During the early evaluation of CP112E Lincoln Laboratory identified unexpected decreases in performance when both pilots follow their RAs. This decrease in performance was traced to the code added to CP112E that was intended to solve the inappropriate reversal RAs in coordinated encounters. Because this component of CP112E was based only on encounters observed in simulations, the designers of CP112E withdrew this portion of the change to avoid delaying implementation of the remainder of CP112E which was based on events observed in European airspace.

To answer the question "does CP112E significantly improve the sense reversal logic where one pilot ignores the TCAS RA," a detailed evaluation of encounters with the Version 7.1 logic was performed comparing the results to those observed with Version 7. The Version 7.1 results for the nonresponding pilot encounters (i.e., encounters where both aircraft are equipped with TCAS and one pilot chooses to ignore the RA) were very good. There are 648 encounters that were NMACs for Version 7 and were not NMACs for Version 7.1. These encounters are called saves. In contrast, there were only 40 encounters that were not NMACs for Version 7 and became NMACs with Version 7.1. These encounters are called "new NMACs." In addition, for encounters with one TCAS equipped aircraft and an unequipped intruder, there are 223 saves and 18 new NMACs. Thus, the answer to the first question is "yes, CP112E significantly improves the sense reversal logic when one pilot ignores the TCAS RA."

To answer the question "does CP112E have any adverse impact on encounters where both pilots follow the TCAS advisory," an overall evaluation was performed on encounters where both pilots have perfect compliance to the TCAS RA. CP112E and CP115 were designed to improve encounters where one pilot ignores the RA so improvements were not expected in these encounters. Indeed, there were no new saves when both pilots follow the RA. Unexpectedly, there were two new unresolved NMACs and 21 new induced NMACs observed in this analysis. A detailed analysis of these 23 new NMACs was undertaken. In most of the new NMAC encounters, one aircraft with a very high initial vertical rate (5000 fpm) was directed by the TCAS RA to reverse its vertical sense. (For example, an aircraft climbing at 5000 fpm was given a TCAS Descend RA.) In these encounters it takes a while to level off and change direction. With tracker lag, these encounters appear to be vertical chase scenarios (i.e., both aircraft moving in the same vertical direction), leading to unnecessary sense reversals generated by CP112E. Twenty one of these new NMACs occurred with a Version 7.1 TCAS reporting its altitude in 100 foot increments and an intruder with Version 7.1 TCAS reporting its altitude in 100 foot increments. Version 7 TCAS units are not often coupled with 100 foot altitude reporting transponders, so the combination of Version 7.1 TCAS and 100 foot altitude reporting transponders is expected to be rare. Thus, the answer to the second question is "yes, CP112E has a small adverse impact on encounters when both pilots follow the TCAS RA. However, the presence of these new

NMACs, while undesirable, is not a cause for alarm given the combination of high vertical rates and uncommon equipage observed in these encounters."

Finally, to answer the third question "does the change from AVSA to LOLO associated with CP115 provide a safety benefit for TCAS," all of the new NMACs and new Saves were studied to determine if CP115 came into play. None of the Representative NMACs for encounters with both pilots following the TCAS RA were caused by CP115. Three of the fourteen Representative NMACs for encounters where one pilot ignores the TCAS RA were caused by CP115. The three Representative NMACs contain a total of four encounters. In the first two cases, the initial LOLO RA caused a different sense to be selected for the subsequent RA, leading to the NMAC. In the third case, the stronger initial RA given by CP115 to a nonresponding aircraft led to a sense reversal, forcing the responding aircraft to reverse sense. This is offset by the fact that ten of the thirty Representative Saves for encounters where one pilot ignores the TCAS RA were solved by the addition of CP115. The ten Representative Saves contain a total of 40 encounters. In most of these cases the stronger initial RA for the nonresponding aircraft allows for a faster detection of nonresponse allowing for a new or more timely sense reversal.

Four of the seven Representative NMACS for encounters with an unequipped intruder were caused by CP115. The four Representative NMACs contain a total of thirteen encounters. In these four cases, the encounters were marginal to begin with and the addition of CP115 changed the timing of the subsequent strengthening RA by one second causing the NMAC. This is offset by the fact that seven of the twenty Representative Saves for encounters with an unequipped intruder were solved by the addition of CP115. The seven Representative Saves contain a total of twenty encounters. In some of these encounters the stronger initial RA made the subsequent strengthened RA more effective. In other cases the addition of CP115 slightly changed the timing of subsequent RAs allowing a necessary sense reversal to occur, or allowing the selection of a more appropriate advisory.

So the answer to the third question is "yes, the change from AVSA to LOLO associated with CP115 does provide a safety benefit." CP115 does cause some unforeseen problems for TCAS in seventeen encounters, but these problems are offset by the sixty encounters that are solved by the addition of CP115.

As mentioned earlier, changes to the CAS logic designed to resolve problems in one type of encounter may unexpectedly degrade the performance of the logic in other types of encounters. One of the most compelling reasons for adding TCAS-TCAS sense reversals to Version 7 was to protect a pilot that is following a TCAS advisory against a pilot that is not responding (either ignoring or moving contrary) to an advisory. The addition of CP112E to Version 7 is a major step toward achieving this goal.

ACKNOWLEDGMENTS

The Lincoln Laboratory Version 7.1 logic evaluation was a team effort and the author would like to thank all of the people involved. Ann Drumm, TCAS project leader at Lincoln Laboratory provided guidance and insight into the TCAS logic. Ann worked tirelessly with Steven George of the FAA Certification Office to convince the RTCA PMC to reconvene SC-147 to address TCAS safety issues that came to light after the implementation of Version 7. James Kuchar, originally a key member of the reconstituted TCAS team, continues to support the TCAS team from his position in the Group 42 Office.

The data used in this evaluation were provided by the FAA WJHTC, with technical lead Kathryn Ciaramella assisted by James Rambone. WJHTC provided copies of their simulation software to Lincoln Laboratory so that a duplicate simulation facility could be set up at Lincoln Laboratory.

Neal Suchy of the TCAS Program Office took over the TCAS program when Steven George left. Neal has been responsible for overseeing this work, keeping the funding solid and keeping the team focused on our goals. His unwavering support of the TCAS team at Lincoln Laboratory is greatly appreciated.

Finally, I would like to thank my husband Joseph and our two sons, Gregory and Jason, who support me and my work at Lincoln Laboratory.

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1. INTRODUCTION

1.1 BACKGROUND

The Traffic Alert and Collision Avoidance System (TCAS) is an airborne collision avoidance system, required since 30 December 1993 by the FAA on all air carrier aircraft with more than 30 passenger seats operating in U.S. airspace. TCAS works by actively interrogating other nearby transponder-equipped aircraft and tracking the transponder replies. For each aircraft TCAS computes a tau value, or time to closest approach. When this value drops below a specified threshold, typically 25–30 seconds, TCAS issues a vertical command, or Resolution Advisory (RA), to the pilot.

There are two levels of TCAS. TCAS II is described above and is the only level discussed in this report. TCAS I is intended for aircraft with 10–30 seats and has lesser capability: i.e., TCAS I issues only Traffic Advisories (warnings) to the pilot, not Resolution Advisories. Both versions display the position of surrounding transponder-equipped aircraft.

The first TCAS versions implemented were 6.02 and 6.04. However, these versions were short-lived, as described in Section 1.1.1. In order to make the operation of TCAS more compatible with the existing air traffic control system, as well as to correct a potential safety problem with unnecessary crossing resolution advisories, all TCAS-equipped aircraft were required to install a new logic version, known as 6.04a, by 30 December 1994.

After the introduction of Version 6.04a, work continued in both the national and international standards communities to monitor TCAS operation and propose changes that would either enhance existing performance or correct problems found. The result of that work was TCAS Version 7 (or "Change 7"), a substantial revision of Version 6.04a, consisting of more than 300 separately defined changes affecting all major TCAS areas. ACAS II, the internationally defined collision avoidance system that was mandated worldwide, is essentially equivalent to TCAS Version 7.

One of the key differences between versions 6.04a and 7 was that in TCAS-TCAS coordinated encounters, the Version 7 logic allowed TCAS to reverse its coordinated RA sense if the encounter geometry indicated that the situation was being degraded. With Version 6.04a, once the coordination had taken place, no reversals were permitted.

Because Lincoln Laboratory had been responsible for development of the TCAS-TCAS coordination logic, Lincoln Laboratory was asked to take an active role in testing MITRE's TCAS-TCAS geometric reversal logic. Lincoln had previously teamed with the FAA's William J. Hughes Technical Center (WJHTC) to perform an overall evaluation of the Version 6.04a CAS logic. This earlier evaluation was the subject of a Lincoln Laboratory Project Report [REF 2], published in February 1996. Lincoln undertook a similar evaluation of the Version 7 CAS logic, with particular attention to the new TCAS-TCAS reversal logic. This evaluation was the subject of a second Lincoln Laboratory Project Report

[REF 1], published in December 1999. This evaluation raised concerns about the TCAS-TCAS reversal logic, but the concerns came too late to be addressed in Version 7. (See Section 3.1.1 of this paper.)

After the introduction of Version 7, the TCAS Program Office at the FAA was phased out. RTCA Special Committee SC-147 was dissolved. No national monitoring of TCAS operation took place in the United States. However, the European component of the international standards community continued to monitor ACAS encounters. They quickly identified TCAS-TCAS encounters where the reversal logic was not performing as expected.

1.1.1 Logic Versions

The original logic mandated was referred to as Version 6.02. Version 6.04, a nonmandated version, was made available in late 1992 and was implemented by a few of the airlines in order to make the TCAS logic more compatible with the existing air traffic control system. Version 6.04 reduced the number of nuisance advisories primarily by reducing the protection volume about the TCAS aircraft and by raising the altitude threshold above which advisories would be issued.

Shortly after the introduction of Version 6.04, a potential safety problem known as the "Seattle encounter" was discovered in both versions 6.02 and 6.04. Version 6.04a was developed to fix this problem. Version 6.04a was mandated in all TCAS installations by 30 December 1994.

Version 7 was a major revision to the Version 6.04a logic. Development on Version 7 started in 1994 as soon as work on Version 6.04a was complete. Modifications to the logic were made in response to Change Request forms (CRFs) and Problem/Trouble reports (PTRs) submitted by the TCAS community. Among the changes were upgrades to the vertical tracker logic. The 100-foot vertical tracker was improved over the tracker used in Version 6.04a. A new tracker using 25-foot intruder altimetry was implemented. These two different trackers gave rise to two different Version 7 logic versions studied: Version 7-100 and Version 7-25.

Version 7 eliminated the three-second RA display deferral logic, meaning that in a simultaneous coordination, if both aircraft selected the same vertical sense, the pilot of the aircraft with the higher Mode S address would see an RA and an immediate reversal of that RA. Also, the ability for TCAS to reverse sense against a TCAS-equipped threat was added. Previously sense reversals were only allowed during the coordination process or against unequipped intruders. In addition to the changes mentioned above, a horizontal miss distance filter was implemented to reduce the number of RAs posted when there was adequate horizontal separation. Also the multiaircraft logic was redesigned.

The newest version of the TCAS logic, known as Version 7.1, is a minor revision to the logic. Portions of the sense reversal logic were modified (CP112E), the "Adjust Vertical Speed Adjust" corrective VSL RAs were replaced by "Level Off Level Off" RAs (CP115) and a change (CP116) was made to remove a corrective annunciation and green arc when an RA weakens solely due to an extreme altitude condition. The technical specification for Version 7.1 is described in RTCA DO185B [11].

In the Version 7.1 logic evaluation described in this report, five logic versions are examined – Version 6.04a, Version 7 using the 100-foot vertical tracker (Version 7-100), Version 7 using the 25-foot vertical tracker (Version 7-25), Version 7.1 using the 100-foot vertical tracker (Version 7.1-100), and Version 7.1 using the 25-foot vertical tracker (Version 7.1-25). The examination of five versions of logic is a bit cumbersome, however all five versions of the logic could be operated simultaneously in the airspace for some period of time, so it is necessary to examine the interactions between versions.

During the Version 7.1 logic evaluation there were many interim versions of the CP112E modifications. In this report there will only be references to the last version of CP112E, namely CP112EV1.2. The CP115 logic change was only studied once because this modification required only a small change to the logic. The CP116 logic change only has an impact on encounters that transition to an extreme low altitude (below 1000 ft AGL). FTEG was not designed to produce encounters at these altitudes; thus, while the CP116 logic change was present in the Version 7.1 code evaluated, it had no impact on the FTEG outputs.

1.1.2 TCAS Development and Testing

During the development of TCAS, through the release of Version 7, MITRE has been responsible for the development of the CAS logic, i.e., the algorithms that perform threat detection and maneuver selection. Lincoln Laboratory has been responsible for the development of the surveillance logic, i.e., the algorithms for maintaining surveillance on other aircraft, and the coordination logic, i.e., the algorithms that ensure complementary maneuvers between two aircraft in an encounter. TCAS Version 7 incorporates Change Proposals 1 through 111.

After the release of Version 7, the TCAS Program Office ceased to exist and CAS logic research and development at MITRE ended as well. RTCA SC-147 was terminated after the 54th plenary session held during June 2001. Monitoring of TCAS encounters within the U.S. airspace was discontinued.

Two significant changes proposed after TCAS Version 7 (CP112E and CP115) were developed by CENA/DSNA, sponsored by EUROCONTROL. One change (CP116) was developed by Lincoln Laboratory, sponsored by the FAA. It is the CAS logic as modified by Change Proposals CP112E, CP115, and CP116 that is the subject of this evaluation.

Testing of the CAS logic is done by means of software simulation of large numbers of aircraft encounters. WJHTC became involved in CAS logic testing to provide an independent check of the performance of the CAS logic and to provide an assessment of the strengths and weaknesses of the logic. In 1991, Lincoln Laboratory was tasked to work with WJHTC to help organize and analyze the large amount of data provided by the WJHTC simulation. The Lincoln Laboratory analysis tools proved to be an excellent predictor of logic problems and have been used to evaluate all versions of the CAS logic beginning with Version 6.04a.

The WJHTC simulation program, referred to as the Fast Time Encounter Generator (or FTEG) was described in detail in [REF 2], Section 2. All encounters run through this simulation belong to one of twenty encounter classes based on, but not limited to aircraft tracks recorded at ARTS sites throughout the United States before TCAS was available. The relative weights applied to encounters in these twenty encounter classes are given in Appendix E. The description of the encounter parameters varied in each of the twenty encounter classes is provided in Appendix A.

The twenty encounter classes are shown in Figure 1-1. The higher numbered encounter classes (10–19) contain encounters where the aircraft do not cross in altitude. The lower numbered classes (0–9) contain encounters where the two aircraft cross in altitude. In Figure 1-1, class 0 appears to be two level aircraft; however there can be vertical rates of up to 400 fpm in class 0.

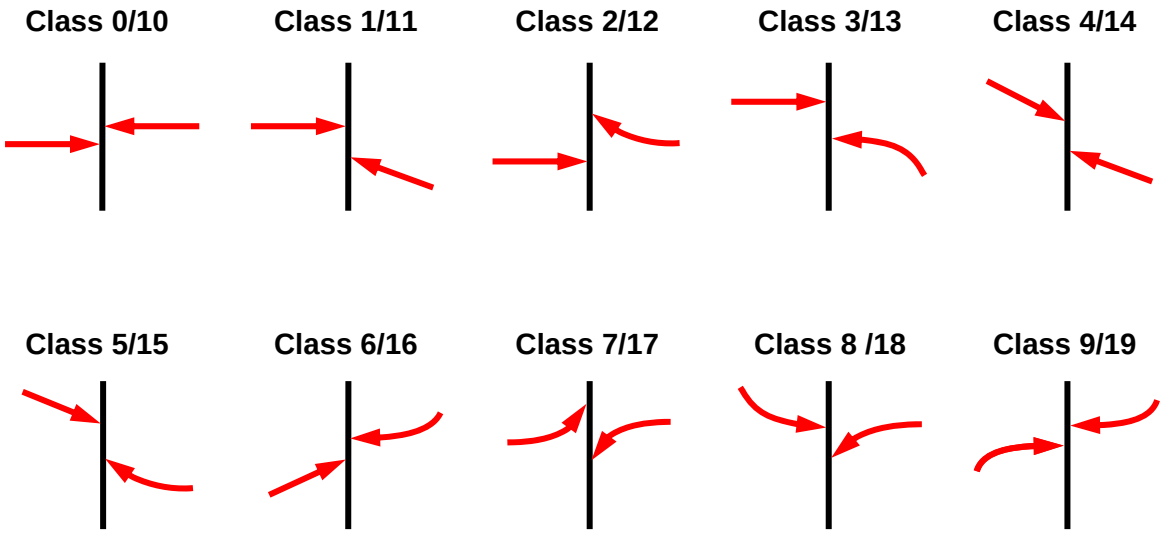

Figure 1-1. Encounter classes (0–9 planned crossing, 10–19 planned non-crossing).

The WJHTC provides Lincoln Laboratory with their simulation source code, simulation input files, and their output file, known as Encounter Recorded Data (ERD). The ERD file contains a condensed description of each encounter run in the simulation.

The six tables below show the combinations of logic version and pilot response used in each of the simulation efforts. An X in a cell means that particular equipage/response combination was run. For example, in Table 1-1, an x in the 6.04a row and Non-TCAS column means that some number of

encounters were run in which aircraft 1 was equipped with TCAS Version 6.04a and aircraft 2 was equipped with Mode C or Mode S.

For all encounters in Table 1-1, Table 1-3, and Table 1-5 both TCAS pilots responded properly to the advisory. In Table 1-2, Table 1-4, and Table 1-6 there were encounters in which one pilot did not respond to (ignored) the TCAS advisory, indicated by PNR (pilot nonresponding) in the input, as well as some encounters where both pilots responded properly to the advisory. The number of encounters run in each of these simulations is described in Appendix B. During the Version 7 logic evaluation the decision was made to collect only the Version 7-25 nonresponding data. This decision was acceptable because the combination of a Version 7 TCAS unit and 100-foot altitude encoding was expected to be very rare. These PNR data were examined to determine if the logic under test improved the protection against a nonresponding pilot.

In the current evaluation, because of the large number of encounters defined and limitations of the number of logic versions per data collection with FTEG, there were ten separate FTEG collection/analysis efforts.

Four collections focus on comparing Version 7 to Version 6.04a. The Version 7 results are used as a benchmark for Version 7.1 performance. These collections are described in Table 1-1 and Table 1-2. The simulations described in Table 1-1 and Table 1-2 were run both at low altitude (below 10,000 feet) and high altitude (above 10,000 feet).

Table 1-1

Baseline Collection, Both Pilots Responding

Dataset 1, Version 6.04a, Version 7-100, Version 7-25

Aircraft 2

Aircraft 1	Non-TCAS	6.04a	V7-100	V7-25
Non-TCAS		x	x	x
6.04a	x	x	x	x
V7-100	x	x	x	x
V7-25	x	x	x	x

Table 1-2

Baseline Collection, One Pilot Nonresponding

Dataset 2, Version 6.04a, Version 7-25

Aircraft 2

Aircraft 1	Non-TCAS	6.04a	V7-25	6.04a PNR	V7-25 PNR
Non-TCAS		x	x		
6.04a	x	x	x	x	x
V7-25	x	x	x	x	x
6.04a PNR		x	x		
V7-25 PNR		x	x		

Four collections focus on comparing Version 7.1 to the last U.S. mandated logic (Version 6.04a). These collections are described in Table 1-3 and Table 1-4. The simulations described in Table 1-3 and Table 1-4 were run both at low altitude (below 10,000 feet) and high altitude (above 10,000 feet). See Appendix B for a breakdown of the numbers of encounters run in each table. See Appendix C for the definition of the equipage pairs run in each data collection.

Table 1-3

Logic Under Test, Both Pilots Responding

Dataset 3, Version 6.04a, Version 7.1-100, Version 7.1-25

Aircraft 2

Aircraft 1	Non-TCAS	6.04a	V7.1-100	V7.1-25
Non-TCAS		x	x	x
6.04a	x	x	x	x
V7.1-100	x	x	x	x
V7.1-25	x	x	x	x

Table 1-4

Logic Under Test, One Pilot Nonresponding

Dataset 4, Version 6.04a, Version 7.1-25
Aircraft 2

Aircraft 1	Non-TCAS	6.04a	V7.1-25	6.04a PNR	V7.1-25 PNR
Non-TCAS		x	x		
6.04a	x	x	x	x	x
V7.1-25	x	x	x	x	x
6.04a PNR		x	x		
V7.1-25 PNR		x	x		

The final two collections omit Version 6.04a and focus on the interoperability of Version 7.1 with Version 7. Table 1-5 describes the interoperability collection with both pilots responding to their TCAS RAs. Table 1-6 describes the interoperability collection with one pilot ignoring the TCAS RA. Due to time constraints the simulations described in Table 1-5 and Table 1-6 were only run at low altitude. The most stressing encounters occur at low altitude with lower time thresholds.

Table 1-5

Interoperability Collection, Both Pilots Responding

Dataset 5, Version 7-100, Version 7-25, Version 7.1-100, Version 7.1-25
Aircraft 2

Aircraft 1	Non-TCAS	V7-100	V7-25	V7.1-100	V7.1-25
Non-TCAS		x	x	x	x
V7-100	x	x	x	x	x
V7-25	x	x	x	x	x
V7.1-100	x	x	x	x	x
V7.1-25	x	x	x	x	x

Table 1-6

Interoperability Collection, One Pilot Nonresponding

Dataset 6, Version 7-25, Version 7.1-25
Aircraft 2

Aircraft 1	Non-TCAS	V7-25 R	V7.1-25 R	V7-25 PNR	V7.1-25 PNR
Non-TCAS		x	x		
V7-25 R	x	x	x	x	x
V7.1-25 R	x	x	x	x	x
V7-25 PNR		x	x		
V7.1-25 PNR		x	x		

1.2 GOALS OF VERSION 7.1 EVALUATION

There were six goals of the Version 7.1 logic evaluation:

1. Study the performance of the proposed CP112E modification to the TCAS-TCAS reversal logic.
2. Study the performance of the proposed CP115 modification to the corrective VSL logic.
3. Do a general evaluation of the Version 7.1 logic, using the Lincoln Laboratory analysis tools, to detect any "areas of concern." This effort primarily checks for areas in which the Version 7.1 logic performance is significantly worse than the baseline Version 7 performance.
4. Many different Versions of TCAS logic will be operating in the airspace simultaneously. Specifically in the United States we will have Version 6.04a (the last mandated TCAS version), Version 7 and Version 7.1. Look for adverse interactions between Version 7 and Version 7.1.
5. Examine the performance of the Version 7.1 logic for the 17 Representative NMACs identified during the Version 7 logic evaluation. Determine if expected improvements occurred.
6. Identify new Representative NMACs and Representative Saves for Version 7.1 for all FTEG simulations, including the encounters against unequipped intruders and encounters where one pilot does not respond to the TCAS RA.

1.3 ORGANIZATION OF REPORT

Section 1 provides background on TCAS development and testing, including descriptions of the two currently deployed versions of CAS logic (Version 6.04a and Version 7) and the proposed update to Version 7 known as Version 7.1. It also describes the major goals of the Version 7.1 analysis effort.

Section 2 describes the programs developed by Lincoln Laboratory to analyze the simulation outputs.

Section 3 provides background information on TCAS-TCAS reversals and describes the two major Change Proposals CP112E and CP115 incorporated into Version 7.1.

Section 4 describes the general evaluation effort.

Section 5 describes a brief study searching for interoperability issues between Version 7 and Version 7.1.

Section 6 describes the outcome of running the Version 7 Representative NMACs with the Version 7.1 logic.

Section 7 describes the Representative NMAC and Representative Save encounters for TCAS-TCAS encounters with both pilots responding to their TCAS RAs, TCAS-TCAS encounters with one pilot not responding to the RA, and TCAS vs. unequipped encounters.

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2. ANALYSIS TOOLS

2.1 OVERVIEW

A block diagram showing the WJHTC simulation facility and the Lincoln Laboratory analysis programs is given in Figure 2-1. There are five analysis programs which have been carried over from previous analysis efforts. In addition, a new technique has been employed which allows merging results from separate data collections for comparative analysis. This technique is described in Figure 2-2. Main inputs to all of the analysis programs are the Encounter Recorded Data (ERD) files from WJHTC. Lincoln Laboratory maintains a duplicate copy of the WJHTC simulation. The simulation can be run for single encounters to produce second-by-second data outputs which are used to generate encounter plots, as well as ERD files necessary for the NMAC analysis program.

The performance metric used in all of the analysis programs is the vertical separation between two aircraft at point of closest approach (CPA). In general, encounters are either acceptable, or not acceptable depending on whether or not the encounter results in an NMAC, or near midair collision, defined as vertical separation of less than 100 feet at CPA.

An important concept in the measurement of performance is the "planned encounter," i.e., an encounter as it would have occurred without TCAS. The "planned" performance of each encounter used by the simulation is generated using a TCAS nonresponding aircraft in an encounter with a Mode C aircraft. This planned performance is compared to the performance of various TCAS equipages to determine if TCAS failed to resolve an existing NMAC (unresolved NMACs) or if TCAS caused an NMAC where none had previously existed (induced NMACs). According to international guidelines, for every 100 existing NMACs, the goal is for TCAS to be able to resolve 90 NMACs without inducing more than 2 NMACs. It is accepted that TCAS will not be able to resolve all NMACs, but there is a very low tolerance for inducing NMACs.

2.2 PHASE I

Referring to Figure 2-1, there are four analysis programs used in the Phase I evaluation of the TCAS logic. The two Reversal Analysis programs were developed specifically for the Version 7 logic evaluation. These programs were described in Reference 1, Section 2.1. The Performance Statistics program and the Hot-Spot program were carried over from the Version 6.04a logic analysis. These programs were described in detail in Reference 2, Section 3. Results from the Phase I analysis are presented in Section 4.

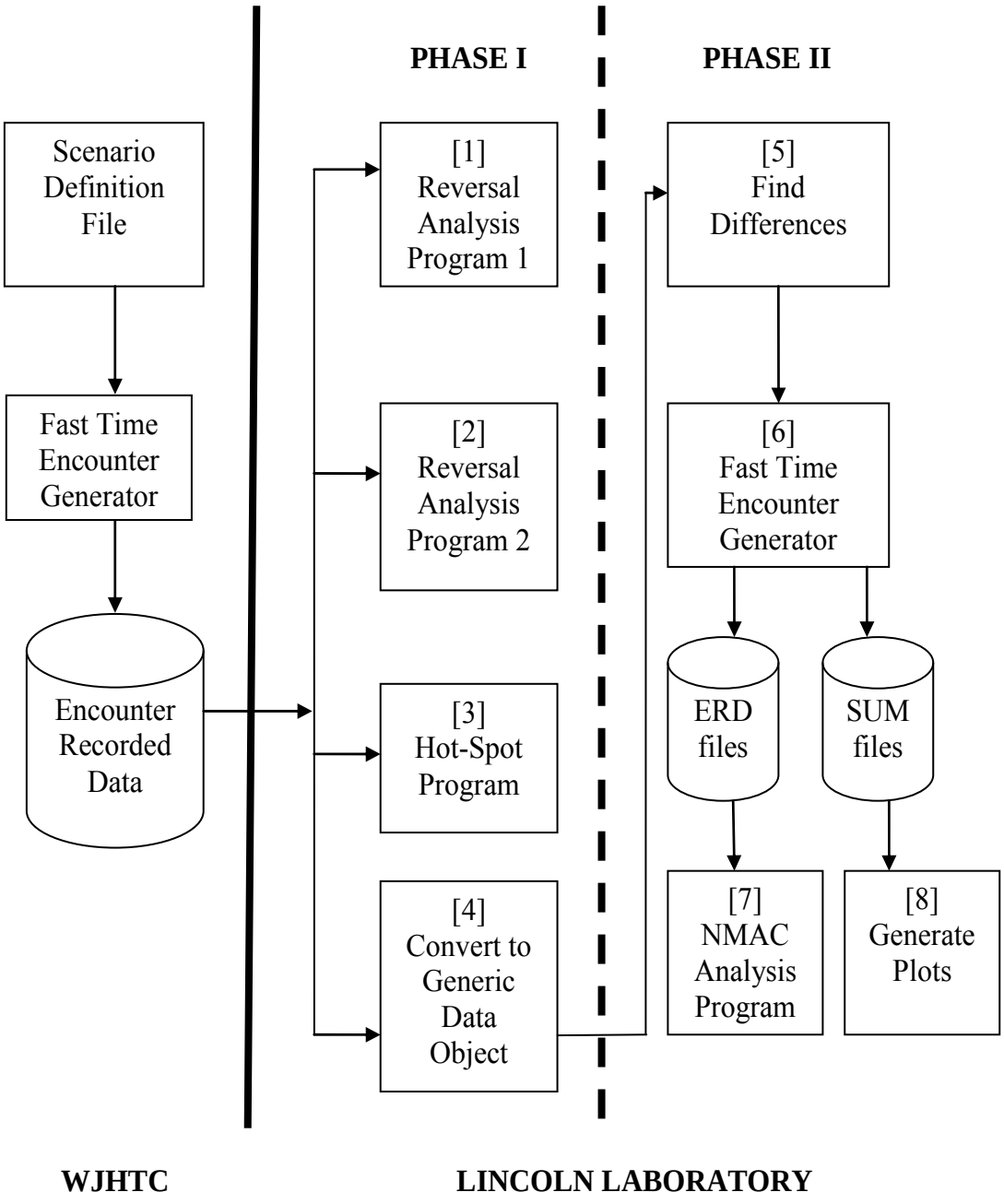

Figure 2-1. Lincoln Laboratory analysis programs.

The Reversal Analysis programs were designed to quickly assess the performance of the reversal logic. Reversal Analysis Program One computes statistics for the behavior of the reversal logic for all equipage combinations, including unequipped aircraft and Version 6.04a. Reversal Analysis Program Two focused on the behavior of Version 7 TCAS-TCAS reversals. Reversal Analysis Program Two uses a metric called the separation difference which is defined as the absolute value of the achieved separation (with TCAS involved) minus the absolute value of the planned separation (i.e., what would have occurred without TCAS). As an example, for a planned separation of –500 feet (meaning aircraft 1 is 500 feet below aircraft 2) and an achieved separation of 400 feet (meaning aircraft 1 is 400 feet above aircraft 2) we get a separation difference of 400–500 or –100 feet; a loss of 100 feet in vertical separation. CP112E is a proposed modification to the reversal logic, including unequipped threats. For this reason, Reversal Analysis Program One provides a more comprehensive view into the behavior of CP112E.

The Performance Statistics program generates statistics on the frequency and outcome of altitude crossing resolution advisories.

The Hot-Spot program generates tables of unresolved and induced NMACs as a function of encounter class (classes 0–19) and equipage pair (Version 6.04a vs. Version 6.04a; Version 6.04a vs. Version 7-100, etc.). This single program can provide useful high-level performance information, both in absolute terms and in relative terms between the different logic versions. The tables identify "hot-spots" or areas of poor performance in a given version of the TCAS logic.

2.3 PHASE II

There are four main steps in the Phase II evaluation of the TCAS logic, as shown in Figure 2-1 (high level) and Figure 2-2 (detail). The first challenge of Phase II, shown in Figure 2-2, is to identify encounters where performance has changed from one version of the logic to another. This process is complicated by the fact that the versions we are trying to compare (Version 7 and Version 7.1) are in different ERD files. Matlab analysis code from another Lincoln Laboratory project was used to simplify this process.

The Phase II analysis begins with step 5 where the ERD files for each logic version were reformatted into Generic Data Object (GDO) files, essentially arrays of variables with meta-data describing the variables (name, attributes, and units). This conversion effort required detailed knowledge of the individual fields of the ERD files to parse the binary data into GDO format.

In step 6 the two GDO files were merged into one larger GDO file containing data for Version 6.04a, Version 7, and Version 7.1. The merged GDO files were then processed to find encounters where Version 7.1 and Version 7 produced different outcomes for the same encounter geometry. The different outcomes were sorted into New Saves (Version 7.1 did not have an NMAC where Version 7 did have an NMAC) and New NMACs (Version 7.1 had an NMAC where Version 7 did not have an NMAC). These are the encounters that are studied in Phase II.

In step 7 the New Save and New NMAC encounters were simulated individually with FTEG generating more detailed output (second by second) encounter summary (SUM) files as well as ERD files for all current versions of the logic as well as the proposed Version 7.1 logic.

In step 8 the ERD files are run through the NMAC Analysis Program. This program is carried over from previous logic analysis work. The NMAC Analysis Program scans through the ERD files produced for each encounter and each logic version, and then provides a summary of key encounter elements, e.g., the sequence of advisories for each aircraft, timing delays in issuing of advisories, the presence of geometric reversals. The new NMACs are sorted into groups by encounter class, NMAC type (unresolved or induced), initial aircraft vertical rates, and the sequence of RAs generated by the two aircraft. One representative encounter, termed a Representative NMAC, is selected from each group for in depth examination. Similarly the new saves are sorted into groups by encounter class, initial aircraft vertical rates, and the sequences of RAs generated by the two aircraft. These groups are further divided by identifying the change proposal (CP112E, CP115, or both) that resolved the NMAC. One representative encounter, termed a Representative Save, is selected from each group for in depth examination.

In step 9, after examination of the NMAC Analysis output, encounters are selectively plotted for each Representative NMAC and Representative Save for the current versions (6.04a and 7) of the TCAS logic, as well as the proposed Version 7.1 logic. This is accomplished using Matlab code to extract the second-by-second data from the SUM files. These plots are used with the output from the NMAC Analysis program to categorize the common features of each Representative NMAC and Representative Save.

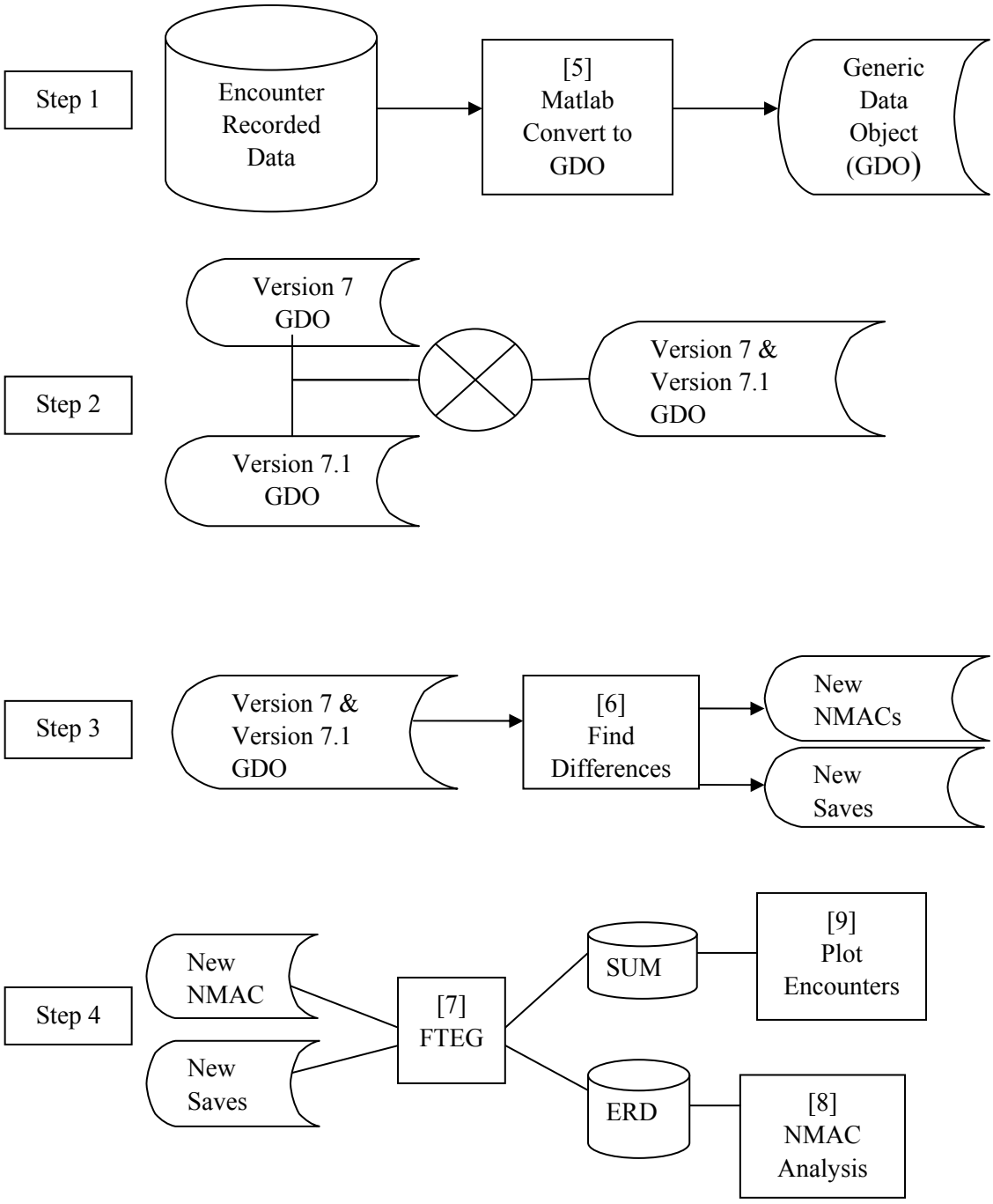

Figure 2-2. Phase II processing.

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3. CHANGES RELATIVE TO VERSION 7

3.1 TCAS-TCAS REVERSALS (CP112E)

3.1.1 Background from Version 7 Study

Version 7 of TCAS II was a significant redesign of the CAS logic. One of the new features of Version 7 was the ability of TCAS to reverse sense against a TCAS-equipped intruder. Earlier versions of TCAS allowed TCAS to reverse sense against unequipped intruders only. The assumption had been that TCAS pilots would follow their advisories and that TCAS-TCAS reversals would not be necessary. The assumption of pilot compliance with all RAs turned out to be false. For Version 7 the TCAS community considered that the ability to reverse sense would provide some protection against a nonresponding intruder, i.e., when the pilot ignored the RA or maneuvered contrary to the RA. This was a major change to TCAS and it was important to show that sense reversals provided a measurable benefit.

Due to its scope, Version 7 was developed in stages, referred to as 'mods,' and each mod was tested as it was developed. Early TCAS-TCAS reversal analysis (Version 7-Mod 10) showed small improvements for encounters with pilots ignoring their RAs, and relatively poor performance of TCAS-TCAS reversals in encounter class 13 (the "Dallas bump up" class) when both pilots responded correctly to their advisories. Alarmingly, TCAS-TCAS reversed encounters tended to lose vertical separation more often than they gained vertical separation.

The next proposed logic change (Version 7-Mod 11) showed dramatic improvement over the Version 7-Mod 10 results. The reversed encounters had fewer separation losses, and those losses were smaller. In addition a significant number of reversed encounters showed gains in separation that were not present for Version 7-Mod 10. Although some concerns remained about the reversal logic, there was agreement that the overall safety performance of Version 7 was significantly better than Version 6.04a. In 1997, with limited time and funding remaining, the TCAS community chose to accept Version 7 with the Mod 11 reversal logic.

Three problems were uncovered during end-to-end TCAS certification testing for Version 7-Mod 11. These problems had to be addressed before the FAA Certification office would approve TCAS units for certification. These problems were uncovered after the in-depth analysis for REF1 was complete.

A subsequent analysis of the proposed solutions to these three problems was undertaken. At that time other less critical change proposals (CPs) were incorporated into the final logic changes for Version 7. This logic is known as TSO-C119B, referring to the name of the TSO for TCAS Version 7. The very high level Lincoln Laboratory evaluation found that the results for TSO-C119B showed no change in NMAC counts for aircraft with 100 foot altitude reporting, and 36 fewer NMACs for aircraft with the 25 foot altitude reporting, compared to Version 7-Mod 11. These results were captured in the Epilogue of REF1. The in-depth analysis was not repeated.

3.1.2 CP112E

3.1.2.1 Emotion-7

In January 2000, a three-year European monitoring effort for TCAS Version 7 began. This effort, the Emotion-7 project (European Maintenance of TCAS II Logic Version 7.0) was sponsored by the EUROCONTROL ACAS Programme. In April 2000, Emotion-7 published their first working paper [REF 3], describing a problem with the TCAS-TCAS sense reversal logic, termed 'issue SA01.' This study indicated that, although the overall safety performance of TCAS II Version 7 seemed to be improved compared to TCAS II Version 6.04a, they observed low safety performance for the new reversal mechanism for coordinated encounters with Version 7 when one pilot did not follow the TCAS RA. In addition when both pilots followed their RAs, induced NMACs could occur that were not observed for Version 6.04a.

By the end of the Emotion-7 project, issue SA01 was expanded to include three distinct components. Issue SA01A involves two TCAS equipped aircraft that are vertically close, with both aircraft climbing or descending toward the same altitude. These are called vertical chase scenarios. In this case one pilot chooses to ignore the TCAS RA and the other aircraft can be prevented from reversing due to the Mode S priority rule (lower Mode S address takes precedence over the higher Mode S address). Issue SA01B involves two aircraft, one equipped with TCAS, the other without TCAS, again both aircraft climbing or descending toward the same altitude. The solution for SA01A and SA01B involves changes to recognize the "vertical chase with low miss distance" encounters and to allow the TCAS logic to determine non-compliance of own aircraft to the RA in order to issue reversals earlier when they can be most effective. Issues SA01A and B were observed in Emotion-7 monitoring data. SA01A and SA01B encounters could not have been identified in the Version 7 FTEG analysis since time and funding constraints limited the in-depth analysis to TCAS-TCAS encounters with both pilots responding to their RAs.

Issue SA01C involves two TCAS-equipped aircraft in an altitude bust scenario. The lower aircraft has a high vertical rate but intends to level-off at a safe separation distance. Due to the high vertical rate the lower aircraft passes its cleared flight level. While returning to the cleared altitude the lower aircraft receives a crossing climb RA. The higher aircraft receives a crossing descend command. Both pilots follow their RAs. In these cases there is an undesirable reversal in a coordinated crossing encounter that leads to an induced NMAC. In SA01C encounters reversal RAs are generated too late to be effective (less than ten seconds before CPA). The solution for SA01C involves changes to prevent issuing RAs close to CPA as these are ineffective. Issue SA01C was not observed in monitoring data; it was observed in simulations only. Encounters similar to SA01C were observed in the Version 7 FTEG analysis in Representative NMAC I14.

Changes to address SA01 came too late to become part of Version 7. Remember SC-147 was terminated by RTCA's Program Management Committee in the summer of 2001, so there was no clear mechanism for addressing these concerns.

3.1.2.2 Safety Issue Rectification (SIR)

In January 2003 after the completion of the Emotion-7 project, a follow-on effort known as Safety Issue Rectification commenced. The goal of the SIR project was to expand and validate CP112 which contained proposed solutions to issues SA01A, SA01B and SA01C. Eventually CP112 was enhanced and became known as CP112E. This effort was finished by the summer of 2004. CP112E Version 1 was documented in Refernce 5 in July 2004. In April of 2004, the 56th meeting of the reconvened SC-147 occurred. At this time MITRE, Johns Hopkins University/Applied Physics Laboratory (JHU/APL), WJHTC and Lincoln Laboratory were able to begin analyzing the impact of CP112E on TCAS Version 7.

3.1.2.3 Safety Issue Rectification Extension (SIRE)

After the SIR project concluded, an additional work package was funded by EUROCONTROL to continue support for CP112E implementation.

Comments from RTCA SC-147 documented in Issue Papers IP-RWG-001 through IP-RWG-009 led to the first major revision to CP112E. CP112E Version 1.1 was documented in Reference 6 in November 2005. Comments relating to CP112E Version 1.1 from RTCA SC-147 were documented in IP-RWG-010 and IP-RWG-011.

During this time members of RTCA SC-147 collaborated to produce a comprehensive document describing the problem with the Version 7 sense reversal logic. This document, RTCA-DO298 [10] provides examples of recorded SA01 events, describes the design principles for CP112E, explains the metrics which measure the safety benefit of CP112E, gives evaluation results from several member organizations, and provides recommendations of a path forward.

3.1.2.4 SIRE+

After the SIRE project, EUROCONTROL funded another work package known as SIRE+. This next revision to CP112E was documented in Reference 7 in May 2006. This version removed the code dealing with SA01C. SA01C was removed because of unexpected decreases in performance with both pilots following their RAs. The SC-147 community decided it was not worth delaying the release of CP112E to fix the SA01C issue which had not been observed operationally.

Based on Lincoln Laboratory and WJHTC analysis of FTEG simulations, there was concern about the relatively poor performance of CP112E below 5000 feet (FL50) when both pilots follow their RAs, possibly due to the lower tau values. At that time a proposal was put forward to shift the 10 to 15 second time window for the initial RA compliance check to 8 to 10 seconds. In addition the code to avoid reversal RAs after increase RAs was removed. This proposed revision was known as mod_3. Analysis of

CP112E+mod_3 was discouraging. As is often the case, mod_3 improved behavior in some encounters, but it caused problems in significantly more encounters.

The final version of CP112E, documented in REF 8 in February 2007, does not include mod_3. It was removed in February 2007 because it had a negative impact on safety performance when both pilots follow their RAs.

3.2 CP115 ADJUST VERTICAL SPEED ADJUST (AVSA)

Opposite initial reactions to corrective Vertical Speed Limit (VSL) RAs were identified in the monitoring data from the Emotion-7 project. Corrective VSL RAs are annunciated to the pilot as "Adjust Vertical Speed, Adjust" (AVSA). The proper response to a corrective VSL RA is always a reduction in vertical speed (a move toward level flight). Several encounters were observed in European airspace where the pilot increased vertical speed, causing further reduction in separation with the intruder aircraft. This issue was discussed at length in the Operations Working Group of RTCA SC-147.

A proposal known as CP115 was put forward to change all corrective VSL RAs requiring vertical rates of 500, 1000, or 2000 fpm to VSL with a vertical rate of 0 fpm. In addition, the ambiguous "Adjust Vertical Speed, Adjust" aural annunciation would be changed to "Level Off, Level Off." CP115 was documented in Reference 9 in May 2007.

The final Version 7.1 FTEG simulations include CP115. We did not expect to see much difference in FTEG results relating to CP115 because it dealt with opposite responses to RAs. FTEG models perfect compliance or noncompliance. FTEG encounters with opposite response to RAs have not been simulated.

4. GENERAL EVALUATION (PHASE I)

4.1 DESCRIPTION

The third goal (see Section 1.2) of the Version 7.1 logic analysis using the Lincoln Laboratory analysis programs was to detect and explain any areas of poor performance remaining in the Version 7.1 logic. These "areas of poor performance" are defined as any encounter class for which Version 7.1 had more NMACs than Version 7.

The following general evaluation results are divided into three main sections: (1) both pilots responding, (2) one pilot nonresponding, and (3) TCAS vs. unequipped aircraft. Each of the three main sections is in turn divided into three subsections, one each for results of Reversal Analysis Program One, Reversal Analysis Program Two, and the Hot-Spot Program. There is a summary at the end of each of the three main sections and an overall summary in 4.2, General Evaluation Summary.

Reversal Analysis Program 1 program produces counts of NMACs for encounters that reversed sense tabulated by encounter class, logic version, and altitude quantization. Results are plotted only for encounters where both aircraft have the same equipage, i.e., the same version of logic and the same altitude encoding (Version 7.1-25 vs. Version 7.1-25: or Version 7.1-100 vs. Version 7.1-100). The terms "low" and "high" refer to the encounters that were run at low altitude (nominally 3,700 and 7,500 feet) and the new set of encounters that were run at high altitude (nominally 15,000 and 21,000 feet) specifically for the Version 7.1 analysis. The results are displayed in this report using four charts. The first two charts show results for aircraft with 25 foot altitude quantization for the encounter classes that planned to cross in altitude (0–9) and for the encounter classes that did not plan to cross in altitude (10–19). The last two charts show results for aircraft with 100 foot altitude quantization for the crossing encounter classes and the non-crossing encounter classes. The 25 foot altitude results are expected to be more favorable than the 100 foot altitude results.

Reversal Analysis Program 2 (Separation Differences) computes the separation difference (described in Section 2.2 above) for all encounters (with and without sense reversals). This program generates results for encounters where both aircraft have the same version of logic, however the two aircraft may have different altitude encoding. For example there will be encounters with Version 7.1-100 vs. Version 7.1-25, Version 7.1-100 vs. Version 7.1-100, Version 7.1-25 vs. Version 7.1-100, and Version 7.1-25 vs. Version 7.1-25. This means the sample space is larger for Reversal Analysis Program 2 than for Reversal Analysis Program 1.

Two sets of four tables are produced for each encounter class. The first set of tables is for encounters with RAs that did not reverse sense. The second set of tables is for encounters with RAs that did reverse sense. Each set contains four tables, showing the number of (1) planned crossing encounters with separation gains, (2) planned crossing encounters with separation losses, (3) planned non-crossing encounters with separation gains, and (4) planned non-crossing encounters with separation losses. These

complete tables are provided in Appendix H for reference. The plots provided in this section focus on losses of separation. The losses tables show the losses in bins of 250 feet. The rows are labeled for the planned separations of 0, 250, 500, 750 and 1000 feet. The columns show the losses in ranges of 0–250 ft; >250–500 ft; >500–750 ft; >750–1000 ft; and 1000 ft.

Within these tables the diagonal formed where the planned separation matches the upper bound of the loss column is called the "critical diagonal." As an example, if the planned separation is 500 feet, and the amount of separation lost is in the bin 250–500 feet, this encounter falls on the critical diagonal. The number of encounters falling on this critical diagonal is shown in the plots for this section.

The Hot-Spot program flags "areas of concern" where one version of TCAS logic has more NMACs than a baseline version of the logic. Version 6.04a is the last version of TCAS mandated in the United States, so information regarding the performance of Version 6.04a is shown for reference. Version 7.0 is used as the baseline logic for this analysis. Information regarding the performance of interim release CP112EV1.2 is shown for reference. The plots in this section are grouped by Unresolved NMACs and Induced NMACs. The percent of NMACs are plotted for encounter classes 0–9 where the aircraft planned to cross in altitude and for encounter classes 10–19 where the aircraft did not plan to cross in altitude. These plots were generated by combining NMAC counts from multiple simulation runs to show overall performance of three versions of TCAS logic at different altitude bands (low and high) and with different altitude quantization (25 foot and 100 foot).

As mentioned in Section 3.1.2.4 the final version of CP112E changes the sense reversal logic for SA01A encounters and SA01B encounters. SA01A encounters have two TCAS equipped aircraft that are vertically close in a vertical chase scenario. In these encounters one pilot ignores the TCAS RA and the other aircraft follows the RA. SA01B encounters have one TCAS equipped aircraft and one aircraft without TCAS. In these encounters the TCAS equipped aircraft ignores the RA. As mentioned in Section 3.2 CP115 involves changes to Adjust Vertical Speed Adjust RAs to prevent opposite responses to AVSA RAs. Simply stated, CP112E and CP115 changes are designed to overcome issues caused by pilots not following the TCAS RA. The "Both Pilots Responding" data collections simulate perfect compliance to TCAS RAs, so we do not expect to see improvements in these encounters. The "One Pilot Nonresponding" and "TCAS vs. Unequipped Aircraft" data collections contain encounters where we would expect to see improved performance due to CP112E and CP115.

Note that the main goal of Version 7.1 was to improve TCAS performance when one pilot does not respond to the RA. Thus, the TCAS community was willing to accept a small degradation in performance when both pilots respond in exchange for a large improvement when one pilot does not respond.

Note also that more attention is paid to induced NMACs than to unresolved NMACS. That is, it is considered worse for TCAS to cause an NMAC when none originally existed than to fail to resolve an NMAC that was present without TCAS.

4.1.1 Both Pilots Responding

4.1.1.1 Reversal Analysis Program 1

A complete set of program results for Reversal Analysis Program 1 for TCAS-TCAS encounters with both pilots responding to their RAs is provided in Appendix G. The histograms provided in this section are derived from these outputs.

4.1.1.1.1 Results for 25 foot altitude

Figure 4-1 and Figure 4-2 show histograms of the Reversal Analysis Program 1 with 25 foot altitude data for Version 7, Version 7 + CP112E V1.2, and Version 7.1. There is no entry for Version 6.04a because TCAS-TCAS reversals were not allowed in Version 6.04a.

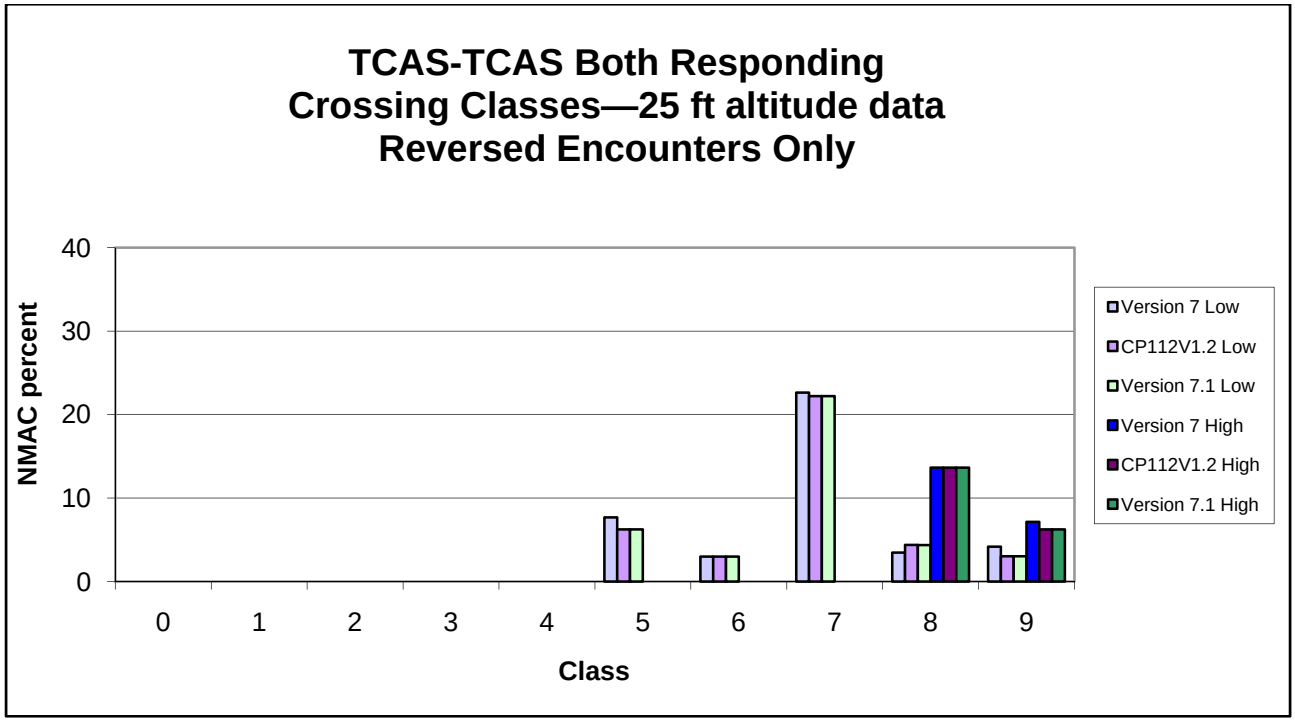

Figure 4-1. Reversal Analysis Program 1, crossing classes, 25 foot altitude.

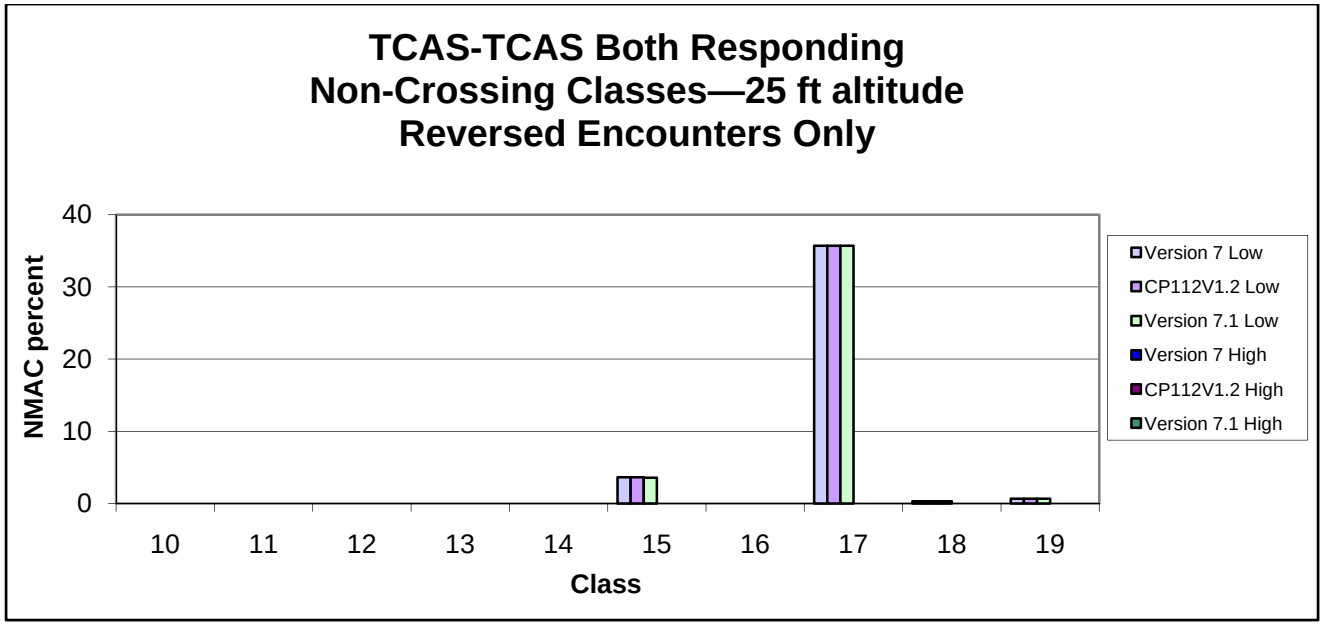

Figure 4-2. Reversal Analysis Program 1, non-crossing classes, 25 foot altitude.

4.1.1.1.1.1 Better

Classes 5-low, 7-low, 9, and 15-low show slightly better performance for reversed RAs with Version 7.1. For these encounter classes the reduction in percent of reversed RAs generating NMACs is entirely due to an increase in the number of reversed RAs, rather than a reduction in the number of NMACs. There are a total of 19 additional reversed RAs in these encounters.

4.1.1.1.1.2 Worse

Class 8-low with 25 ft altitude shows slightly worse performance since the addition of CP112E. For this encounter class there is a small increase in the number of encounters that reversed sense (206) with Version 7.1 compared to Version 7 (202). Two of these new reversals generated NMACs.

4.1.1.1.2 Results for 100 foot altitude

Figure 4-3 and Figure 4-4 show histograms of the Reversal Analysis Program 1 with 100 foot altitude data for Version 7, Version 7 + CP112E V1.2, and Version 7.1. There is no entry for Version 6.04a because TCAS-TCAS reversals were not allowed in Version 6.04a.

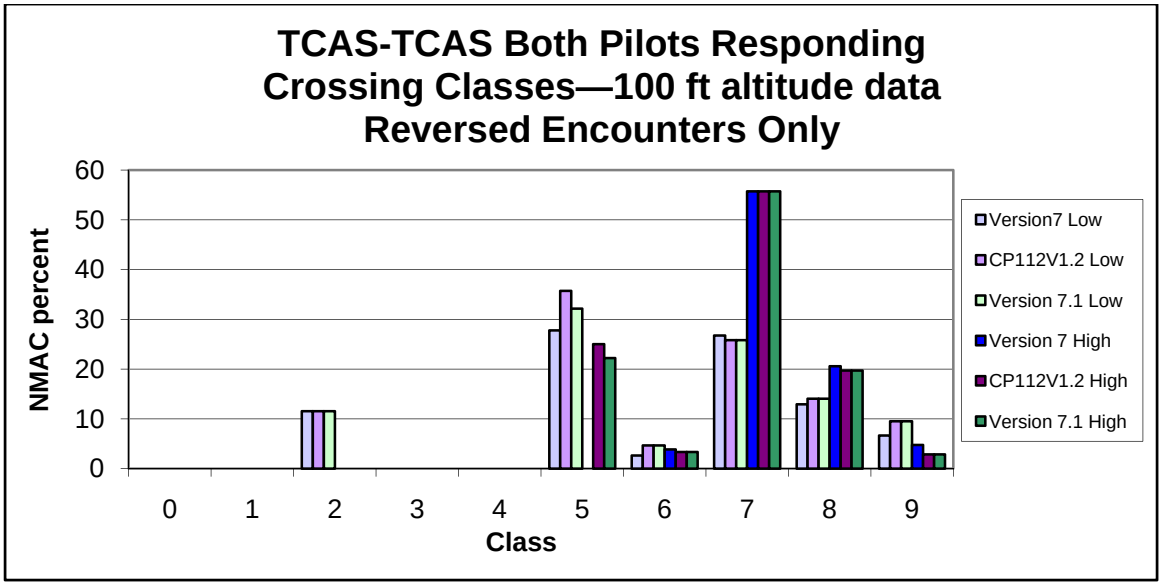

Figure 4-3. Reversal Analysis Program 1, crossing classes, 100 foot altitude.

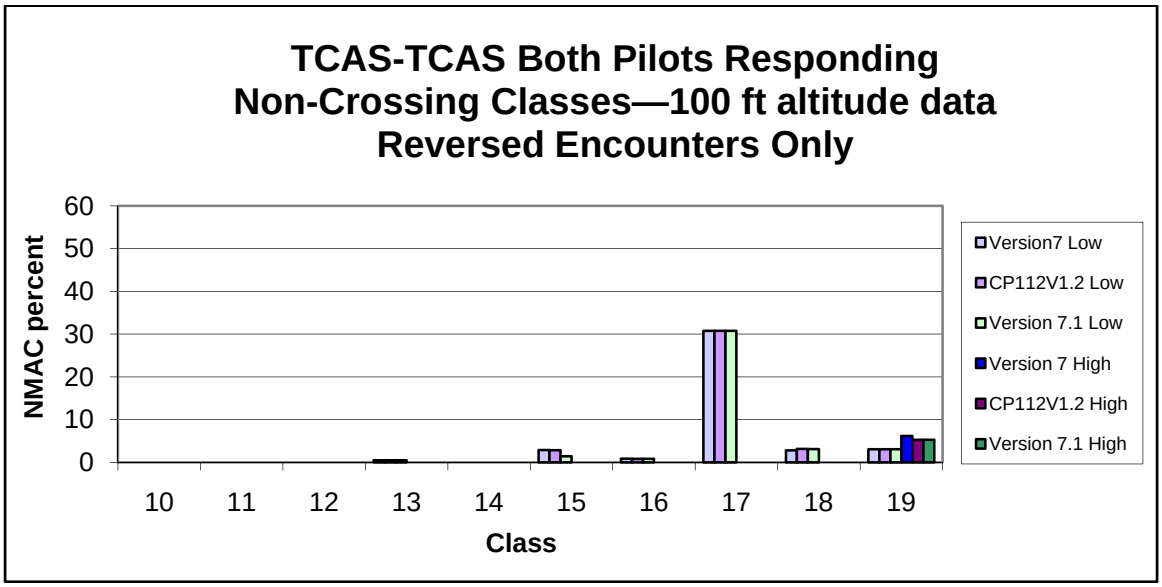

Figure 4-4. Reversal Analysis Program 1, non-crossing classes, 100 foot altitude.

4.1.1.1.2.1 Better

Classes 6-high, 7-low, 8-high, 9-high, 15-low, 16-low, and 19-high show slightly better performance for reversed RAs with Version 7.1 using 100 foot altitude data. For five of these encounter classes the reduction in percent of reversed RAs generating NMACs is entirely due to an increase in the number of reversed RAs, rather than a reduction in the number of NMACs. Encounter class 7-low had 1 more NMAC and an increase in the number of reversed RAs. Encounter class 15-low had 1 additional reversed RA and eliminated one NMAC with Version 7.1.

4.1.1.1.2.2 Worse

Classes 5-low, 5-high, 6-low, 8-low, 9-low, and 18-low 100 foot altitude have slightly more NMACs since the addition of CP112E. Version 7.1 is slightly better than CP112EV1.2. All of the increases in the percent of reversed RAs generating NMACs have a combination of more NMACs and more reversals. This sample represents 20 additional NMACs and 71 additional reversed RAs.

4.1.1.2 Reversal Analysis Program 2—Separation Differences

The plots provided in this section focus on losses of separation. The losses tables show the losses in bins of 250 feet. This number was selected because the planned separations for FTEG encounters vary from –1000 feet to 1000 feet in steps of 250 feet. The rows are labeled with the absolute value of planned separation 0, 250, 500, 750 and 1000 feet. The columns show the losses in ranges of 0–250 ft; >250–500 ft; >500–750 ft; >750–1000 ft; and >1000 ft.

Within these tables the diagonal formed where the planned separation matches the upper bound of the loss column is called the "critical diagonal." As an example, if the planned separation is 500 feet, and the amount of separation lost is in the bin 250–500 feet, this encounter falls on the critical diagonal. The number of encounters falling on this critical diagonal is shown in the plots for this section. It is important to remember that an encounter on the critical diagonal is not necessarily an NMAC.

A complete set of results for Reversal Analysis Program 2 for TCAS-TCAS encounters with both pilots responding to their RAs is provided in Appendix H. The histograms provided in this section are derived from these outputs.

4.1.1.2.1 Nonreversed RAs

Figure 4-5 below shows a histogram of the results from the Separation Differences Program for encounters that did not reverse the sense of their TCAS RA during the encounter. For encounters that do not reverse sense, Version 7.1 exhibits comparable performance or better performance than Version 7.

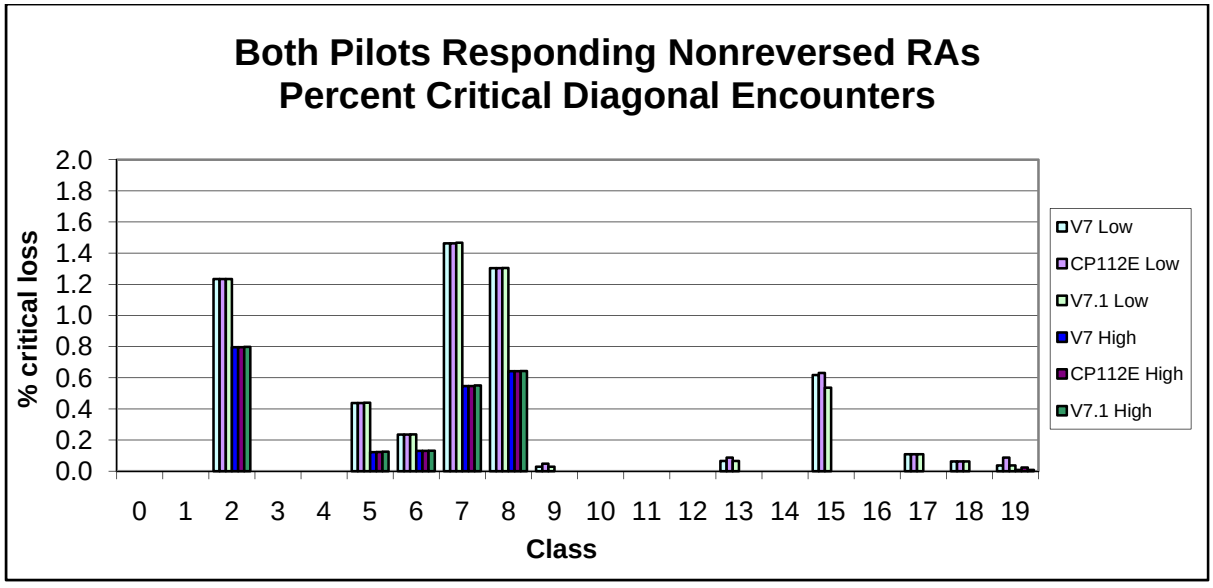

Figure 4-5. Reversal Analysis Program 2, nonreversed RAs.

4.1.1.2.2 Reversed RAs

Figure 4-6 shows a histogram of the Separation Differences Program for encounters with RAs that reversed sense.

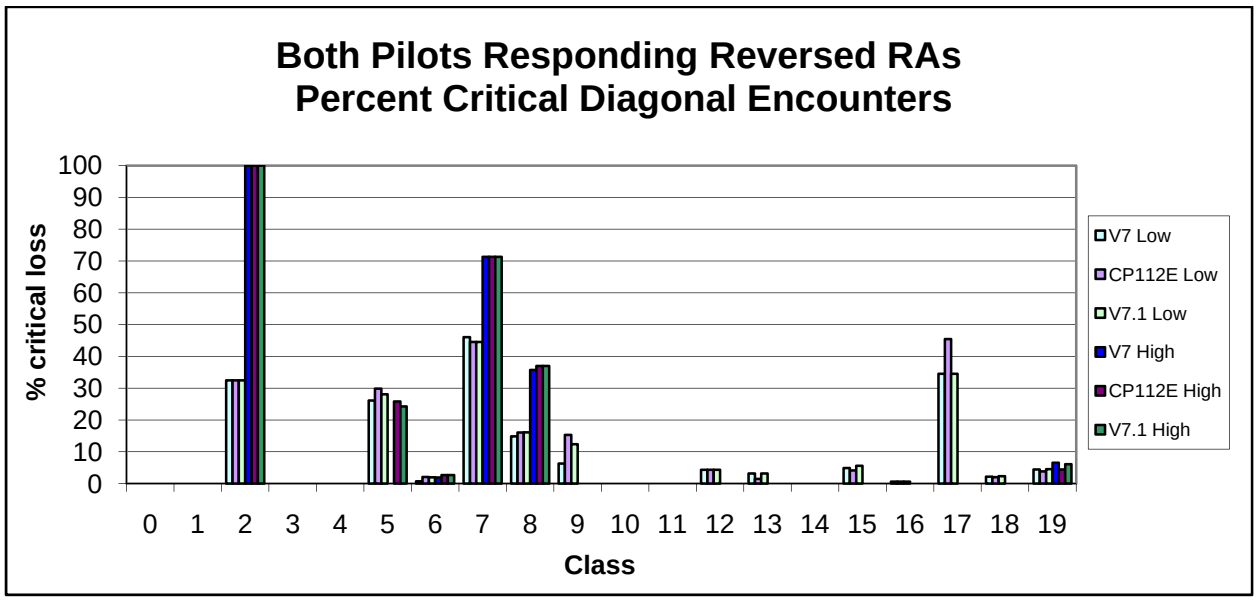

Figure 4-6. Reversal Analysis Program 2, reversed RAs.

4.1.1.2.2.1 Better

Class 7-low shows slightly better performance for Version 7.1.

4.1.1.2.2.2 Worse

Classes 5-low, 6, 8, 9-low, 15-low, and 19-low Version 7.1 show a small increase in the percentage of encounters on the critical diagonal compared to Version 7. For class 5 high altitude Version 7.1 new encounters are observed on the critical diagonal where none are observed for Version 7.

4.1.1.2.3 Combined performance (nonreversed and reversed RAs)

It is important to consider the combination of the reversed and nonreversed encounters for each version of the logic. With logic changes some encounters move from the nonreversed group to the reversed group. In order to accurately measure the value of a logic change, the combined performance is the best metric.

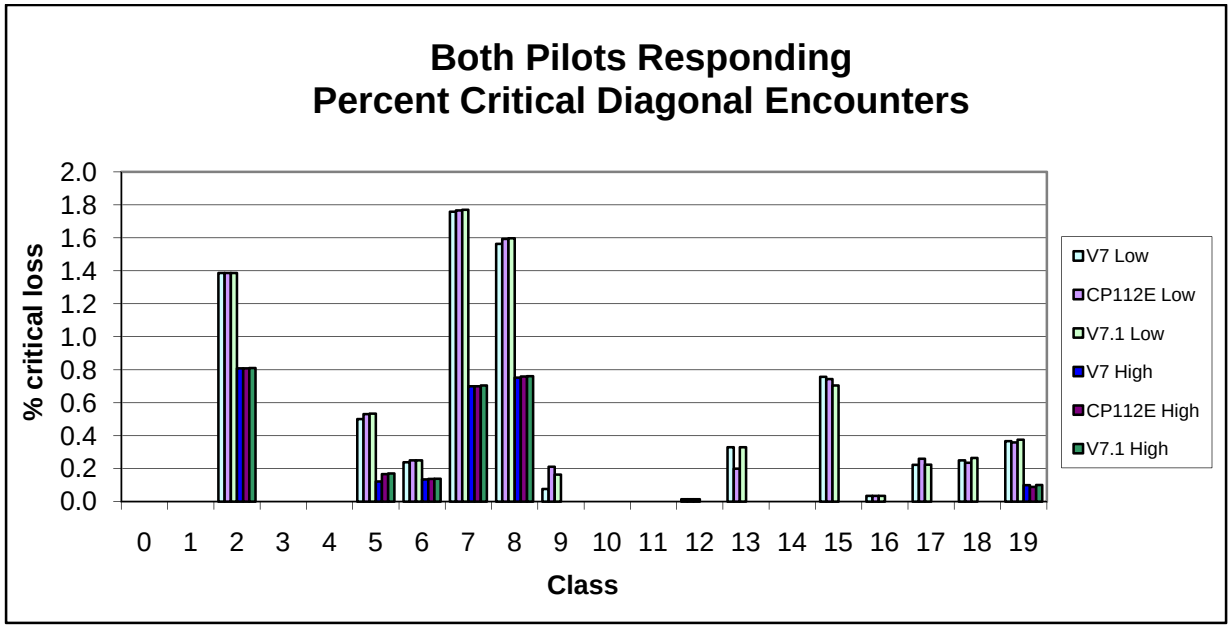

Figure 4-7. Reversal Analysis Program 2, combined performance.

4.1.1.2.3.1 Better

Class 15 has fewer encounters on critical diagonal for Version 7.1.

4.1.1.2.3.2 Worse

Classes 5, 6-low, 7-low, 8-low, 9-low, 18-low, and 19-low show a small increase in the percentage of encounters on the critical diagonal. This increase represents 60 encounters out of approximately 2.4 million scenarios run. Of these 60 new encounters on the critical diagonal 35 represent new NMACs. Note Reversal Analysis Program 1 located 21 new induced NMACs because that analysis was focused on encounters with the same altitude encoding.

4.1.1.3 Hot-Spot Program

A complete set of program results for Hot-Spot Program for TCAS-TCAS encounters with both pilots responding to their RAs is provided in Appendix J. The histograms provided in this section are derived from these outputs. The Hot-Spot tables are generated by combining the relevant cells from the tables produced by the WJHTC Matrix Generator Program. The output of the Matrix Generator program is provided in Appendix I. The results from Version 6.04a and interim release CP112EV1.2 are shown for reference. Comparisons below refer only to Version 7 and Version 7.1.

4.1.1.3.1 Unresolved NMACs

Figure 4-8 and Figure 4-9 show histograms of unresolved NMAC data from the Hot-Spot Program for Version 6.04a, Version 7, Version 7 + CP112E, and Version 7.1.

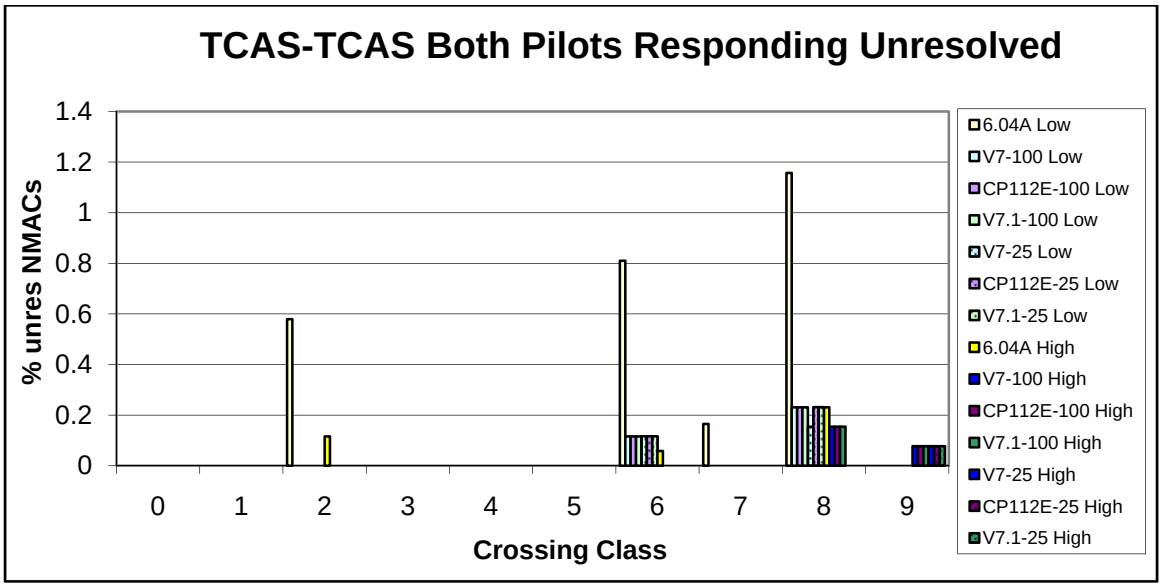

Figure 4-8. Hot-Spot Program, crossing classes, unresolved NMACs.

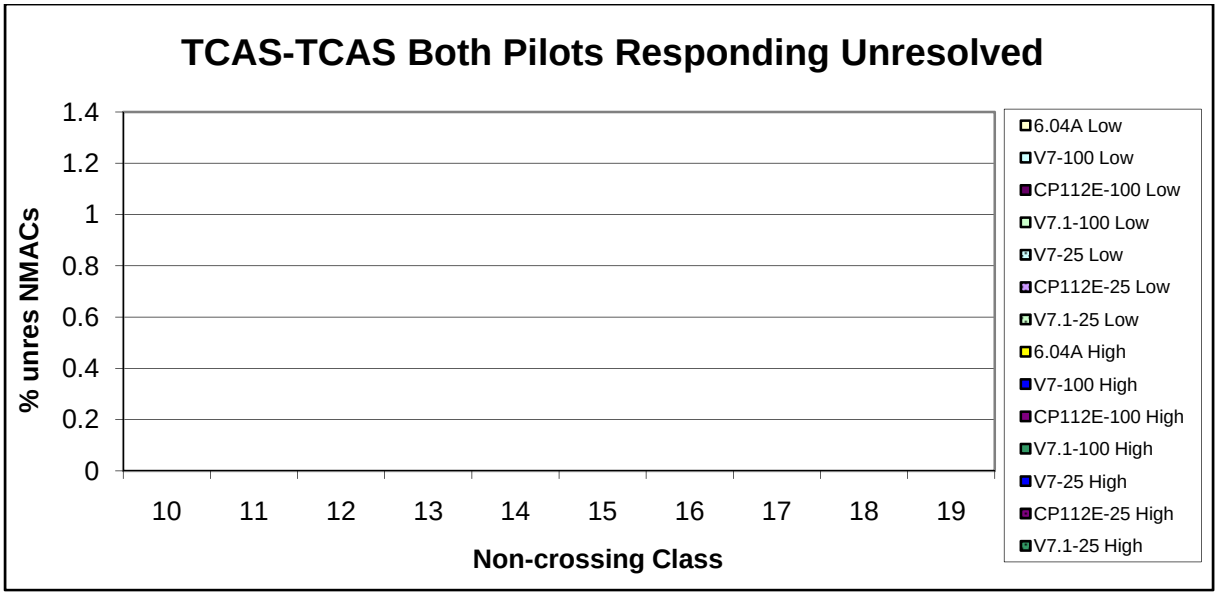

Figure 4-9. Hot-Spot Program, non-crossing classes, unresolved NMACs.

4.1.1.3.1.1 Better

There were no encounters where the performance improved for unresolved NMACs with both pilots responding to their TCAS RAs.

4.1.1.3.1.2 Worse

For class 8 at low altitudes, Version 7.1 has more unresolved NMACs than Version 7 for 25 foot altitude encounters. These two encounters had reversals initiated by the lower Mode S address aircraft. Version 7 did not have reversals for these two encounters. These encounters belong to Representative NMAC Unres1 described in Section 7.1.2.1.

4.1.1.3.2 Induced NMACs

Figure 4-10 and Figure 4-11 show histograms of induced NMAC data from the Hot-Spot Program for Version 6.04a, Version 7, Version 7 + CP112E, and Version 7.1.

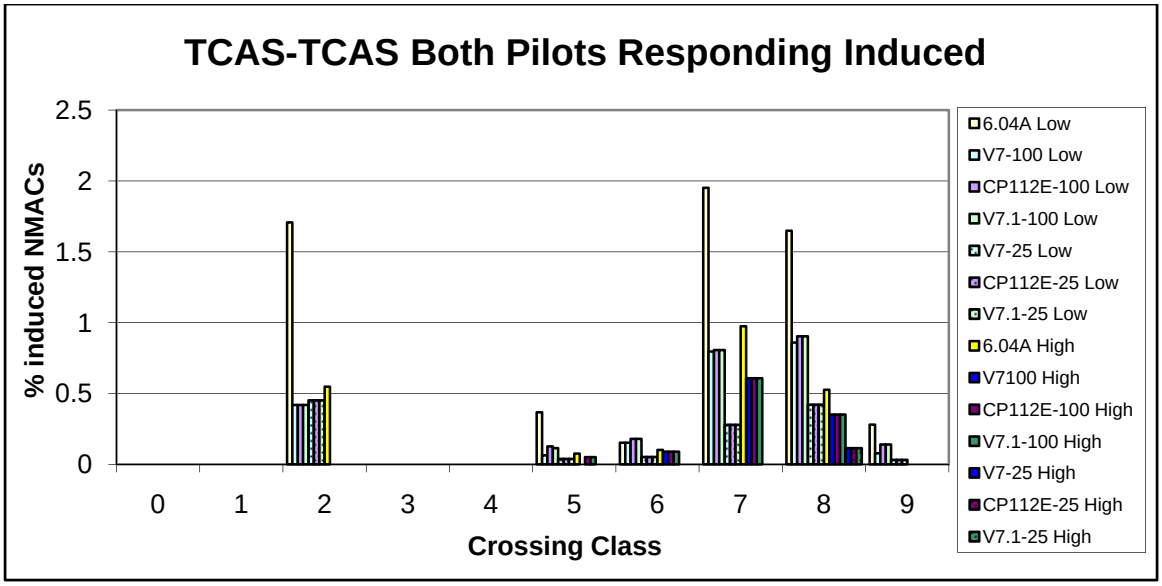

Figure 4-10. Hot-Spot Program, crossing classes, induced NMACs.

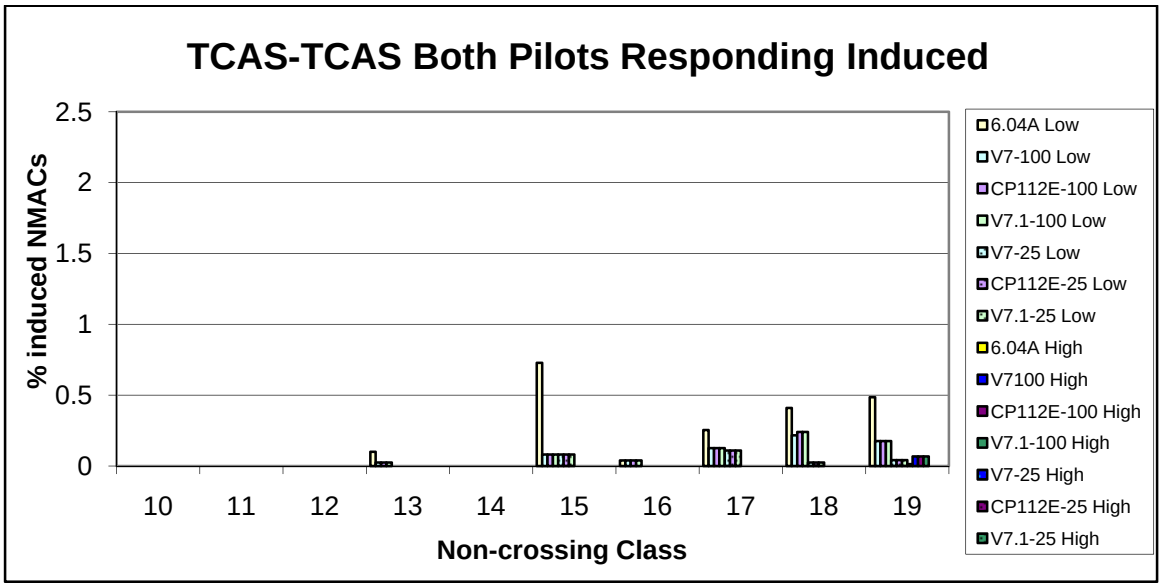

Figure 4-11. Hot-Spot Program, non-crossing classes, induced NMACs.

4.1.1.3.2.1 Better

There were no encounter classes where Version 7.1 had a reduction in induced NMACs for Version 7.1 compared to Version 7.

4.1.1.3.2.2 Worse

For classes 5, 6, 7, 8, 9, and 18-low Version 7.1-100 had more induced NMACs than Version 7. There are a total of 21 new induced NMACs with Version 7.1-100 that were not NMACs for Version 7. All of these NMACs have reversals where Version 7 did not have a reversal. In all 21 cases the same geometry with Version 7.1-25 did not produce an NMAC. These encounters are members of Representative NMACs Ind01 through Ind06, described in Section 7.1.2.2.

4.1.1.4 Both Pilots Responding Summary

As mentioned in Section 4.1, CP112E was designed to improve encounters where one aircraft is not following the RA. In addition CP115 was designed to reduce incorrect responses to corrective VSL RAs. All of the encounters in this section model perfect compliance to the TCAS RA so we did not expect to see improvements in these encounters. We did observe some changes in the percentage of reversed encounters that resulted in NMACs, but these changes were mostly due to changes in the number of reversed RAs, rather than significant increases in NMACs. We did observe 21 new induced NMACs with the Hot-Spot Program.. These will be examined in detail in the Phase II analysis found in Section 7.1.

4.1.2 One Pilot Nonresponding

In the nonresponding data collection any TCAS aircraft with Version 7, Version 7 + CP112E or Version 7.1 equipage are simulated with 25 foot altitude data.

4.1.2.1 Reversal Analysis Program 1

A complete set of results for Reversal Analysis Program 1 for TCAS-TCAS encounters with one pilot not responding to the TCAS RA can be found in Appendix L. The histograms shown in this section are derived from the more detailed data in these tables. Again, this analysis uses only encounters where both aircraft are equipped with the same logic version and use the same altitude encoding.

Figure 4-12 and Figure 4-13 show histograms of the Reversal Analysis Program 1 with 25 foot altitude data for Version 7, Version 7 + CP112E V1.2, and Version 7.1 where one pilot ignores the TCAS RA. There is no entry for Version 6.04a because TCAS-TCAS reversals were not allowed in Version 6.04a.

4.1.2.1.1 Better

Encounter classes 2, 4-low, 5, 6, 7, 8, 9-low, 17-high, and 19-high all have a lower percentage of reversed RAs resulting in NMACs with Version 7.1. Six groups have both a reduction in the number of

NMACs and an increase in the number of reversed RAs. Six groups have a slight increase in the number of NMACs and a more significant increase in the number of reversed RAs. The remaining two groups have the same number of NMACs and an increase in the number of reversed RAs. There are 1564 additional reversed RAs and 4 additional NMACs for this set of encounters.

4.1.2.1.2 Worse

Encounter classes 3-high, 9-high, 15, 17-low, 18, and 19-low all have a higher percentage of reversed RAs resulting in NMACs with Version 7.1. Three of the increases in percent of reversed RAs resulting in NMACs occur where Version 7 does not have any NMACs.

There are 838 additional reversed RAs and 54 additional NMACs for this set of encounters.

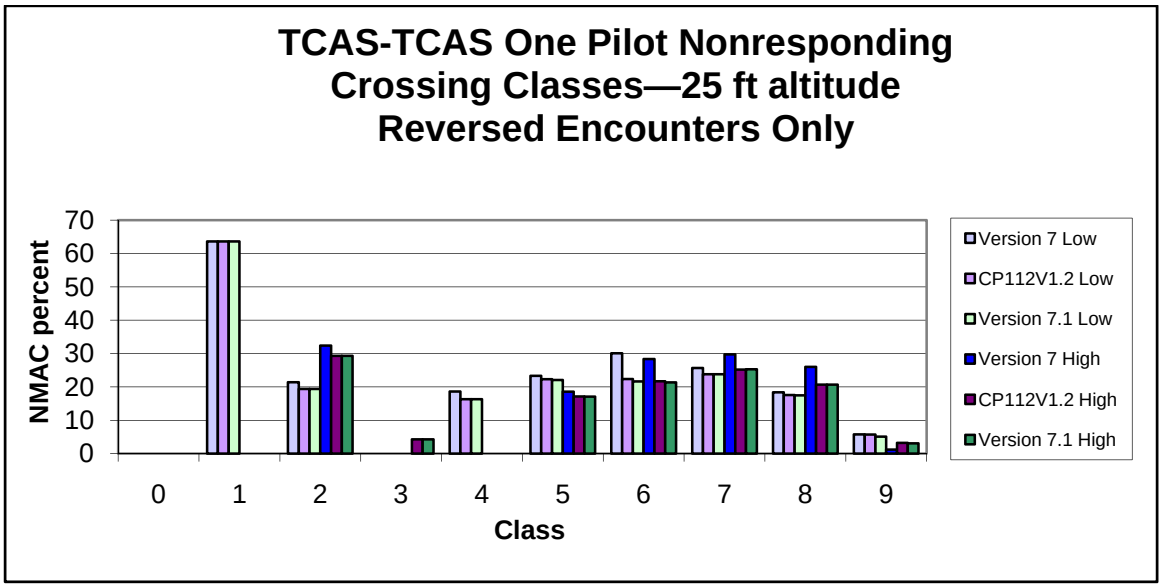

Figure 4-12. Reversal Analysis Program 1, crossing classes, 25 foot altitude.

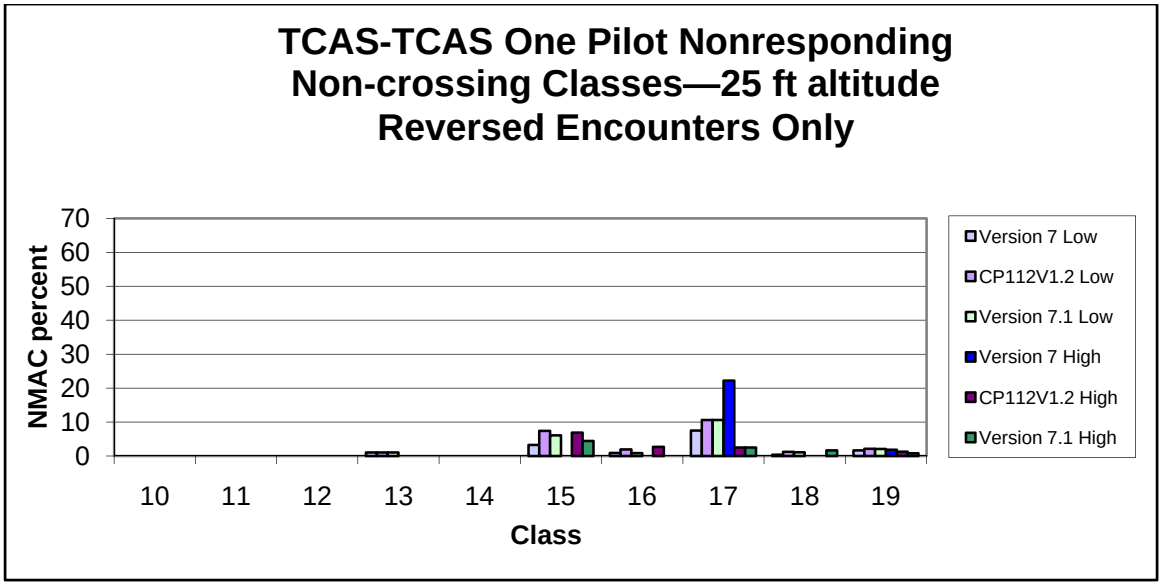

Figure 4-13. Reversal Analysis Program 1, non-crossing classes, 25 foot altitude.

4.1.2.2 Reversal Analysis Program 2—Separation Differences

The following three charts show the percentage of encounters on the critical diagonal for encounters where one aircraft ignores the TCAS RA. The critical diagonal is described in Section 4.1.1.2.

4.1.2.2.1 Nonreversed RAs

Figure 4-14 below shows a histogram of the results from the Separation Differences Program for encounters that did not reverse the sense of their TCAS RA during the encounter.

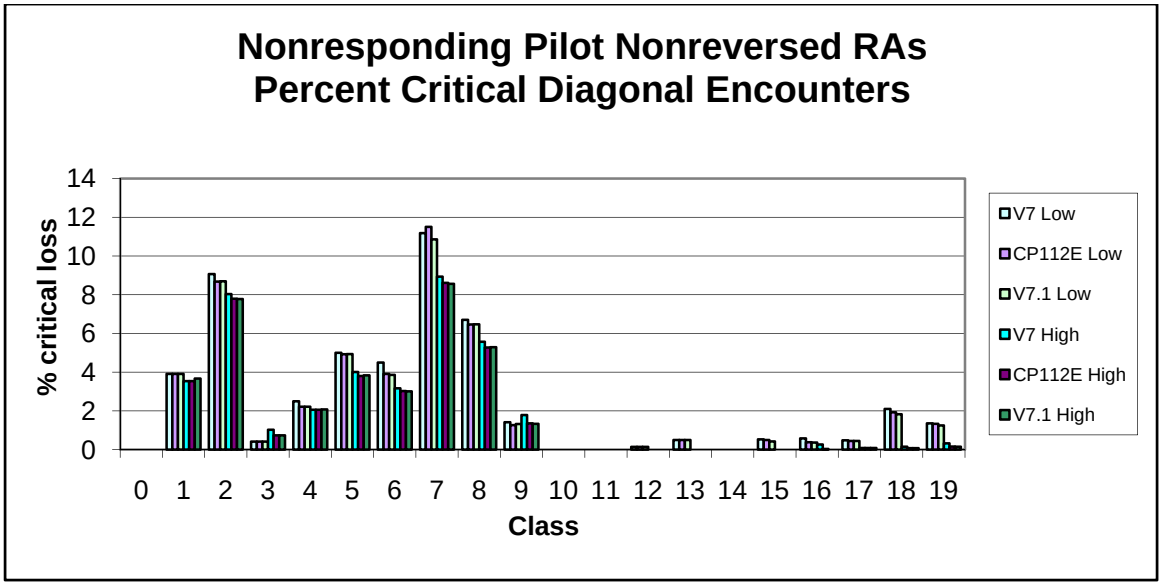

Figure 4-14. Reversal Analysis Program 2, nonreversed RAs.

4.1.2.2.1.1 Better

For encounter classes 2, 3-high, 4-low, 5, 6, 7, 8, 9, 15, 16, 18-low, and 19 we observe a lower percentage of encounters on the critical diagonal for Version 7.1

4.1.2.2.1.2 Worse

For encounter class 1 at higher altitude Version 7.1 has a slightly higher percentage encounters on the critical diagonal. This is due to a reduction in the number of RAs rather than an increase in the number of encounters on the critical diagonal.

4.1.2.2.2 Reversed RAs

Figure 4-15 below shows a histogram of the results from the Separation Differences Program for encounters that reversed the sense of their TCAS RA during the encounter.

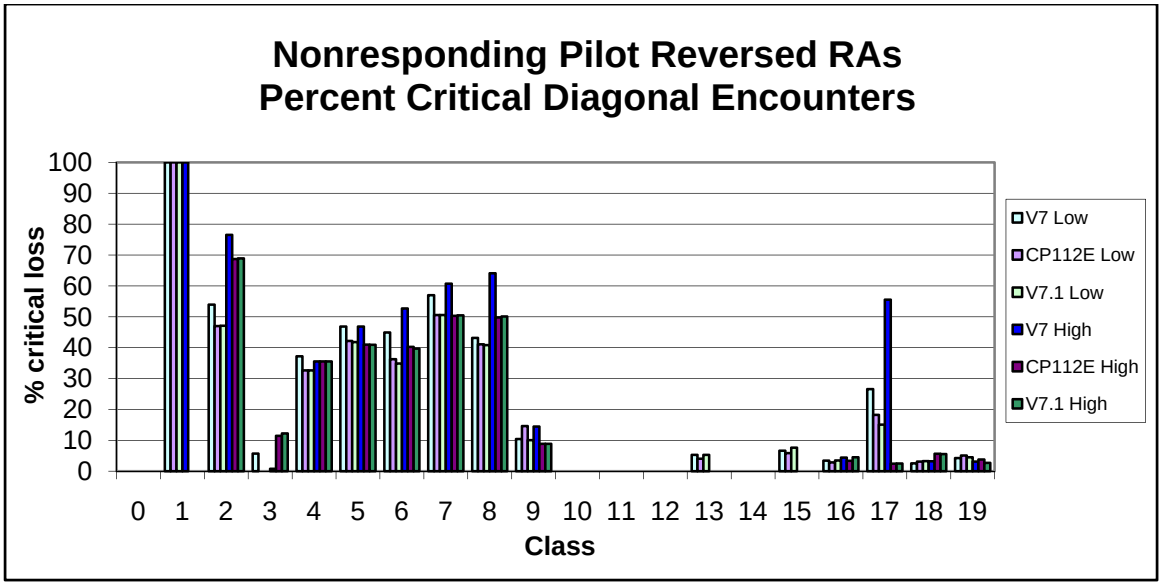

Figure 4-15. Reversal Analysis Program 2, reversed RAs.

4.1.2.2.2.1 Better

Encounter classes 2, 4 at low altitude, 5, 6, 7, 8, 9, and 17 have a lower percentage of encounters on the critical diagonal.

4.1.2.2.2.2 Worse

Encounter class 3 at high altitude and encounter class 18 have a higher percentage of encounters on the critical diagonal.

4.1.2.2.3 Combined performance (nonreversed and reversed RAs)

It is important to consider the combined results because encounters might reverse with one version of the logic, but not with another. Figure 4-16 shows a histogram of the combined performance for Version 7, Version 7 + CP112E, and Version 7.1.

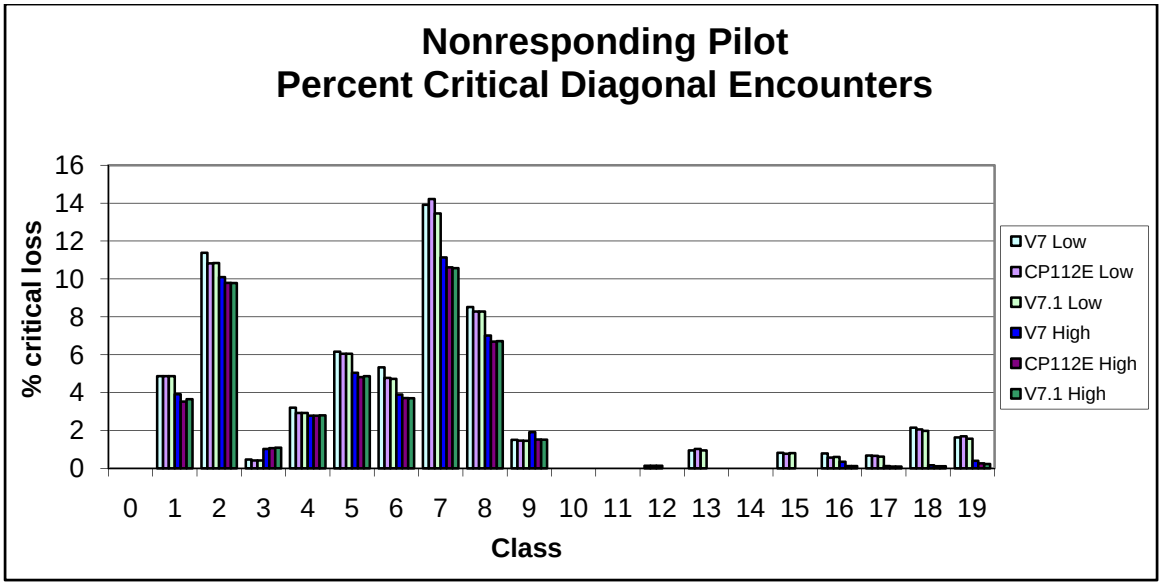

Figure 4-16. Reversal Analysis Program 2, combined performance.

4.1.2.2.3.1 Better

Encounter classes 1-high, 2, 3-low, 4-low, 5, 6, 7, 8, 9-high, 15-low, 16, 18-low, and 19-high have a lower percentage of encounters on the critical diagonal.

4.1.2.2.3.2 Worse

Encounter class 3 at high altitude has a higher percentage of encounters on the critical diagonal. For this class there are five additional encounters on the critical diagonal for Version 7.1, compared to Version 7. However, there are 13 fewer NMACs in class 3 for Version 7.1 than for Version 7, so this is an acceptable trade-off.

4.1.2.3 Hot-Spot Program

A complete set of program results for the Hot-Spot Program for TCAS-TCAS encounters with one pilot not responding to the RA is provided in Appendix K. The histograms provided in this section are derived from these outputs.

4.1.2.3.1 Unresolved NMACs

Figure 4-17 and Figure 4-18 show histograms of unresolved NMAC data from the Hot-Spot Program for Version 6.04a, Version 7, Version 7 + CP112E, and Version 7.1 for encounters where one pilot does not respond to the TCAS RA. These are the encounters with planned separation of 0 feet.

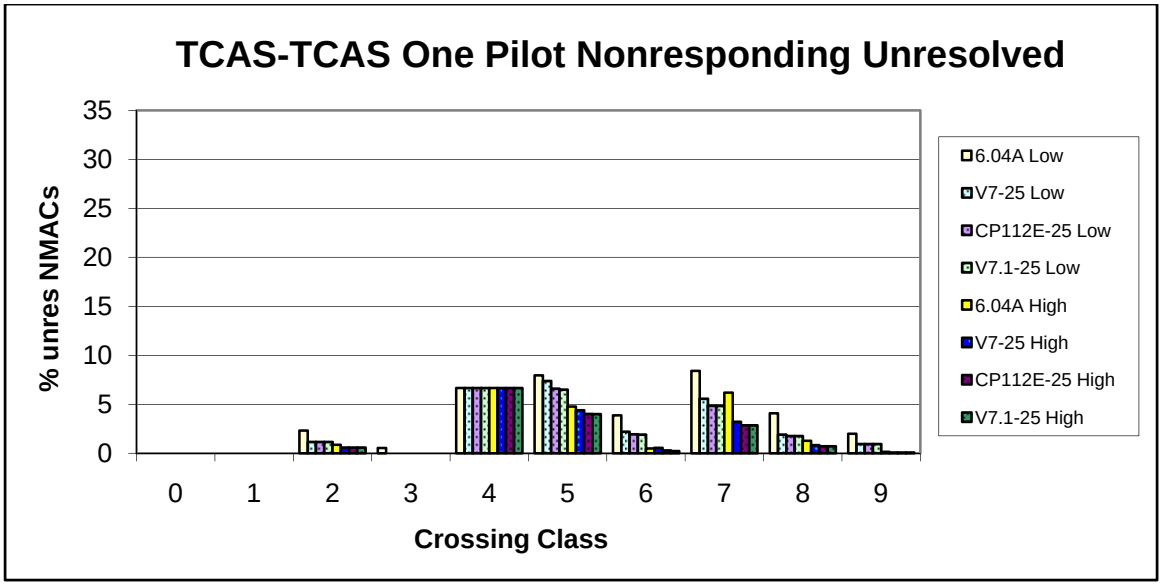

Figure 4-17. Hot-Spot Program, crossing classes, unresolved NMACs.

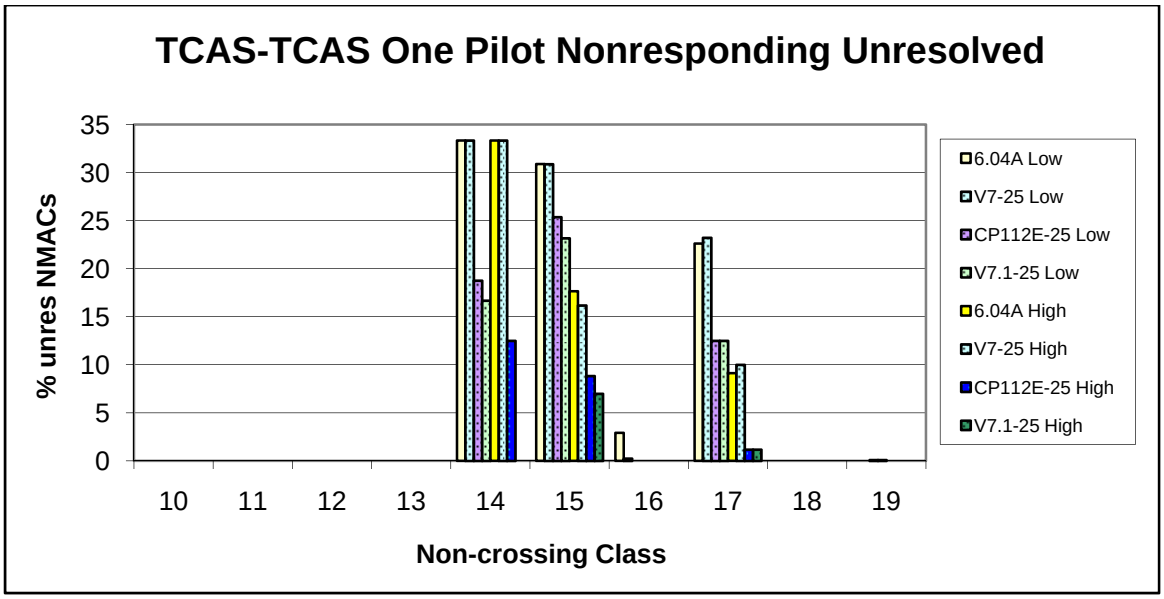

Figure 4-18. Hot-Spot Program, non-crossing classes, unresolved NMACs.

4.1.2.3.1.1 Better

Encounter classes 5, 6, 7, 8, 9, 14, 15, 16, 17 all have a reduction in unresolved NMACs with Version 7.1. These encounters are members of Representative Saves 6, 7, 9, 11, 13, 16, 22, 23, 25, 26, and 28 in Table 7-2.

4.1.2.3.1.2 Worse

There are no encounter classes where Version 7.1 had more unresolved NMACs than Version 7.

4.1.2.3.2 Induced NMACs

Figure 4-19 and Figure 4-20 show histograms of induced NMAC data from the Hot-Spot Program for Version 6.04a, Version 7, Version 7 + CP112E, and Version 7.1 when one pilot does not respond to the TCAS RA.

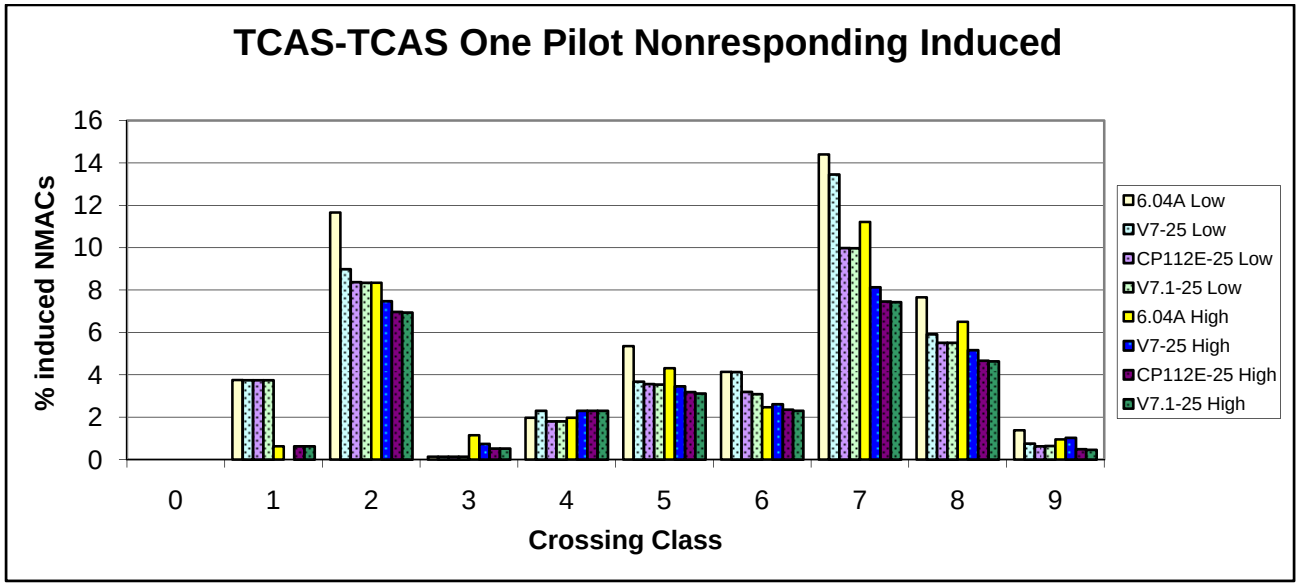

Figure 4-19. Hot-Spot Program, crossing classes, induced NMACs.

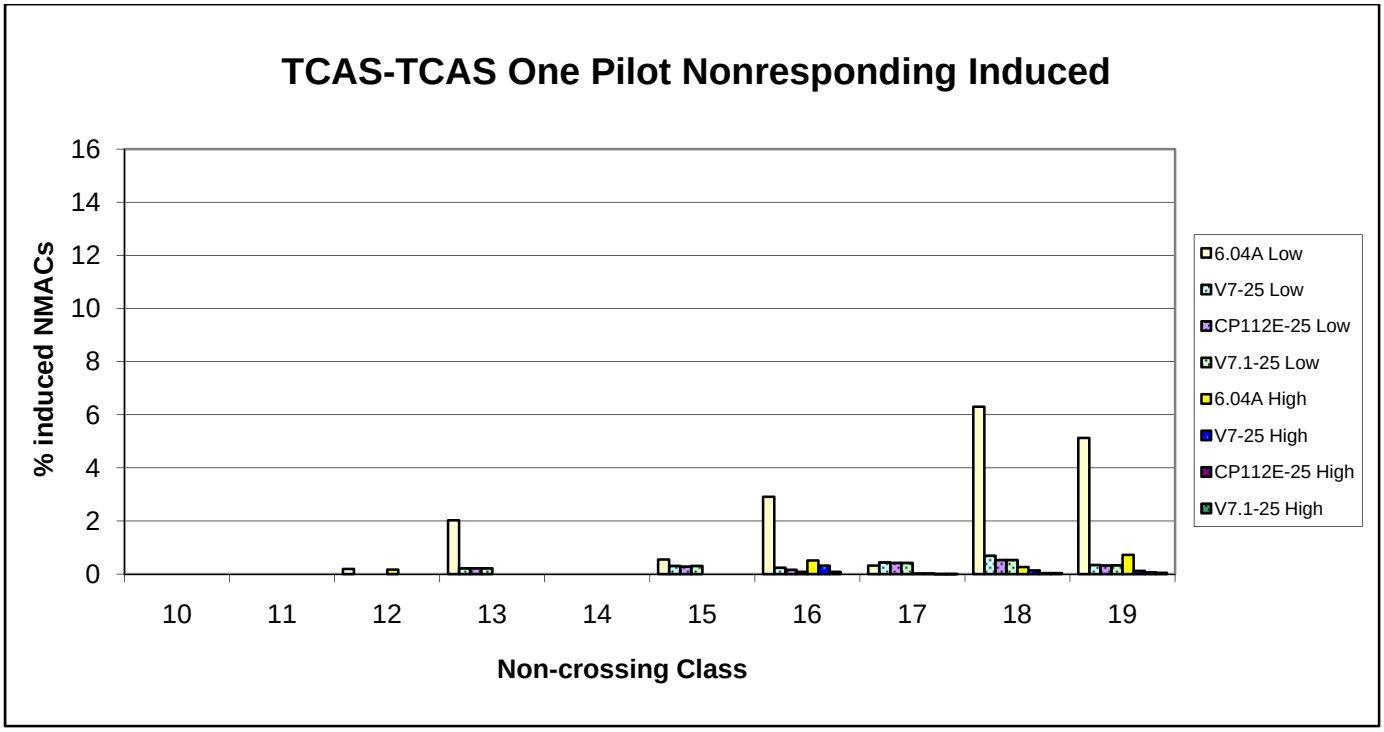

Figure 4-20. Hot-Spot Program, non-crossing classes, induced NMACs.

4.1.2.3.2.1 Better

Encounter classes 2, 3, 4-low, 5, 6, 7, 8, 9, 16, 18, 19-low show improved performance for Version 7.1. These encounters are members of Representative Saves 1–5, 8, 10, 12, 14, 15, 17, 19–21, 24, and 27–30 in Table 7-2. These are the encounters with planned separation of more than 0 feet.

4.1.2.3.2.2 Worse

In encounter class 1 at high altitude with 25 foot altitude data Version 7.1 is slightly worse than Version 7. The performance of class 1 in the high altitude encounters reverts back to the performance of Version 6.04a with the introduction of CP112E.

4.1.2.4 One Pilot Nonresponding Summary

As mentioned in Section 4.1, CP112E was designed to improve encounters where one aircraft is not following the RA. In addition CP115 was designed to reduce incorrect responses to corrective VSL RAs. The analysis of encounters where one pilot does not respond to the TCAS RA shows a dramatic reduction in induced NMACs.

Reversal Analysis Program 1 results indicate that fourteen groups of encounters have a lower percentage of reversed RAs resulting in NMACs with Version 7.1 compared to Version 7, eight encounter groups have a higher percentage of reversed encounters resulting in NMACs, and the remaining eighteen groups show no change. Some of these differences are caused by increases in the number of reversed RAs. CP112E was designed to allow for reversals when one pilot does not respond to the TCAS RA, so we expected to see significant increases in the number of RA reversals.

Reversal Analysis Program 2 shows significant reductions in encounters on the critical diagonal for most of the encounter classes with only a few minor exceptions. The Hot-Spot Program shows improved performance for most encounter classes with one minor exception. The combination of increased number of reversed RAs and reduced NMAC percentages indicate that CP112E improves the performance of TCAS when one pilot does not follow the TCAS RA. Overall these results show a measurable benefit for Version 7.1.

4.1.3 TCAS vs. Unequipped Aircraft

4.1.3.1 Reversal Analysis Program 1

4.1.3.1.1 25 foot altitude data

Figure 4-21 and Figure 4-22 show histograms of the Reversal Analysis Program 1 for Version 7, Version 7 + CP112E V1.2, and Version 7.1 with 25 foot altitude data against an unequipped intruder. Reversals against unequipped intruders were allowed with Version 6.04a, however Version 6.04a did not provide 25 foot altitude tracking, so there is no entry for Version 6.04a in this section.

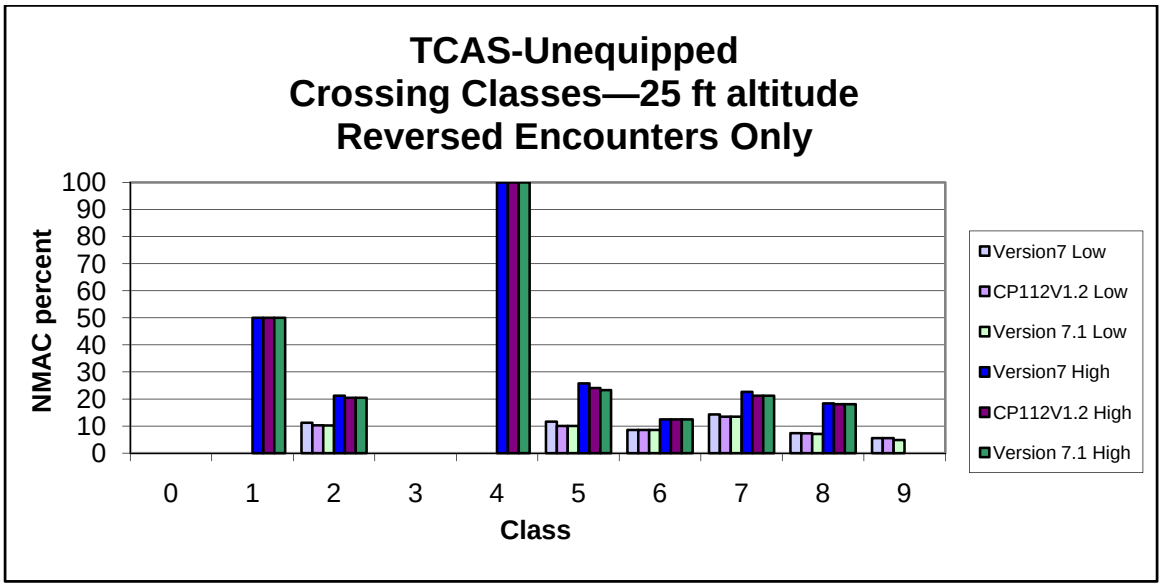

Figure 4-21. Reversal Analysis Program 1, crossing classes, 25 foot altitude.

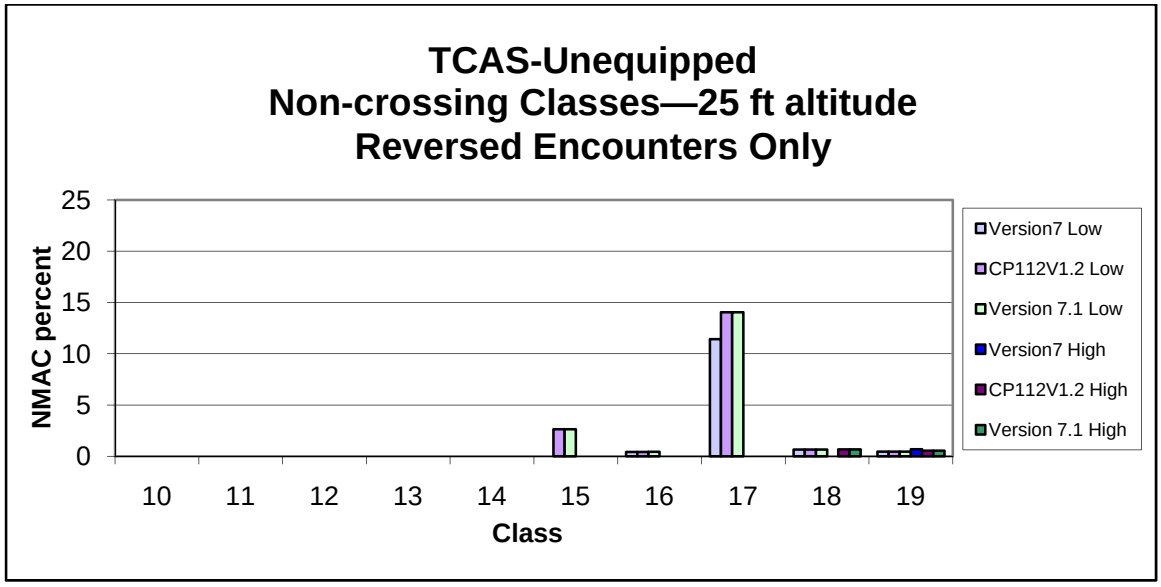

Figure 4-22. Reversal Analysis Program 1, non-crossing classes, 25 foot altitude.

4.1.3.1.1.1 Better

Encounter classes 2, 5, 7, 8, 9-low, 18-low, and 19-high have decreased percentages of reversed encounters resulting in NMACs against unequipped intruders with Version 7.1. There are 435 additional reversed RAs in these encounters, and 8 fewer NMACs.

4.1.3.1.1.2 Worse

Encounter classes 15-low, 17-low, and 18-high all have increased percentages of reversed RAs resulting in NMACs against unequipped intruders with Version 7.1. There are 28 additional reversed RAs with Version 7.1, and there are 7 more NMACs.

4.1.3.1.2 100 foot altitude data

Figure 4-23 and Figure 4-24 show histograms of results from the Reversal Analysis Program 1 for Version 6.04a, Version 7, Version 7 + CP112E, and Version 7.1 with 100 foot altitude data against an unequipped intruder. Version 6.04a and CP112E are shown for reference only.

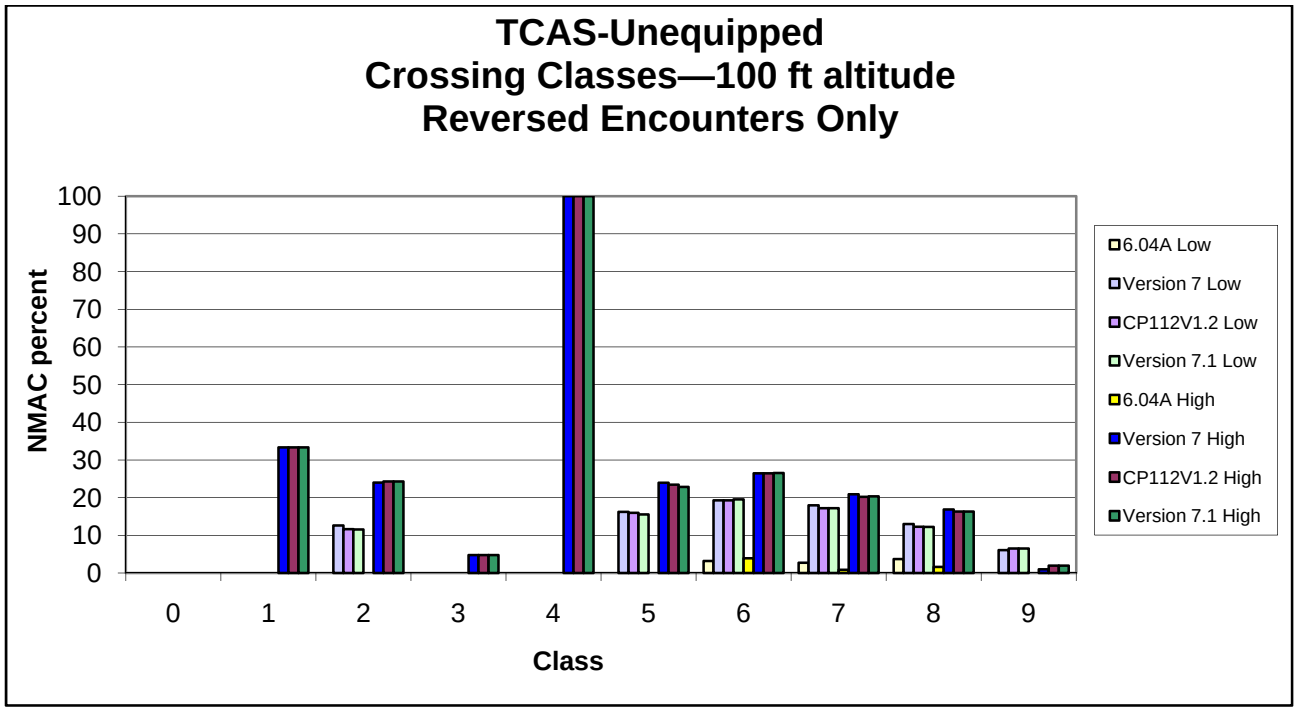

Figure 4-23. Reversal Analysis Program 1, crossing classes, 100 foot altitude.

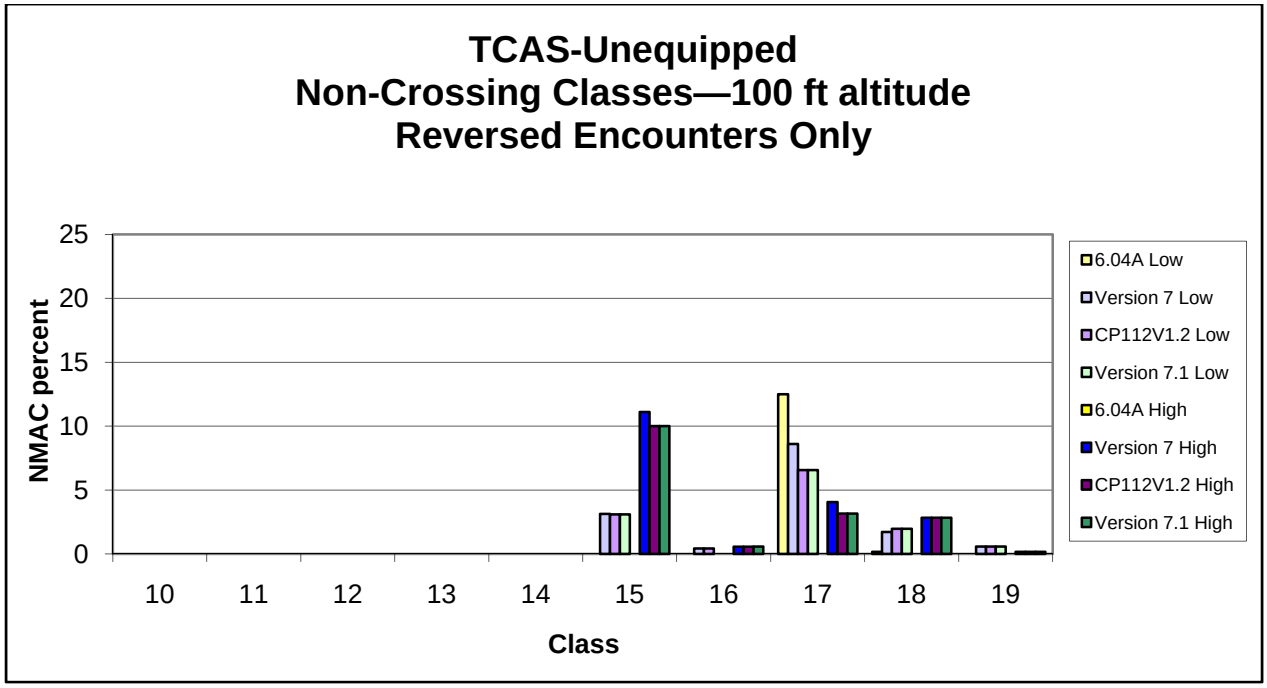

Figure 4-24. Reversal Analysis Program 1, non-crossing classes, 100 foot altitude.

4.1.3.1.2.1 Better

Encounter classes 2-low, 5, 7, 8, 15, 16-low, 17, 18-low all show improvement with Version 7.1. There are 225 additional reversed RAs and 15 fewer NMACs in these encounters.

4.1.3.1.2.2 Worse

Encounter classes 2-high, 6, and 9 have increased percentages of reversed encounters resulting in NMACs. Encounter classes 6-low and 6-high have the same number of NMACs and a reduction in reversed RAs. Encounter classes 9-high and 9-low and 2-high each have 1 additional NMAC and 1 additional reversed RA. There are two fewer reversed RAs and three additional NMACs in these encounters.

4.1.3.2 Reversal Analysis Program 2—Separation Differences

There are no analysis results to report for Reversal Analysis Program 2 for TCAS vs. unequipped encounter. The program was designed to examine only those encounters where both aircraft are equipped with TCAS.

4.1.3.3 Hot-Spot Program

4.1.3.3.1 Unresolved NMACs

Figure 4-25 and Figure 4-26 show histograms of unresolved NMAC data from the Hot-Spot Program for Version 6.04a, Version 7, Version 7 + CP112E, and Version 7.1 against unequipped intruder aircraft.

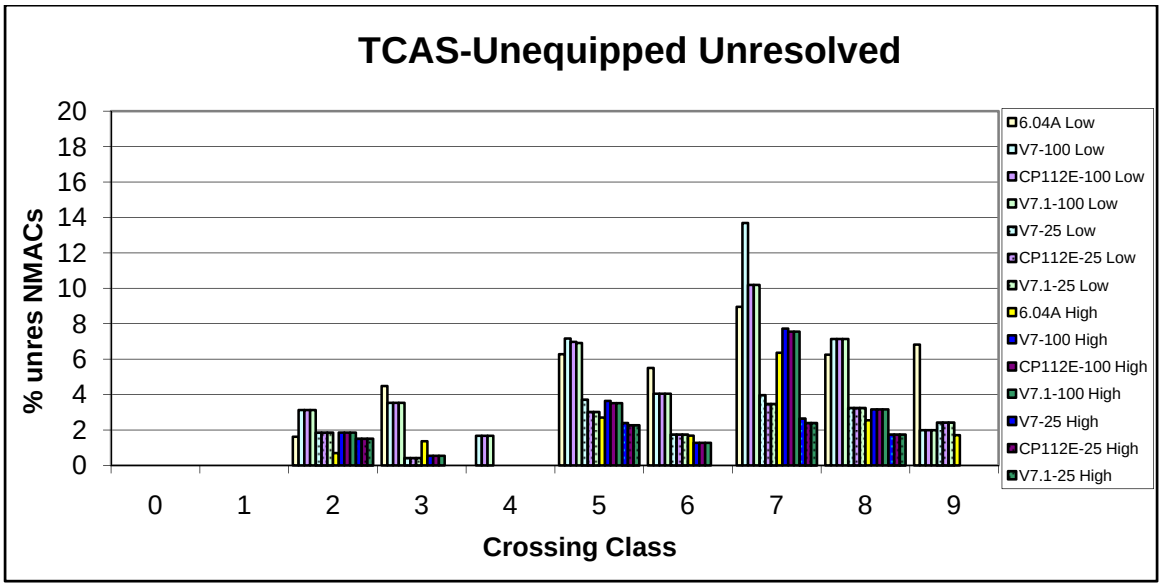

Figure 4-25. Hot-Spot Program, crossing classes, unresolved NMACs.

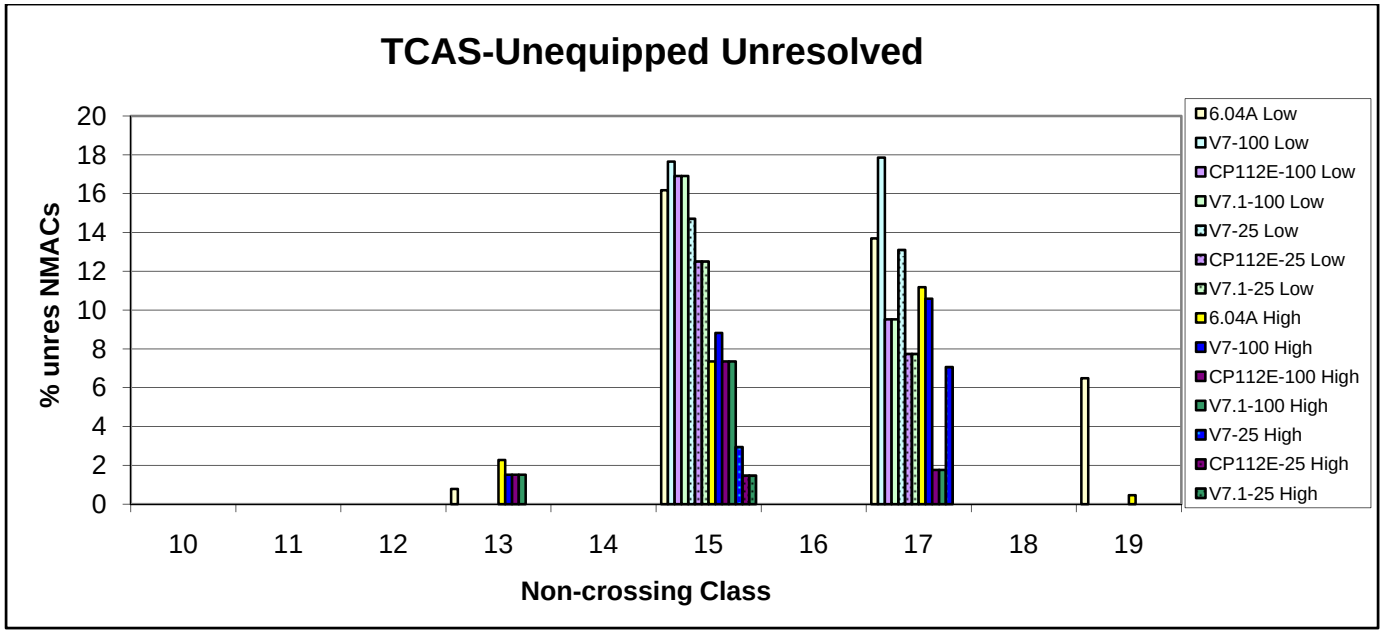

Figure 4-26. Hot-Spot Program, non-crossing classes, unresolved NMACs.

4.1.3.3.1.1 Better

Encounter classes 5, 7, 15, and 17 all show improved performance with Version 7.1. These encounters are members of Representative Saves 3, 4, 5, 15, and 17 in Table 7.4. Theses encounters with 0 feet of planned separation.

4.1.3.3.1.2.Worse

There are no encounter classes where Version 7.1 has worse performance than Version 7 against unequipped intruders.

4.1.3.3.2 Induced NMACs

Figure 4-27 and Figure 4-28 show histograms of induced NMAC data from the Hot-Spot Program for Version 6.04a, Version 7, Version 7 + CP112E, and Version 7.1 against unequipped intruder aircraft.

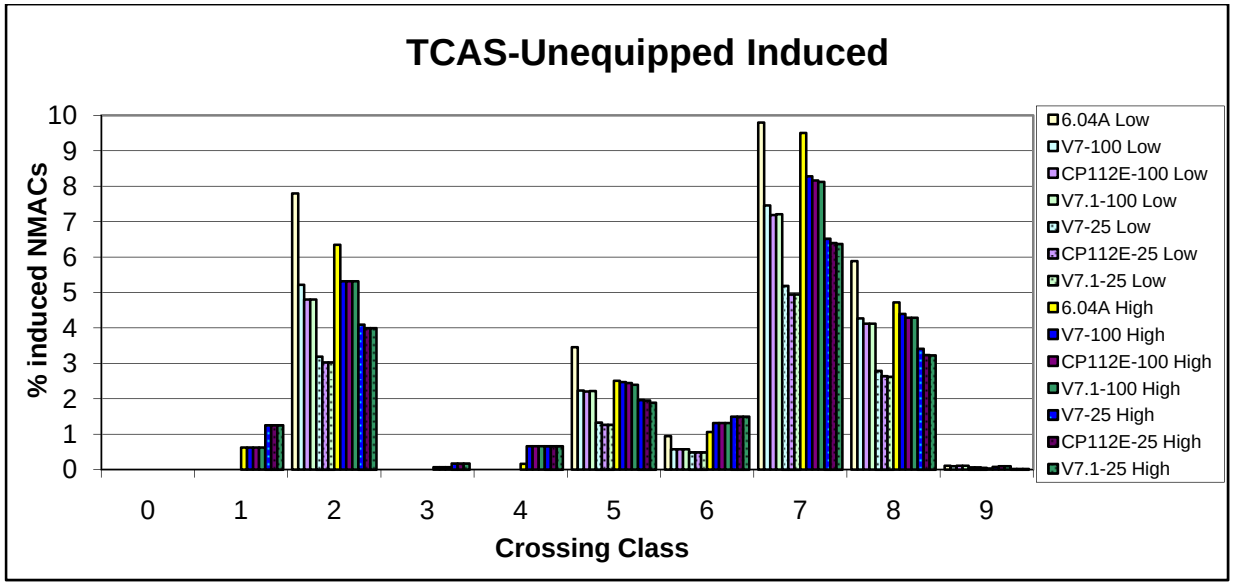

Figure 4-27. Hot-Spot Program, crossing classes, induced NMACs.

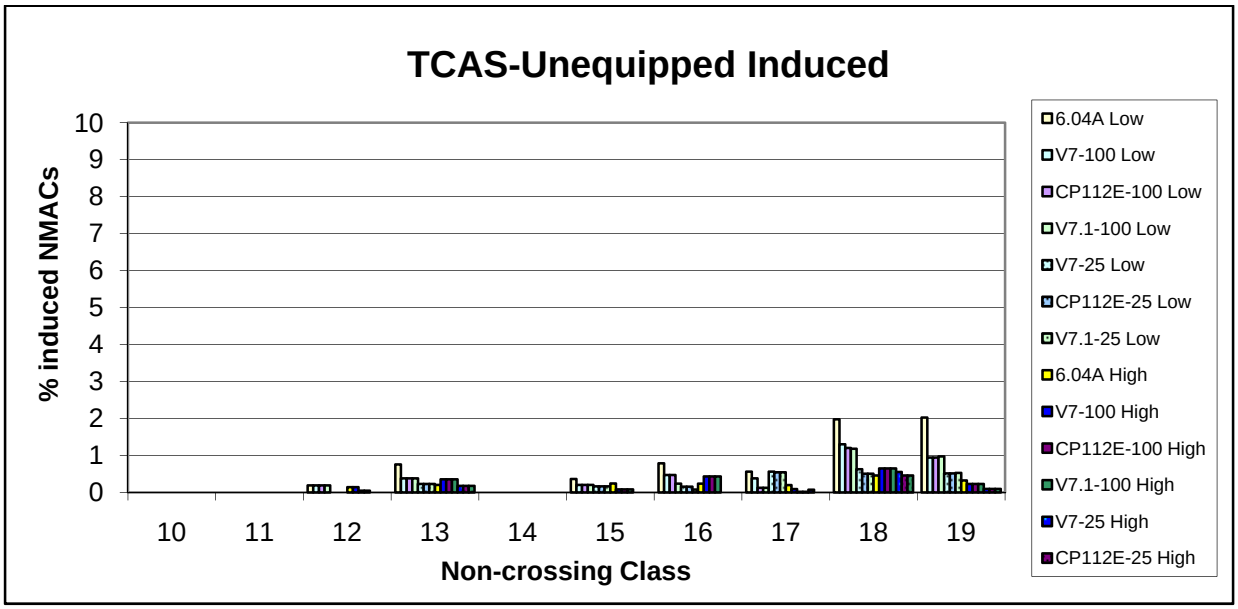

Figure 4-28. Hot-Spot Program, non-crossing classes, induced NMACs.

4.1.3.3.2.1 Better

Encounter classes 2, 5, 7, 8, 9-low, 25 ft, 12-high, 16-low, 17-low 100 ft, 17 high, 18-low, 18 high 25 ft have better performance with Version 7.1. These encounters are members of Representative Saves 1, 2, 4, 6–14, 16, and 18–20 in Table 7.4. These are encounters with more than 0 feet of planned separation.

4.1.3.3.2.2.Worse

Encounter class 9 low 100 ft, and encounter class 19 low have slightly worse performance with Version 7.1 against unequipped intruder aircraft. Class 9 low 100 ft has a slight increase in NMAC percentage is due to one single encounter. Class 19 low 100 ft has a slight increase in NMAC percentage due to two encounters. Class 19 low 25 ft has a slight increase in NMAC percentage due to a single encounter. These encounters are found in Representative NMACs Ind06 and Ind07 for TCAS vs. unequipped aircraft, described in Section 7.3.2.

4.1.3.4 TCAS-Unequipped Summary

As mentioned in Section 4.1, CP112E was designed to improve encounters where one aircraft is not following the RA. In addition CP115 was designed to reduce incorrect responses to corrective VSL RAs. The analysis of encounters with an unequipped intruder aircraft also show some improvement.

For Reversal Analysis Program 1, ten encounter groups have better performance for reversed RAs with Version 7.1. Three encounter groups had worse performance for reversed RAs with Version 7.1. Because the number of RAs with reversals fluctuates, this is not cause for concern unless the overall NMAC count is higher, which is not the case. For the Hot-Spot program, most of the encounter classes have a reduction in induced NMACs. There are two encounter classes with increased induced NMAC percentages, and these can be traced to only four encounters. These will be examined in detail in Phase II, Section 7.2.2.

4.2 GENERAL EVALUATION SUMMARY

This section provides results for the Phase I analysis of TCAS II Version 7.1. Significant improvements are observed in encounters where both aircraft are TCAS equipped and one aircraft does not respond to the RA. In addition, measurable improvements are observed in encounters where only one of the two aircraft is equipped with TCAS. A small increase in the number of NMACs is observed in encounters where both aircraft are TCAS equipped and both aircraft respond properly to the RA. The benefit from reduced NMACs observed in encounters with nonresponding TCAS aircraft and unequipped aircraft more than offset the small increase in NMACs where both pilots respond to the RA. The differences between Version 7 and Version 7.1 will be discussed in depth in Section 7.

5. INTEROPERABILITY STUDY

The first four data collections (Tables 1-1 through 1-4 in Section 1.1.2) compare the last U.S. mandated version of TCAS (6.04a) to either Version 7 or Version 7.1. It was decided that we needed a way to examine the behavior of a mixture of Version 7 and Version 7.1 in order to check for incompatibilities between versions of the CAS logic that could coexist in the U.S. airspace for a significant period of time. Tables 1-5 and 1-6 describe these two data collections. These were run only for the low altitude encounter sets, since these encounters have proven to be the most challenging in the past.

Previous experience with interoperability studies predicts that the performance for a mixed-equipage encounter will fall somewhere between the performance observed if both aircraft were equipped with the same version of CAS logic. If both aircraft are equipped with Version 7, assume we observe X% induced NMACs. Similarly if both aircraft are equipped with Version 7.1, assume we observe Y% induced NMACs. With one aircraft equipped with Version 7 and the other aircraft equipped with Version 7.1 we expect to observe between X% and Y% induced NMACs.

5.1 BOTH PILOTS RESPONDING

There are very few unresolved NMACs when both pilots correctly follow their TCAS RAs. Figure 5-1 shows the percentage of unresolved NMACs for TCAS aircraft with 100 foot altitude data. There are only two encounter classes with unresolved NMACs. Note the NMAC percentage for mixed equipage is the same as the NMAC percentage for Version 7-only equipage and Version 7.1-only equipage.

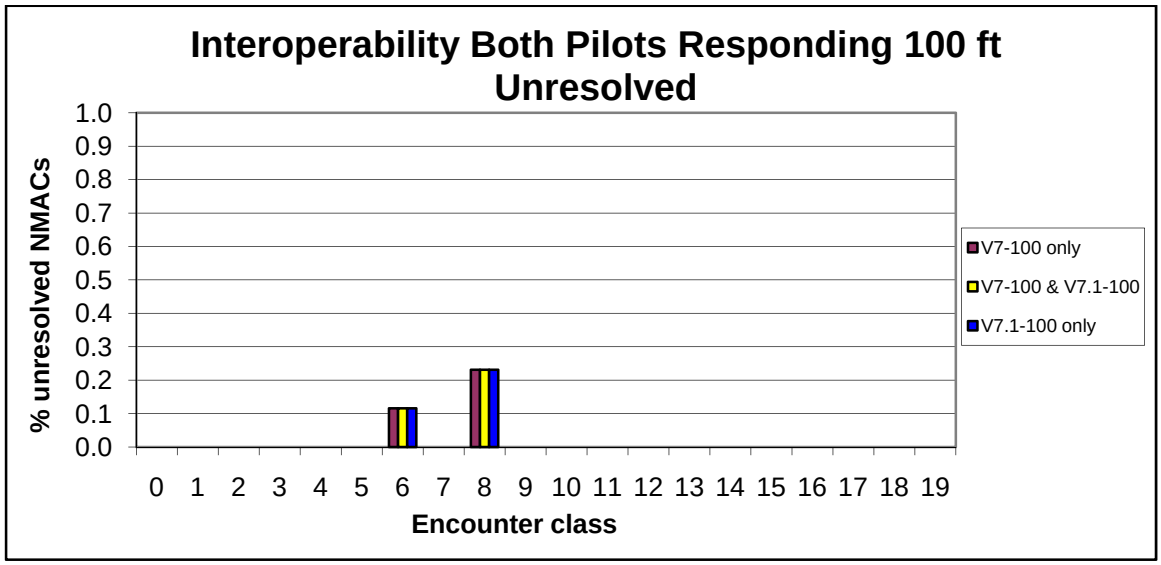

Figure 5-1. Interoperability, both pilots responding, 100 ft altitude, unresolved NMACs.

Figure 5-2 shows the percentage of unresolved NMACs for TCAS aircraft with 25 foot altitude data. There are only two encounter classes with unresolved NMACs. For encounter class 6 all three equipage variations (Version 7-only, mixed Version 7 and Version 7.1, and Version 7.1-only) have the same NMAC percentage. For encounter class 8 the mixed Version 7 and Version 7.1 equipage NMAC percentage falls between the lower Version 7 value and the higher Version 7.1 value, as expected.

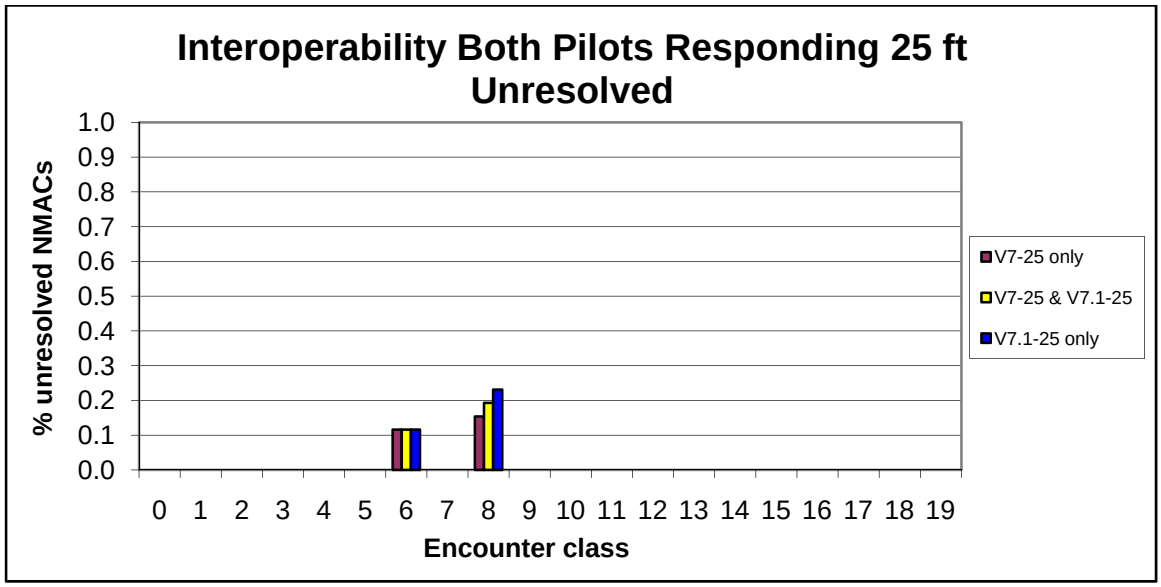

Figure 5-2. Interoperability, both pilots responding, 25 ft altitude, unresolved NMACs.

Figure 5-3 shows the percentage of induced NMACs with both TCAS aircraft using 100 foot altitude data and with both aircraft following their RAs. In every case the mixed equipage performance falls between the Version 7 and Version 7.1 performance.

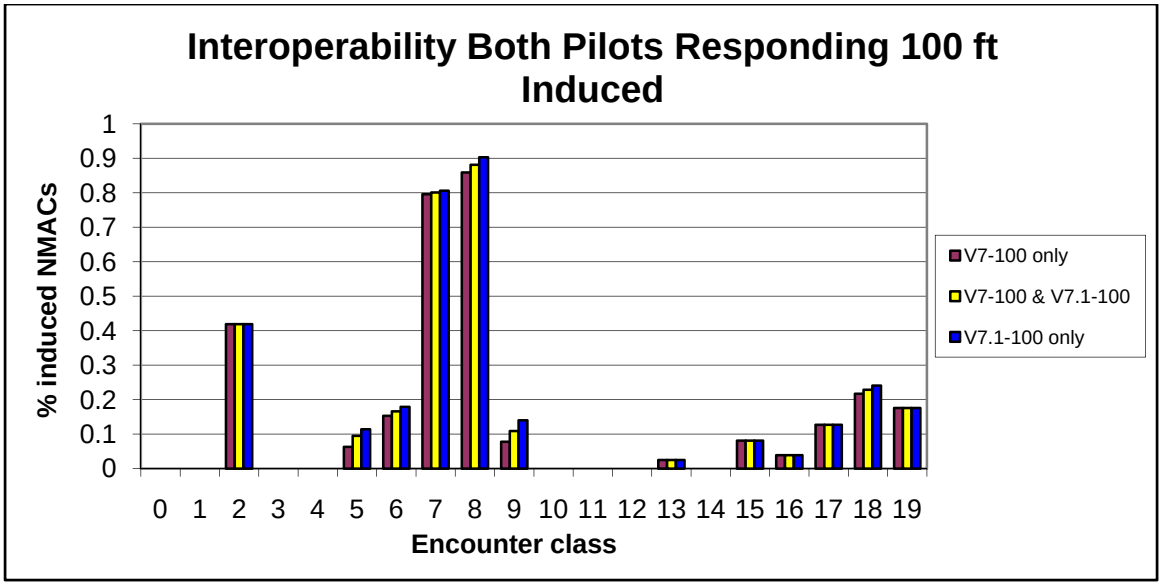

Figure 5-3. Interoperability, both pilots responding, 100 ft altitude, induced NMACs.

Figure 5-4 shows the percentage of induced NMACs with both TCAS aircraft using 25 foot altitude data and with both aircraft following their RAs. In every case the mixed equipage performance falls between the Version 7 and Version 7.1 performance.

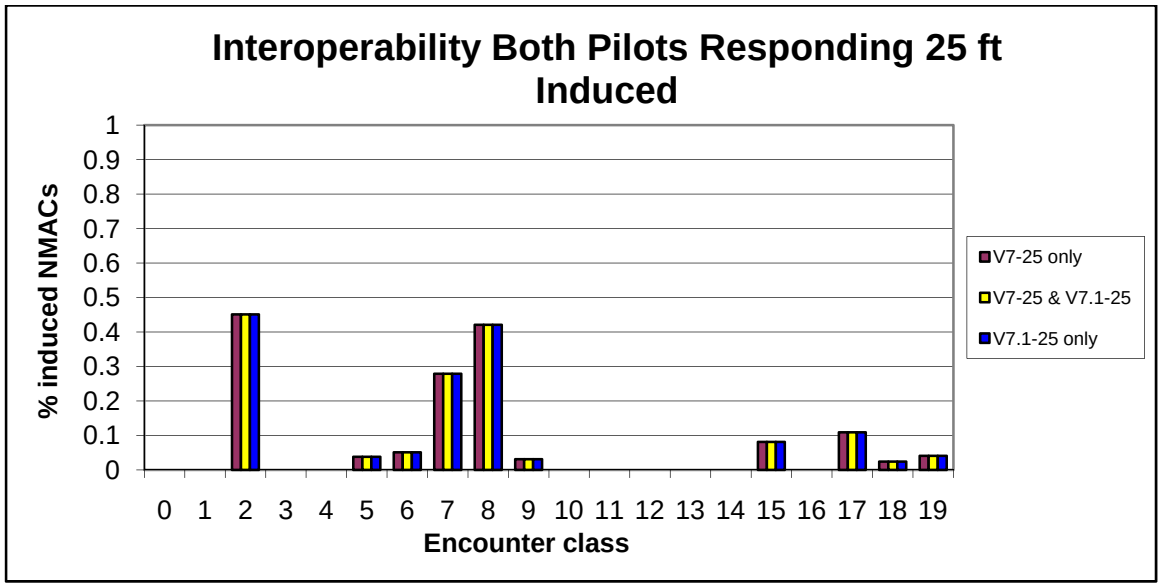

Figure 5-4. Interoperability, both pilots responding, 25 ft altitude, induced NMACs.

5.2 ONE PILOT NONRESPONDING

The data collections with one pilot nonresponding are run only with 25 foot altitude data.

In Figure 5-5 there are two bars for mixed-equipage encounters because we distinguish between the Version 7 aircraft ignoring the RA or the Version 7.1 aircraft ignoring the RA. In each case the mixed equipage performance lies between the Version 7 performance and the Version 7.1 performance. However there are four encounter classes (6, 7, 15, and 19) where the mixed equipage performance is better when the responding aircraft is equipped with Version 7, and there are three encounter classes (5, 8, 14) where the mixed equipage performance is better when the responding aircraft is equipped with Version 7.1. The number of unresolved NMACs increases when one pilot does not respond to the TCAS RA. Notice the y axis is quite different compared to the previous plots.

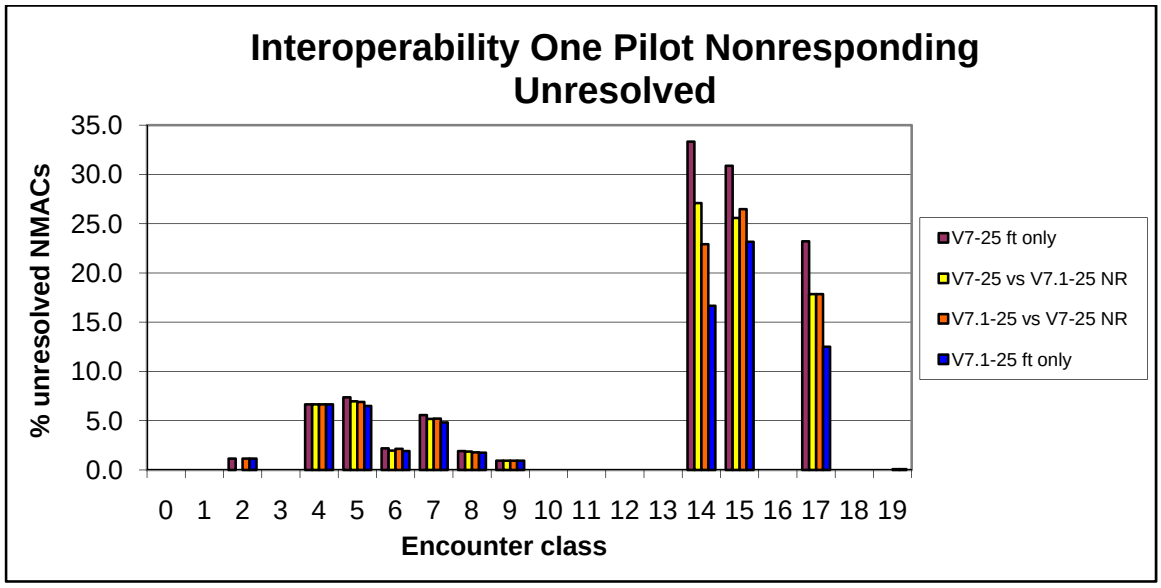

Figure 5-5. Interoperability, one pilot nonresponding, unresolved NMACs.

Figure 5-6 shows performance for induced NMACs with one pilot not responding to the TCAS RA. There are considerably fewer induced NMACs than unresolved NMACs. In most cases the mixed equipage performance lies between the Version 7 performance and the Version 7.1 performance. Encounter class 15 is the only exception to this rule. Class 15 has more NMACs than Version 7-only (0.303) and Version 7.1-only (0.303) with mixed equipage (0.324) when the responding aircraft is equipped with Version 7.1. This increase was caused by a single encounter, so there is no cause for concern.

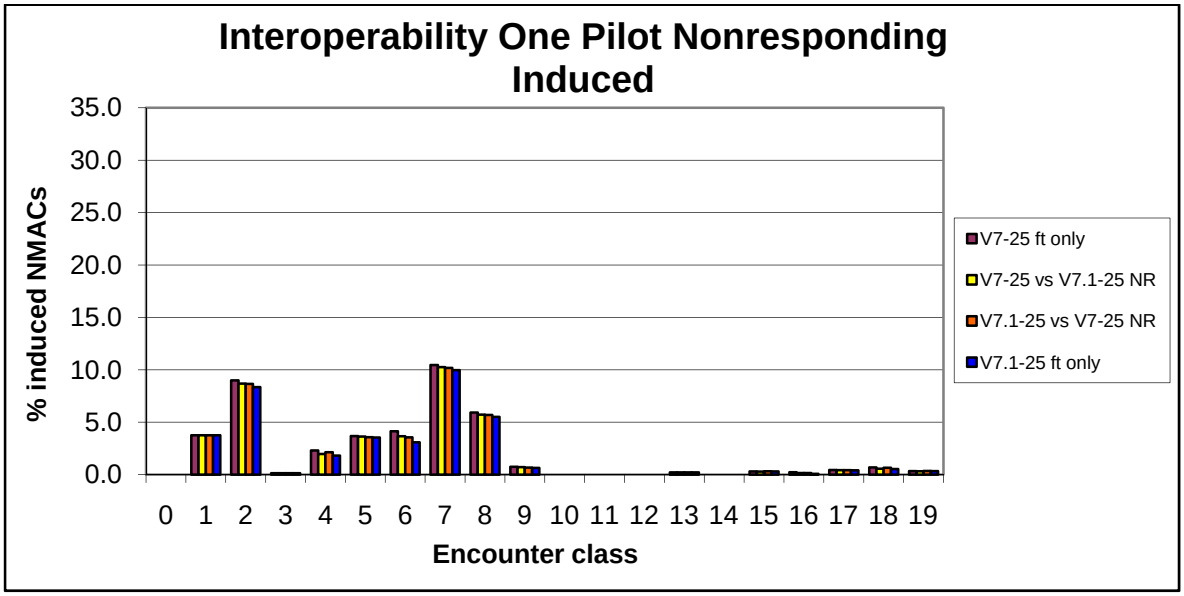

Figure 5-6. Interoperability, one pilot nonresponding, induced NMACs.

5.3 SUMMARY

As expected there are no significant interoperability issues between Version 7 and Version 7.1 of TCAS. In almost all cases, the mixed equipage performance falls between the Version 7 and Version 7.1 performance.

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6. VERSION 7 REPRESENTATIVE NMAC RESOLUTION

Previous TCAS logic evaluation work at Lincoln Laboratory for Version 6.04a and Version 7 performed Phase I evaluations for TCAS-TCAS encounters with both aircraft responding to the RA, TCAS-TCAS encounters where one aircraft ignores the RA, and for TCAS-unequipped encounters. During these evaluations the Phase II analysis was performed only for the TCAS-TCAS encounters with both aircraft responding to the RA. During these evaluations the assumption of pilot compliance to TCAS RAs was still in place. In addition the sheer number of failed encounters with one TCAS ignoring the RA precluded this work. Prior to the Version 7.1 analysis, the assumption of pilot compliance has been undermined by European and U.S. monitoring efforts. In addition, updated analysis tools and improvements in processing speed make the in depth analysis of encounters where one aircraft ignores the TCAS RA and encounters with unequipped intruders possible.

At the conclusion of the Version 7 logic evaluation there were three unresolved Representative NMACs and fourteen induced Representative NMACs defined from the encounters where both pilots responded to their TCAS RAs. There were small changes made to Version 7 after the in-depth analysis was completed. At that time only the high level analysis was performed on the revised logic.

As previously mentioned in Section 3.1.1 there were changes made to Version 7 TCAS logic after the Phase II analysis was complete and ready to publish. As part of the Version 7.1 analysis, all 17 Representative NMAC encounters were run with the "newer" Version 7 baseline as well as Version 7.1.

Table 6-1 contains the results of re-running these encounters. In the Status column of Table 6-1, "Fixed V7" means these encounters were resolved by the TSO-C119B Version 7 logic. Notice there were no Version 7 Representative NMACs for TCAS-TCAS enounters with both pilots responding to their TCAS RAs that are solved by Version 7.1.

Remember, the Version 7 Representative NMAC analysis was only performed on encounters with both aircraft correctly following the TCAS RAs. Given that CP112E and CP115 focus on improving encounters where one pilot ignores the TCAS RA, it is not surprising that we did not find cases where only Version 7.1 "fixed" the Representative NMACs.

Table 6-1

Outcome for Version 7 Both Pilots Responding Representative NMACs with Version 7.1

UNRESOLVED NMACs (Total 22)

Group (table)	No. Of NMACs	Planned Separation	RA cross	Geom Rev?	Aircraft Rates		6.04a NMAC group	Status
					AC1	AC2		
1. (6.3)	8	0	No	No	5000	5000	7	Fixed V7 And V7.1
2. (6.3)	4	0	Yes	Yes	$\geq$ 3000	$\leq$ –3000	7	NMAC
3. (8.3)	10	0	No	No	$\leq$ -3000	–5000	12	NMAC

INDUCED NMACs (Total 385)

Group (table)	No. Of NMACs	Planned Separation	RA cross	Geom Rev?	Aircraft Rates		6.04a NMAC group	Status
					AC1	AC2		
1. (2.4)	32	–500, –750	No	No*	0, ±400	5000	2	NMAC
2. (5.4)	1	500	No	No	5000	3000	4	Fixed V7 And V7.1
3. (5.4)	10	–750	No	No	–1000	5000	5	Fixed V7 And V7.1
4. (6.4)	16	–500	No	No	–5000	–5000	8	NMAC
5. (7.4)	1	500	No	No	5000	3000	26	NMAC
6. (7.4)	118	250, –750	No	No	$\geq$ 1000	$\leq$–1000	9	NMAC
7. (8.4)	24	–500	No	No*	$\leq$ –1000	-5000	17	NMAC
8. (8.4)	130	250, –750	No	No*	$\leq$ –1000	$\leq$ -3000	16	NMAC
9. (9.4)	7	–250	Yes	No*	5000	–5000	19	NMAC
10.(13.4)	3	250	Yes	Yes	0,400	5000	22	NMAC
11.(15.4)	4	–500	Yes	No	5000	5000	23	NMAC
12.(17.4)	13	500	Yes	No*	5000	3000	26	NMAC
13.(18.4)	10	750	Yes	Yes	–5000	$\leq$ –1000	27	NMAC
14.(19.4)	16	–250, –500	Yes	Yes	$\geq$ 1000	$\leq$ –3000	none	Fixed V7 And V7.1

* Means a small number of encounters had reversals that came too late to be effective.

7. VERSION 7.1 REPRESENTATIVE SAVES AND NMACS (PHASE II)

In past TCAS logic analysis efforts, the concept of selecting representative NMACs was a useful analytical exercise, so this process was repeated with Version 7.1. After the higher level Phase I analysis is finished, the more in-depth Phase II analysis begins. This process was described in Section 2.3.

Every encounter that was not an NMAC for Version 7 and became an NMAC for Version 7.1 is called a new NMAC. Similarly, every encounter that was an NMAC for Version 7 and was not an NMAC for Version 7.1 is called a new Save.

The sections below present Representative Save and Representative NMAC information for encounters with both pilots responding to their TCAS RAs, encounters with one pilot not responding to the RA, and for encounters with TCAS aircraft against unequipped intruders. For each Representative Save and Representative NMAC the change in behavior was attributed to either CP112E or CP115.

Note again the philosophy expressed in Section 4.1: the main goal of Version 7.1 was to improve TCAS performance when one pilot does not respond to the RA. Thus, the TCAS community was willing to accept a small degradation in performance when both pilots respond in exchange for a large improvement when one pilot does not respond. Improved performance was expected in TCAS-unequipped encounters as well.

7.1 BOTH PILOTS RESPONDING

7.1.1 Representative Saves

There were no new Representative Saves with both pilots responding to their RAs for Version 7.1.

7.1.2 Representative NMACs

For the set of encounters with both pilots responding to their TCAS RAs, every encounter that produced a new NMAC for either Version 7.1-100 or Version 7.1-25 was individually simulated using FTEG for five versions of the logic (Version 6.04a, Version 7-100, Version 7-25, Version 7.1-100, and Version 7.1-25). For each set of simulations, a one-page summary of the TCAS RAs generated by each version of the logic was produced. These Encounter Summary pages are useful tools in understanding the different outcomes produced by successive versions of TCAS logic.

These encounter summaries were sorted based on encounter class, NMAC type (unresolved or induced), the aircraft vertical rates, and the sense of the RAs generated by the two aircraft in the encounter. Once the sorting was complete one encounter was chosen to represent each group and a full set of encounter plots was generated for this Representative NMAC. For Version 7.1 there is one new unresolved Representative NMAC, and there are six new induced Representative NMACs.

Because Version 7.1 is a focused change to the TCAS logic, any differences between the behavior of Version 7 and Version 7.1 should be traceable to either CP112E or CP115. Each representative NMAC was studied to look for the cause of the loss in separation compared to Version 7. See Table 7-1 below for the Version 7.1 Representative NMACs.

A brief summary of each representative encounter follows the table. Appendix M contains detailed information including the encounter summary page and plots for the five versions of TCAS for the representative encounter.

Table 7-1

New Representative NMACs, Version 7.1, Both Pilots Responding

Group (Table)	# NMACs	Planned separation	Crossing RA?	Geometric Reversal?	AC1 rates	AC2 rates	Caused by
Unres1(8.3)	2	0	No	Yes	–5000	–3000	CP112E
Ind01 (5.4)	8	–500	No	Yes	1000, 3000	3000, 5000	CP112E
Ind02 (6.4)	2	–750	No	Yes	–3000	–5000	CP112E
Ind03 (7.4)	1	–750	No	Yes	3000	5000	CP112E
Ind04 (8.4)	5	± 750	No	Yes	–1000	±3000	CP112E
Ind05 (9.4)	4	750,1000	No	Yes	5000	5000	CP112E
Ind06(18.4)	1	500	Yes	Yes	–3000	–3000	CP112E

7.1.2.1 Unresolved Representative NMACS

Representative NMAC Unres1 has two members in the group. Both of these NMACs occurred with the 25 foot altitude encoding. These are the only new NMACs with the 25 foot vertical tracker. Aircraft 1 (AC1) was descending at 5000 fpm and received a DDES RA. At the time the reversal was selected AC1 appeared to be still descending. With this very high vertical rate, even if the pilot follows the command and tries to level off, there isn't enough time (with tracker lag) to level off before the reversal is triggered.

At the time the reversal occurred, this appeared to be a vertical chase encounter, which would have triggered the CP112E reversal. The same encounter with 100 foot altitude encoding triggered the RA one second earlier and picked different sense commands.

7.1.2.2 Induced Representative NMACS

All of the induced Representative NMACs occurred with 100 foot altitude encoding.

Representative NMAC Ind01 has eight members in encounter class 5. Half of the encounters were in the low altitude FTEG simulations, the other half were in the high altitude FTEG collections. These are the only new NMAC encounters from the high altitude FTEG collection. At the time the reversal was initiated, both aircraft had a positive vertical rate.

Representative NMAC Ind02 has two members in encounter class 6. At the time of the reversal AC2 was below AC1 and descending. Due to tracker lag AC1 appears to also be descending when in fact AC1 had just stopped descending to respond to the CL RA. This is a case of RAs and planned maneuvers happening at the most inopportune moment.

Representative NMAC Ind03 has one member in encounter class 7. In this encounter AC2 is slightly below AC1 when AC2 begins a planned maneuver (0.15 g acceleration to 5000 fpm climb). At the same time AC1 begins a planned maneuver (0.05 g acceleration to 3000 fpm climb). AC2 with the higher vertical rate received DES RA. Because the higher vertical rate aircraft received the DES command, even though AC2 was complying with the RA, with tracker lag this still appeared to be a vertical chase encounter, so an undesirable reversal occurred.

Representative NMAC Ind04 has five members in encounter class 8. In these encounters the higher vertical rate aircraft (AC2) received a positive RA in the opposite sense. At the time the reversal was selected, AC2 was barely beginning to level off. These appeared to be SA01 encounters. Four of these encounters ended with ± 94 feet vertical separation.

Representative NMAC Ind05 had four members in encounter class 9. These encounters had very high vertical rates. In each case, AC2 with the low ID initiated the reversal. At the time of the reversal AC1 was reducing the climb rate and almost level. If you allow for tracker lag, these encounters looked like vertical chase scenarios. These encounters had 750 or 1000 feet planned separation.

Representative NMAC Ind06 has one member in encounter class 18. In this encounter the reversal came too late to be effective. The Version 7-25 and Version 7.1-25 encounters had reversals that occurred five seconds earlier. These reversals were effective.

7.1.3 Summary

The new NMACs for Version 7.1, while undesirable, represent a relatively small number (23) of encounters. The two unresolved encounters with 25 foot altitude reporting had 5000 fpm vertical rate for one aircraft. After 10 seconds the aircraft still appeared to be descending, which resulted in an unnecessary sense reversal. The remaining 21 encounters occurred with 100 foot altitude reporting, which is rarely coupled with a Version 7 (and by extension Version 7.1) TCAS. Most of these encounters had one aircraft with 5000 fpm vertical rate. In all of these encounters, one aircraft has to reverse a high vertical rate. In these examples it takes a while to level off and change direction, so these encounters still look like vertical chases, leading to sense reversals.

7.2 ONE PILOT NONRESPONDING

For the set of encounters with one pilot not responding to the TCAS RA, every encounter that produced a new NMAC or a new Save for Version 7.1-25 was individually simulated using FTEG for four versions of the logic (Version 6.04a, Version 7-25, Version 7 + CP112EV1.2-25, and Version 7.1-25). For each set of simulations, a one-page summary of the TCAS RAs generated by each version of the logic was produced.

7.2.1 Representative Saves

Encounters that generated new Saves for Version 7.1 are summarized in Table 7-2 below. There are thirty groups of encounters that represent 648 total encounters. A brief summary of each Representative Save follows the table. Appendix N contains encounter summaries and plots for the nonresponding Representative Saves. Twenty of the Representative Saves were attributed to CP112E; ten were attributed to CP115.

Table 7-2

New Representative Saves, Version 7.1, One Pilot Nonresponding

Group (Class)	# Saves	Planned separation	CrossRA?	Reversal	AC1 rates	AC2 rates	Solved by
Save01 (2)	38	-500, -750	No	Yes	400	3000, 5000	CP112E
Save02 (2)	2	-750	No	No	Level	5000	CP115
Save03 (4)	6	±500	No	Yes	1000, 3000	1000, 3000	CP112E
Save04 (5)	12	-750	No	Yes	-1000	3000	CP112E
Save05 (5)	12	-500	No	Yes	1000	3000	CP112E
Save06 (5)	25	0	Yes	Yes	3000	3000, 5000	CP112E
Save07 (5)	3	0	No	Yes	3000	3000, 5000	CP115
Save08 (5)	8	-500, -750	No	No	-1000, -3000, -5000	5000	CP115
Save09 (6)	11	0	No	Yes	-3000	-5000	CP112E
Save10 (6)	149	-250, ±500,-750	No	Yes	-1000, -3000, -5000	-1000, -3000, -5000	CP112E
Save11 (6)	1	0	No	Yes	-3000	-5000	CP115
Save12 (6)	16	-250, -500, -750	No	Yes	-3000, -5000	-3000, 5000	CP115
Save13 (7)	35	0	No	Yes	3000, 5000	3000, 5000	CP112E
Save14 (7)	28	750	No	Yes	1000, 3000, 5000	-1000, -3000, -5000	CP112E
Save15 (7)	79	±250, ±500, ±750	No	Yes	1000, 3000, 5000	1000, 3000, 5000	CP112E
Save16 (7)	1	0	No	Yes	3000	3000	CP115
Save17 (7)	2	750	No	No	5000	-1000	CP115
Save18 (8)	8	0	No	Yes	-5000	-3000	CP112E
Save19 (8)	56	-250, 500, ±750	No	Yes	-1000, -3000, -5000	-1000, -3000, -5000	CP112E

Save20 (8)	40	-500, -750	No	Yes	-1000, -3000, -5000	-3000, 3000	CP112E
Save21 (9)	21	250, ±500, ±750, ±1000	No	Yes	1000, 3000, 5000	1000, 3000, 5000	CP112E
Save22(14)	7	0	No	Yes	3000, 5000	3000, 5000	CP112E
Save23(14)	1	0	No	Yes	3000	3000	CP115
Save24(15)	17	0, -250	No	Yes	1000, 3000, 5000	3000, 5000	CP112E
Save25(15)	3	0	No	Yes	3000	3000	CP115
Save26(15)	3	0	No	Yes	3000	3000	CP115
Save27(16)	7	-750	No	Yes	-3000	-3000	CP112E
Save28(17)	37	0, -500	No	Yes	3000, 5000	3000, 5000	CP112E
Save29(18)	13	250, 500, 750	Yes	Yes	-3000, -5000	-3000,-5000	CP112E
Save30(19)	7	250, 500, 750, 1000	Yes	Yes	3000, 5000	3000, 5000	CP112E

Representative Save01 has 38 members in encounter class 2. These climbing vertical chase encounters all had poor performance for Version 6.04a and Version 7, with achieved separations less than 150 feet. The addition of CP112E allowed the TCAS on the nonresponding lower ID aircraft to recognize the lack of response and reverse the RA providing significant improvement in achieved separation.

Representative Save02 has two members in encounter class 2. These encounters had good performance with Version 6.04a, but resulted in NMACs with Version 7 and Version 7 + CP112E. The addition of CP115 (DCL instead of LC5) caused the responding aircraft to reduce its rate of climb faster so the NMAC was barely averted.

Representative Save03 has six members in encounter class 4. Four of these encounters were NMACs for Version 6.04a and all six were NMACs for Version 7. These are climbing vertical chase scenarios that are degraded because the responding aircraft increases its rate of climb in response to the CL RA and climbs toward the same altitude as the nonresponding aircraft. With the addition of CP112E, the worsening situation is recognized and a reversal solves the encounter.

Representative Save04 has 12 members in encounter class 5. Most of these encounters performed badly with Version 6.04a, with one significant exception (750 feet achieved separation). These encounters are climbing vertical chases that were caused by the combination of the response to the initial RA and the existing climb rate of the nonresponding aircraft. The addition of CP112E allowed a geometric reversal that barely resolved the encounter.

Representative Save05 has 12 members in encounter class 5. These climbing vertical chase encounters were all NMACs for Version 6.04a as well as Version 7. The addition of CP112E allowed the TCAS on the nonresponding aircraft to reverse the DES RA (which was being ignored) to a CL RA. The responding aircraft followed the reversal. Significant improvements in achieved separation were achieved because the reversal occurred 14 seconds prior to CPA.

Representative Save06 has 25 members in encounter class 5. Twenty four of these 25 previously unresolved NMAC encounters were also unresolved NMACs for Version 6.04a. In these encounters a relatively late planned climb maneuver sets up a climbing vertical chase. The addition of CP112E allows the nonresponding aircraft to reverse the RA resolving the encounter.

Representative Save07 has three members in encounter class 5. All of these encounters were NMACs for Version 6.04a, Version 7, and Version 7 + CP112E. The addition of CP115 replaced the RA sequence of LC1, LC5, DES, and CL for the nonresponding aircraft with DCL, CL. The reversal occurred one second earlier with the addition of CP115.

Representative Save08 has eight members in encounter class 5. Half of these encounters were NMACs for Version 6.04a. All eight encounters were NMACs for Version 7 and Version 7 + CP112E. In these encounters the responding aircraft received a DCL or DDES RA instead of the Adjust Vertical

Speed Adjust (AVSA) RAs. The change to Level Off, Level Off (LOLO) slightly changed the timing of the subsequent RAs, leading to enough increase in separation to avoid the NMAC.

Representative Save09 has 11 members in encounter class 6. Four of these descending vertical chase encounters were also NMACs for Version 6.04a. The addition of CP112E allowed for the sense reversal that resolved the encounter successfully.

Representative Save10 has 149 members in encounter class 6. This is a large group of descending vertical chase encounters with varying combinations of vertical rates and planned separation. The common theme in these encounters is the ability to recognize the unfolding vertical chase and reverse sense to resolve the NMAC.

Representative Save11 has one member in encounter class 6. This previously unresolved NMAC was not solved with the addition of CP112E. With the addition of CP115 for the nonresponding aircraft the first RA was DDES, the second RA is a DES which is a reversal. This allows the responding aircraft to reverse to a CL and solve the NMAC.

Representative Save12 has 16 members in encounter class 6. Twelve of these encounters were NMACs for Version 6.04a. All sixteen were NMACs for Version 7 and Version 7 + CP112E. In all these encounters with the addition of CP115 the nonresponding aircraft received a DCL or DDES initial RA that reversed sense. This allowed the responding aircraft to reverse and resolve the NMAC.

Representative Save13 has 35 members in encounter class 7. Eight of these encounters were not NMACs for Version 6.04a. The remaining 27 encounters were NMACs for Version 6.04a and Version 7. These climbing vertical chase encounters were resolved by the addition of CP112E. The nonresponding aircraft was able to reverse sense due to the TCAS logic recognizing the lack of response to the TCAS RA. This allowed the responding aircraft to reverse sense and solve the NMAC.

Representative Save14 has 28 members in encounter class 7. These encounters have two aircraft co-altitude until about 20 seconds before CPA. At this point the nonresponding aircraft begins a planned maneuver that is contrary to the selected RA. The responding aircraft maneuvers in the same direction as the nonresponding aircraft by following the RA. The addition of CP112E allows TCAS to detect the vertical chase and reverse sense to resolve the encounter.

Representative Save15 has 79 members from encounter class 7. This is a large group of climbing vertical chase encounters with varying combinations of vertical rates and planned separation. The common theme in these encounters is the ability to recognize the unfolding vertical chase and reverse sense to resolve the NMAC. This is a mirror image of Representative Save10.

Representative Save16 has one member in encounter class 7. This encounter was an unresolved NMAC for Version 6.04a, Version 7, and Version 7 + CP112E. The nonresponding aircraft received a

DCL followed by a reversal to CL with CP115, rather than the LC1, LC5, DES, IDES with CP112E. The reversal with CP115 triggered a DES for the responding aircraft which resolved the encounter.

Representative Save17 has two members in encounter class 7. In these encounters Version 7 and Version 7 + CP112E almost resolved the NMAC, but fell 6 feet short. With CP115 the responding aircraft receives a DCL rather than the advisories LC1, LC5 provided with Version 7 and Version 7 + CP112E. The DES advisory comes one second later with CP115, but the IDES comes 5 seconds sooner with CP115. The earlier increase advisory seems to have contributed significantly to the increase in separation.

Representative Save18 has eight members in encounter class 8. Six of these eight descending vertical chase encounters were unresolved NMACs for Version 6.04a. With the addition of CP112E the vertical chase was recognized and a reversal was issued early enough to resolve the encounter.

Representative Save19 has 56 members in encounter class 8. Forty four of these descending vertical chase encounters were NMACs for Version 6.04a. With the addition of CP112E a reversal was issued just in time to resolve the encounter.

Representative Save20 has 40 members in encounter class 8. Twenty eight of these climbing vertical chase encounters were NMACs for Version 6.04a. The combination of a planned climb by the nonresponding aircraft and response to a CL RA by the other aircraft created a vertical chase. A reversal was issued with plenty of time to resolve the encounter.

Representative Save21 has 21 members in encounter class 9. Seventeen of these climbing vertical chase encounters were NMACs for Version 6.04a. The addition of CP112E allowed the RA to reverse sense with plenty of time to resolve the encounter.

Representative Save22 has seven members in encounter class 14. All of these climbing vertical chase encounters were unresolved NMACs for Version 6.04a and Version 7. The addition of CP112E allowed the vertical chase to be detected and the reversal solved the NMAC.

Representative Save23 has one member in encounter class 14. This encounter is the same geometry as Save22, but the nonresponding aircraft has the lower Mode S address in this case. For the nonresponding aircraft, CP112E gave the following sequence of RAs: LC1 @34, LC5 @48, DES @49, IDES @51. For the same aircraft, CP115 gave the following sequence of RAs: DCL @34, CL @46 (reversal). This reversal allowed the responding aircraft to descend and solve the NMAC.

Representative Save24 has 17 members in encounter class 15. Fifteen of these vertical chase encounters were previously unresolved NMACs, the other two encounters were previously induced NMACs. These are all climbing vertical chase encounters that were successfully resolved with the addition of CP112E.

Representative Save25 has three members from encounter class 15. These three climbing vertical chase encounters were successfully resolved when the addition of CP115 allowed a reversal that was not present with Version 7 + CP112E.

Representative Save26 has three members from encounter class 15. These three climbing vertical chase encounters were barely resolved when the addition of CP115 allowed an earlier reversal than Version 7 + CP112E.

Representative Save27 has seven members from encounter class 16. These descending vertical chase encounters were all NMACs for Version 6.04a as well as Version 7. The addition of CP112E allowed the responding aircraft to recognize the vertical chase and reverse the RA to solve the NMAC.

Representative Save28 has 37 members in encounter class 17. Thirty five of these climbing vertical chase encounters had no planned separation at CPA. Thirty two of these encounters were NMACs for Version 6.04a. The addition of CP112E allowed a sense reversal that successfully resolved the encounter.

Representative Save29 has 13 members in encounter class 18. These descending vertical chase encounters were resolved by RA reversals made possible by CP112E.

Representative Save30 has seven members in encounter class 19. Three of these encounters were NMACs for Version 6.04a. These climbing vertical chase encounters are resolved by the RA reversal allowed by the addition of CP112E.

7.2.2 Representative NMACs

Encounters that generated new NMACs for Version 7.1 with one pilot not responding to the RA are summarized in Table 7-3 below. There are fourteen groups of encounters that represent 40 total encounters. A brief summary of each Representative NMAC follows the table. Appendix O contains encounter summaries and plots for the fourteen Representative NMACs. Eleven of the new Representative NMACS were attributed to CP112E; three were attributed to CP115.

Table 7-3

New Representative NMACs, Version 7.1, One Pilot Nonresponding

Group (Table)	# NMACs	Planned separation	Crossing RA?	Reversal?	AC1 rates	AC2 rates	Caused by
Unres1(6.3)	2	0	No	Yes	–1000	–5000	CP112E
Unres2(9.3)	1	0	No	Yes	5000	3000	CP112E
Ind01 (5.4)	3	±500	No	Yes	5000	3000	CP112E
Ind02 (5.4)	2	–500	No	Yes	–1000	100	CP112E
Ind03 (5.4)	2	–500	No	Yes	3000	5000	CP115
Ind04 (6.4)	1	–500	No	Yes	–3000	–5000	CP112E
Ind05 (7.4)	10	250, 500	No	Yes	1000	–1000	CP112E
Ind06 (7.4)	1	–750	No	Yes	3000	5000	CP112E
Ind07 (8.4)	2	250	Yes	Yes	–3000	–3000	CP112E
Ind08 (8.4)	3	250	No	Yes	–1000	–3000	CP112E
Ind09 (9.4)	6	250, ±500, 750	No	Yes	1000, 3000, 5000	3000, 5000	CP112E
Ind10(15.4)	1	–250	Yes	Yes	3000	3000	CP115
Ind11(19.4)	5	–250, 500	No	Yes	3000, 5000	3000, 5000	CP112E
Ind12(19.4)	1	750	Yes	Yes	3000	5000	CP115

7.2.2.1 Unresolved Representative NMACS

Representative NMAC Unres1 has two members in encounter class 6. In these encounters a planned level-off maneuver by the nonresponding aircraft defeated the new reversal allowed by CP112E.

Representative NMAC Unres2 has one member in encounter class 9. In this encounter a planned level-off maneuver by the nonresponding aircraft defeated the new reversal allowed by CP112E.

7.2.2.2. Induced Representative NMACS

Representative NMAC Ind01 has three members in encounter class 5. These are vertical chase encounters. In these encounters the responding aircraft is climbing at a very high vertical rate (5000 fpm). The nonresponding aircraft begins a planned climb maneuver just before the RA. The responding aircraft receives a DES RA. The responding aircraft climbing at a high vertical rate complies with the RA, but it takes a long time to change from climbing at 5000 fpm to descending at 1500 fpm. The responding aircraft then receives a CL RA.

Representative NMAC Ind02 has two members in encounter class 5. The two aircraft are essentially co-altitude when the first RA occurs. The level nonresponding aircraft receives a DES RA just as it begins a planned climb maneuver and the descending aircraft receives a CL RA. This sets up a climbing vertical chase encounter. The new reversal allowed by CP112E comes too late to resolve the encounter.

Representative NMAC Ind03 has two members in encounter class 5. These encounters were not NMACs with CP112E, but became NMACs with the addition of CP115. With CP112E the responding aircraft received LC2 @37, LC1 @41, DES @42, IDES @45, CL @49, ICL@51. With the addition of CP115 the responding aircraft received DCL @37, CL @49. This was enough of a difference to generate an NMAC.

Representative NMAC Ind04 has one member in encounter class 6. This encounter was an NMAC for Version 6.04a. In this encounter the nonresponding aircraft was initially descending, and then a planned level-off maneuver triggered a reversal. The responding aircraft was descending at 3000 fpm. This aircraft received a CL RA that reversed two seconds later to a DES.

Representative NMAC Ind05 is the largest group with ten members in class 7. These encounters have relatively benign vertical rates (± 1000 fpm). In these encounters the responding aircraft begins a planned descend maneuver just as a CL RA is received. The nonresponding aircraft begins a planned climb maneuver just as a DES RA is received. This sets up a climbing vertical chase. By the time the responding aircraft reverses the RA, it is too late to resolve the encounter.

Representative NMAC Ind06 has one member in encounter class 7. In this encounter a planned 5000 fpm climb by responding AC2 triggers a DES RA. One second later nonresponding AC1 gets a CL RA and begins a planned climb maneuver. AC2 begins to respond to the DES just as a reversal to CL is given.

Representative NMAC Ind07 has two members from encounter class 8. The combination of initial RAs and nonresponse by one aircraft sets up a descending vertical chase. The reversal generated by CP112E almost resolves the encounter.

Representative NMAC Ind08 has three members in encounter class 8. In these encounters the initial RA coupled with a planned contrary maneuver by the nonresponding aircraft cause a descending vertical chase. The reversal allowed by CP112E comes too late to resolve the encounter.

Representative NMAC Ind09 has six members in encounter class 9. In these encounters both aircraft are initially climbing. The nonresponding aircraft receives a CL RA, but performs a planned gradual level-off maneuver. The responding aircraft receives a DCL RA which reversed to a CL in response to the intruder's level-off maneuver.

Representative NMAC Ind10 has one member in class 15. This encounter is not an NMAC for CP112E. The encounter begins with the nonresponding aircraft climbing at 3000 fpm. The responding aircraft is initially level then begins a planned acceleration at 40 seconds to achieve a 3000 fpm climb rate. At this time the responding aircraft receives a LC5 RA, followed by DCL RA three seconds later. At 50 seconds elapsed time the responding aircraft receives a CL RA, which is a reversal. The nonresponding aircraft ignores the reversal and an NMAC is generated. The responding aircraft in the CP112E encounter receives only descend sense RAs which effectively solves the encounter.

Representative NMAC Ind11 has five members in encounter class 19. In these encounters both aircraft are initially climbing at 3000 or 5000 fpm. A planned level-off maneuver by the nonresponding aircraft defeats the reversal leading to the NMAC.

Representative NMAC Ind12 has one member in encounter class 19. This encounter is not an NMAC for CP112E. With CP112E the nonresponding aircraft receives LC2 followed by LC1. At this point the nonresponding aircraft is beginning a slow planned level-off maneuver, which may have appeared to be compliant to the RAs. No reversal is generated in the CP112E encounter. The LC2 and LC1 are followed by DES and IDES commands which are ignored as well. The responding aircraft continues responding to the CL RA and the encounter is successfully resolved. With CP115 the nonresponding aircraft receives a stronger DCL initial RA. This is followed by DES, IDES and eventually a reversal. This forces the responding aircraft to reverse reducing the achieved separation and leading to the NMAC.

7.2.3 Summary

The Phase II analysis of encounters where one TCAS aircraft ignores the RA is very encouraging. There are 648 encounters where Version 7.1 resolved an NMAC that Version 7 did not resolve. Forty of these "saves" can be traced to CP115, the remaining 608 "saves" can be traced to CP112E. In contrast there are only forty encounters the have NMACs where Version 7 did not have an NMAC. Four of these new NMACs can be traced to CP115, the remaining thirty six encounters can be traced to CP112E.

7.3 TCAS VS. UNEQUIPPED AIRCRAFT

For the set of encounters with a TCAS-equipped aircraft and an unequipped intruder aircraft, every encounter that produced a new NMAC or a new Save for Version 7.1 was individually simulated using FTEG for three versions of the logic (Version 7, Version 7 + CP112EV1.2, and Version 7.1). The altitude quantization was not varied for these encounters. For each set of simulations, a one-page summary of the TCAS RAs generated by each version of the logic was produced.

7.3.1 Representative Saves

Encounters that generated new Saves for Version 7.1 are summarized in Table 7-4 below. There are twenty groups of encounters that represent 223 total encounters. A brief summary of each Representative Save follows the table. Appendix P contains encounter summaries and plots for the twenty Representative Saves. Thirteen of the twenty Representative Saves were attributed to CP112E seven were attributed to CP115.

Table 7-4

New Representative Saves, Version 7.1, TCAS vs. Unequipped Intruder

Group (Class)	# Saves	Planned separation	Crossing RA?	Reversal?	AC1 rates	AC2 rates	Solved by
Save01 (2)	18	–500, –750	No	Yes	0, ±400	3000, 5000	CP112E
Save02 (5)	7	–500, -750	No	Yes	±1000	3000	CP112E
Save03 (5)	14	0	Yes	Yes	3000	3000, 5000	CP112E
Save04 (4)	6	0, –250, –500, –750	No	No	–1000, –3000, –5000	5000	CP115
Save05 (7)	24	0	No	Yes	3000, 5000	3000, 5000	CP112E
Save06 (7)	20	–250, –500, –750	No	Yes	1000, 3000, 5000	3000, 5000	CP112E
Save07 (7)	15	750	No	Yes	1000, 3000, 5000	–3000, –5000	CP112E
Save08 (7)	17	250, 500, 750	No	Yes	3000, 5000	1000, 3000, 5000	CP112E
Save09 (7)	2	750	No	Yes	5000	–3000	CP115
Save10 (8)	17	500, 750	No	Yes	–3000, –5000	–3000, –5000	CP112E
Save11 (8)	20	–500, –750	No	Yes	–1000, –3000	3000	CP112E

Group (Class)	# Saves	Planned separation	Crossing RA?	Reversal?	AC1 rates	AC2 rates	Solved by
Save12 (8)	2	500	No	Yes	–5000	–3000	CP115
Save13 (8)	1	–500	No	Yes	–5000	5000	CP115
Save14 (9)	1	500	No	Yes	5000	5000	CP115
Save15(15)	4	0	No	Yes	3000, 5000	3000, 5000	CP112E
Save16(16)	7	–250, –750	Yes	No	–1000, –3000	–5000	CP115
Save17(17)	23	0	No	Yes	3000, 5000	3000, 5000	CP112E
Save18(17)	15	250, –500	No	Yes	3000, 5000	1000, 5000	CP112E
Save19(18)	9	500, 750	No	Yes	–1000, –3000, –5000	–3000, –5000	CP112E
Save20(18)	1	750	No	Yes	–5000	–3000	CP115

Representative Save01 has 18 members in encounter class 2. These climbing vertical chase encounters were caused by the response of the TCAS aircraft to the initial RA. The reversal allowed by the addition of CP112E solved the NMAC. All 18 encounters have AC1 as the unequipped intruder.

Representative Save02 has seven members in encounter class 5. These climbing vertical chase encounters were caused by the planned maneuver of the unequipped intruder and the response of the TCAS aircraft to the initial RA. The addition of CP112E allowed for new reversals or earlier reversals to resolve the NMAC. All seven encounters have AC1 equipped with TCAS.

Representative Save03 has 14 members in encounter class 5. These were preexisting climbing vertical chase encounters caused by the planned maneuver of the unequipped intruder aircraft. The addition of CP112E allowed for new reversals to solve the previously unresolved NMAC. All 14 encounters have AC1 equipped with TCAS.

Representative Save04 has six members in encounter class 5. Version 7 and Version 7 + CP112E had initial AVSA RAs (LD2 followed by LD5) that strengthened to CL and reversed to DES after CPA. The addition of CP115 changed the initial AVSA RA to LOLO (DDES). The subsequent strengthening to CL was sufficient to solve the NMAC. All six encounters have AC1 equipped with TCAS.

Representative Save05 has 24 members in encounter class 7. These were climbing vertical chase encounters caused by the planned maneuvers of the two aircraft. The addition of CP112E allowed for reversals to solve the previously unresolved NMAC. Five encounters have AC1 equipped with TCAS.

Representative Save06 has 20 members in encounter class 7. These climbing vertical chase encounters were caused by the planned maneuver of the unequipped intruder and the response of the TCAS aircraft to the initial RA. The addition of CP112E allowed the RA to reverse sense solving the NMAC. All twenty encounters have AC1 equipped with TCAS.

Representative Save07 has 15 members in encounter class 7. These were climbing vertical chase encounters caused by the planned maneuver of the unequipped intruder and the response of the TCAS aircraft to the initial RA. The addition of CP112E allowed for a reversal to solve the NMAC. Nine encounters have AC1 equipped with TCAS.

Representative Save08 has 17 members in encounter class 7. These climbing vertical chase encounters were caused by planned maneuvers of the two aircraft. The addition of CP112E allowed for a sense reversal to solve the NMAC. All 17 encounters have AC1 as the unequipped intruder.

Representative Save09 has two members in encounter class 7. Version 7 and Version 7 + CP112E had initial AVSA RAs (LC1 followed by LC5) that strengthened to DES and increased to IDES. The addition of CP115 changed the initial AVSA RA to LOLO (DCL). The slight change in timing of the strengthened RA allowed for a sense reversal to CL which solved the NMAC. Both encounters have AC1 equipped with TCAS.

Representative Save10 has 17 members in encounter class 8. These descending vertical chase encounters were caused by the response of the TCAS aircraft to the initial RA. The addition of CP112E allowed for a sense reversal to solve the NMAC. All 17 encounters have AC1 equipped with TCAS.

Representative Save11 has 20 members in encounter class 8. These climbing vertical chase encounters were caused by the response of the TCAS aircraft to the initial RA. The addition of CP112E allowed for a more timely sense reversal to solve the NMAC. All twenty encounters have AC1 equipped with TCAS.

Representative Save12 has two members in encounter class 8. Version 7 and Version 7 + CP112E had initial AVSA RAs (LD2 followed by LD1) that strengthened to CL, increased to ICL, reversed to DES, and strengthened to IDES. The addition of CP115 changed the initial AVSA RA to LOLO (DDES). The subsequent strengthening to CL occurred two seconds later. The reversal to DES and increase to

IDES occur at the same time they were observed with Version 7 and Version 7 + CP112E. The change from AVSA to LOLO was enough to resolve the NMAC. Both encounters have AC1 as the unequipped intruder.

Representative Save13 has one member in encounter class 8. Version 7 and Version 7 + CP112E had initial AVSA RAs (LD2, LD1, and DDES) that strengthened to CL and increased to IDES. The encounter did reverse sense, but this occurred after CPA. The addition of CP115 changed the initial AVSA RA to LOLO (DDES). The slight change in timing of the CL RA allowed for a timely sense reversal to DES which solved the NMAC. AC1 is equipped with TCAS.

Representative Save14 has one member in encounter class 9. Version 7 and Version 7 + CP112E had initial AVSA RAs (LC2 followed by LC1) that strengthened to DES, increased to IDES, and eventually reversed to CL. The addition of CP115 changed the initial AVSA RA to LOLO (DCL). The first positive RA occurred 3 seconds later with CP115. This delay on the DES RA leads to more separation when the command eventually reverses to CL. AC1 is equipped with TCAS.

Representative Save15 has four members in encounter class 15. These were climbing vertical chase encounters caused by the planned maneuver of the unequipped intruder aircraft. The addition of CP112E allowed for reversals to solve the previously unresolved NMAC. All four encounters have AC1 equipped with TCAS.

Representative Save16 has seven members in encounter class 16. With Version 7 and Version 7 + CP112E the initial descending vertical chase encounter generated an AVSA (LD2) RA. A planned level-off maneuver by the unequipped intruder defeats the LD2 RA. With the addition of CP115, the initial RA is LOLO (DDES) followed by CL and ICL. The change from AVSA to LOLO reduces the descent of the TCAS aircraft and solves the NMAC. All seven encounters have AC1 equipped with TCAS.

Representative Save17 has 23 members in encounter class 17. These were climbing vertical chase encounters caused by the planned maneuvers of the two aircraft. The addition of CP112E allowed for a reversal to solve the NMAC. Fourteen encounters have AC1 equipped with TCAS.

Representative Save18 has 15 members in encounter class 17. These climbing vertical chase encounters were initiated by planned maneuvers of the two aircraft and were made worse by the response of the TCAS aircraft to the initial RA. The addition of CP112E allowed for a sense reversal to solve the NMAC. Only one encounter has AC1 equipped with TCAS.

Representative Save19 has nine members in encounter class 18. These descending vertical chase encounters were caused by the response of the TCAS aircraft to the initial RA. The addition of CP112E allowed for a sense reversal to solve the NMAC. All nine encounters have AC1 equipped with TCAS.

Representative Save20 has one member in encounter class 18. This brief descending vertical chase encounter was caused by the planned maneuver of the unequipped intruder aircraft. The addition of

CP115 delayed the first positive RA allowing the selection of a more appropriate advisory. AC1 is the unequipped intruder.

7.3.2 Representative NMACs

Encounters that generated new NMACs for Version 7.1 are summarized in Table 7-5 below. There are seven groups of encounters that represent eighteen total encounters. A brief summary of each Representative NMAC follows the table. Appendix Q contains encounter summaries and plots for the seven Representative NMACs. Three of the seven Representative NMACs were attributed to CP112E; four were attributed to CP115.

Table 7-5

New Representative NMACs, Version 7.1, TCAS vs. Unequipped Intruder

Group (Class)	# NMACs	Planned separation	Crossing RA?	Reversal ?	AC1 rates	AC2 rates	Caused by
Ind01 (5)	5	0, –250, –500, –750	No	No	–1000, –3000, –5000	3000, 5000	CP115
Ind02 (7)	1	–250	No	Yes	5000	3000	CP112E
Ind03 (7)	4	750	No	No	3000, 5000	–3000	CP115
Ind04 (8)	3	250	No	Yes	–3000	–1000	CP112E
Ind05 (8)	1	–250	No	No	–5000	5000	CP115
Ind06 (9)	1	500	No	Yes	3000	5000	CP112E
Ind07(19)	3	–250, –500	Yes	No	5000	1000, 3000	CP115

Representative NMAC Ind01 has five members in encounter class 5. These are encounters where the two aircraft planned to cross in altitude. The RA selected by the TCAS aircraft is defeated by the planned maneuver of the unequipped intruder. These encounters were marginal with Version 7 and Version 7 + CP112E. The slight change in timing caused by the addition of CP115 caused the NMAC.

Representative NMAC Ind02 has one member in encounter class 7. This is a climbing vertical chase encounter caused by the planned maneuvers. This vertical chase became more pronounced with the response to the initial RA. The addition of CP112E allowed the TCAS aircraft to reverse sense causing an NMAC.

Representative NMAC Ind03 has four members in encounter class 7. These aircraft planned to cross in altitude. The response to the initial RA established a downward vertical chase. Version 7 and Version 7 + CP112E barely resolved the encounter with a reversal. The slight delay in issuing the first positive RA with CP115 prevented the reversal, causing an NMAC.

Representative NMAC Ind04 has three members in encounter class 8. These aircraft planned to cross in altitude. The response to the initial RA, coupled with a planned descent by the intruder aircraft set up a descending vertical chase. Version 7 stuck with the initial RA, Version 7 + CP112E reversed the sense of the initial RA and caused an NMAC.

Representative NMAC Ind05 has one example in encounter class 8. These aircraft plan to cross in altitude. The response of the TCAS aircraft to the initial RA sets up a climbing vertical chase. Version 7 and Version 7 + CP112E did not reverse the encounter and barely resolved the encounter. The addition of CP115 delayed the DES RA by one second and caused the NMAC.

Representative NMAC Ind06 has one example in encounter class 9. These aircraft intended to cross in altitude and level off 500 feet apart. The response to the initial RA caused a climbing vertical chase. With Version 7 the RA was not reversed. A level-off maneuver by the unequipped intruder prevented the NMAC. The addition of CP112E allowed the initial RA to reverse. Unfortunately this reversal was defeated by the planned level-off maneuver of the unequipped intruder.

Representative NMAC Ind07 has three members in encounter class 19. These aircraft planned to cross in altitude and level-off 250 or 500 feet apart. Version 7 and Version 7 + CP112E solve the encounter by descending, crossing back through the intruder aircraft's path. The addition of CP115 delays the DES RA by one second, causing the NMAC.

7.3.3 Summary

The Phase II analysis of encounters with TCAS with an unequipped intruder is also encouraging. There are a total of 223 encounters where Version 7.1 resolved an NMAC that Version 7 did not resolve. Twenty of these "saves" can be traced to CP115, the remaining 203 "saves" can be traced to CP112E. In contrast, there are only eighteen encounters that have NMACs for Version 7.1 where Version 7 did not have an NMAC. Thirteen of these new NMACs can be traced to CP115, the remaining five can be traced to CP112E.

7.4 SUMMARY OF VERSION 7.1 REPRESENTATIVE SAVES AND NMACS

The analysis of any change in TCAS II logic always entails trade-offs. Whenever there is a change made to the CAS logic, improvements are made in one set of encounters, while trying to minimize unintended negative outcomes in other encounters. In the case of TCAS Version 7.1, the two Change Proposals (CP112E and CP115) are focused on the sense reversal logic, specifically for nonresponding and unequipped intruder aircraft and the corrective VSL or Adjust Vertical Speed, Adjust encounters.

Improvements are documented in the case of TCAS-TCAS encounters with one nonresponding aircraft. Specifically 640 “saves” are observed for Version 7.1 while 40 new NMACs are observed.

Improvements are documented in the case of TCAS-unequipped encounters as well. Specifically 223 “saves” are observed for Version 7.1 while eighteen new NMACs are observed.

A reduction in performance is documented in the case of TCAS-TCAS encounters with both aircraft following the RA. There are no “saves” and there are 23 new NMACs observed. Two of these new NMACs occur when one aircraft has a very high initial vertical rate and both aircraft use 25 foot altitude data. The remaining 21 new NMACs occur with 100 foot altitude data. The pairing of 100 foot altitude encoding transponder with Version 7 TCAS units is somewhat rare, so these 23 NMACs are thought to be unlikely.

As mentioned in Section 3.1.2.4 an earlier implementation of CP112E with code to address SA01C had unexpected decreased performance with both aircraft following the RA. An attempt was made to correct the SA01C problem, but the revisions generated more new NMACs in different encounters. The SA01C change was proposed based on simulated encounters only, these encounters were not observed in monitoring data. A decision was taken by SC-147 to remove the code implementing the SA01C change from CP112E to avoid delays in the implementation of the remaining components of CP112E which have been observed operationally. This decision resulted in a reduced number of new NMACs for Version 7.1.

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8. SUMMARY OF TCAS II VERSION 7.1 LOGIC EVALUATION

8.1 BACKGROUND

Lincoln Laboratory carried out a thorough study of the incremental releases of CP112E which were produced under the sponsorship of the EUROCONTROL ACAS Programme. An FAA-sponsored assessment team (including The Johns Hopkins Applied Physics Laboratory (JHUAPL), the FAA William J. Hughes Technical Center (WJHTC), MITRE, and Lincoln Laboratory) worked with the designers of CP112E (CENA, DSNA, and SofreAvia) for this effort. CP112E is a focused change to the sense reversal logic of TCAS Version 7. Lincoln Laboratory has prior experience with evaluating TCAS sense reversals from our work on TCAS Version 7. Lincoln Laboratory detected problems with the TCAS-TCAS component of CP112E (unexpected decreases in performance when both aircraft follow the RA) that were mitigated by revisions to CP112E.

Previous logic analysis efforts at Lincoln Laboratory focused on TCAS-TCAS encounters where both aircraft follow the RA. High-level analysis was performed on all equipage combinations including TCAS-TCAS encounters with one aircraft not following the RA and TCAS-unequipped encounters. In depth analysis was limited to TCAS-TCAS encounters with both aircraft following the RA. For the current logic evaluation effort, the high level analysis is performed as before. Because the final version of CP112E is tailored to TCAS-TCAS encounters where one aircraft ignores the RA and TCAS-unequipped encounters the in depth analysis is expanded to include all equipage combinations.

Lincoln Laboratory carried out a thorough evaluation of the proposed Version 7.1 logic. This includes CP112E as well as CP115 which deals with corrective VSL RAs which are annunciated to the flight crew as “Adjust Vertical Speed, Adjust.” CP115 changes all corrective VSL RAs requiring vertical rates of 500, 1000, or 2000 fpm to VSL RAs requiring a vertical rate of 0 fpm. In addition the confusing “Adjust Vertical Speed, Adjust” annunciation is changed to “Level Off, Level Off.” The proper response to corrective VSL or AVSA RA is always a move toward level flight, in other words a reduction in vertical speed. Several encounters were observed in European airspace where the flight crew increased their vertical speed in response to an AVSA RA causing reduced separation with the intruder aircraft.

A separate study at Lincoln Laboratory evaluated the behavior of Version 7.1 using a new 2008 United States encounter model. The results of this effort have been published separately, in Reference 12.

8.2 ANALYSIS

8.2.1 High-Level Analysis

The high level analysis, known as Phase I indicates that the performance for Version 7.1 for TCAS-TCAS encounters with both aircraft following the RA is slightly worse than the performance for Version 7. While this is disappointing, the Version 7.1 performance is improved when compared to the original release of CP112E.

In contrast, the performance for TCAS-unequipped encounters is improved from Version 7 to Version 7.1. The TCAS-TCAS encounters with one aircraft ignoring the TCAS RA show the greatest improvement from Version 7 to Version 7.1.

8.2.2 In-Depth Analysis

To begin the Phase II analysis, every encounter that resulted in an NMAC for either Version 7 or Version 7.1 was isolated. Every encounter that was not an NMAC for Version 7 and became an NMAC for Version 7.1 is called a "new NMAC." Every encounter that was an NMAC for Version 7 and was not an NMAC for Version 7.1 is called a "new save."

Each new NMAC and new save was individually simulated for Version 6.04a, Version 7, and Version 7.1. For each group of simulations, a one-page summary of RAs generated by each logic version is generated. These encounter summaries are sorted by encounter class, NMAC type, the sense of the RA generated, and the aircraft vertical rates. One encounter is selected to represent each group of new saves and new NMACs. These are called Representative Saves and Representative NMACs.

Each of the Representative NMACs and Representative Saves were studied. Tables were produced summarizing common parameters observed within each group. This information provides the reader with some insight into the mechanism for each new Save and each new NMAC.

The results from this in depth level analysis of the stress testing simulations indicate that the performance for Version 7.1 for TCAS-TCAS encounters with both aircraft following the RA is slightly worse than the performance for Version 7. There are 23 new NMACs and no new saves out of 183072 total encounters, representing a decrease in effectiveness for these simulated encounters of 0.01256%. As mentioned above the Version 7.1 performance is improved when compared to the original release of CP112E. In addition, 21 of the 23 new NMACs are found in encounters with Version 7.1 using 100 foot altitude data. This is expected to be a very rare pairing of old transponders and new TCAS units.

In contrast, the performance of the stress testing simulations of TCAS-unequipped encounters is improved from Version 7 to Version 7.1. There are 233 new saves and 18 new NMACs out of 91536 total encounters. This is a net gain of 215 saves representing an increase in effectiveness for these simulated encounters of 0.23488%.

The stress testing simulations of TCAS-TCAS encounters with one aircraft not following the RA show the greatest improvement from Version 7 to Version 7.1. There are 648 new saves and 40 new NMACs out of 183073 total encounters. This is a net gain of 608 saves representing an increase in effectiveness for these simulated encounters of 0.33211%.

The improvement for the TCAS-TCAS encounters with one aircraft not following the RA, coupled with the improvement for TCAS-unequipped encounters offsets the small degradation in performance for the TCAS-TCAS encounters with both aircraft following the RA.

8.2.3 Interoperability

The analysis presented above is based on baseline simulations conducted with a mixture of Version 6.04a equipped aircraft and Version 7 equipped aircraft contrasted with the "logic under test" simulations with a mixture of Version 6.04a equipped aircraft and Version 7.1 equipped aircraft. There is no one collection with a mixture of Versions 6.04a, 7, and 7.1. This is due to the limited number of aircraft equipages allowed by the existing FTEG software. An additional set of simulations were conducted for a mixture of Version 7 aircraft and Version 7.1 aircraft. With this final set of simulations we are able to check for incompatibilities between all versions of the CAS logic that could exist in the U.S. airspace for a significant period of time.

Previous experience with mixed equipage encounters suggests that the performance will be no worse than the performance observed if both aircraft are equipped with the same version of CAS logic. From the baseline and "logic under test" it was determined that there are no significant interoperability issues between Version 6.04a and Version 7, or between Version 6.04a and Version 7.1. From the additional set of simulations it was determined that, as expected there were no significant interoperability issues between Version 7 and Version 7.1.

8.3 CONCLUSIONS

An international team of subject matter experts have recommended improvements to TCAS Version 7 targeted mainly at improving the sense reversal logic and simplifying corrective Vertical Speed Limit (VSL) RAs. These changes will be added to TCAS Version 7 and released as Version 7.1. Several organizations have studied the effectiveness of TCAS Version 7.1.

Lincoln Laboratory performed an analysis comparing Version 7.1 to Version 6.04a and Version 7 using simulated encounters that are designed to stress the design limits of TCAS. Three separate groups of encounters were studied. The first group of encounters is two TCAS-equipped aircraft that both follow the TCAS RA. The second group of encounters is two TCAS-equipped aircraft where one aircraft ignores the TCAS RA. The third group of encounters is one TCAS-equipped aircraft with an unequipped intruder.

There is a slight decrease in performance for the TCAS-TCAS encounters with both aircraft following the RA. Most of these questionable encounters were simulated with Version 7.1 coupled with a

100 foot altitude encoding transponder. This particular configuration is expected to be quite rare. In addition the improvement in performance observed for TCAS Version 7.1 in TCAS-TCAS encounters with one aircraft ignoring the RA and TCAS-unequipped encounters greatly offsets the small decrease in performance in the TCAS-TCAS with both aircraft following the RA.

REFERENCES

1 B. J. Chludzinski, "Lincoln Laboratory Evaluation of TCAS II Logic Version 7," MIT Lincoln Laboratory, Lexington, MA, Project Report ATC-268 (13 December 1999).

2 A. C. Drumm, "Lincoln Laboratory Evaluation of TCAS II Logic Version 6.04a," MIT Lincoln Laboratory, Lexington, MA, Project Report ATC-240 (21 February 1996).

3 Stéphan Chabert, EMOTION-7 WP1/012/D version 1.0, Issue analysis report - Issue SA01 - Inappropriate reversal logic initiation in co-ordinated encounters, 13 April 2000.

4 Stéphan Chabert, EMOTION7/WP2/024/D, Issue rectification report - Issue SA01 - Inappropriate reversal logic initiation in co-ordinated encounters, 13 October 2000.

5 Stéphan Chabert, SIR/WP3/20D Version 1.2, SIR Final Report, 16 July 2004.

6 Hérve Drévillon, SIRE/WP2/50W Version 1.1, CP112E pseudo-code baseline, 28 November 2005.

7 Hérve Drévillon and Stéphan Chabert, SIRE+/WP1/13/D Version 1.0, Pseudo-code for CP112E final version, 12 May 2006.

8 Hérve Drévillon and Stéphan Chabert, SIRE+/WP1/13/D Version 1.2, Pseudo-code for CP112E final version, 28 February 2007.

9 Thierry Arino, Eric Vallauri, Hérve Drévillon, Stéphan Chabert and Christian Aveneau, SIRE+/WP5/40/D, CP115 (LOLO) Evaluation Report, 16 May 2007.

10 RTCA/DO-298, "Safety Analysis of Proposed Change to TCAS RA Reversal Logic," 8 November 2005.

11 RTCA/DO185B, "Minimum Operational Performance Standards for Traffic Alert and Collision Avoidance System II (TCAS II)," 19 June 2008.

12 L.P. Espindle, J.D. Griffith and J.K. Kuchar, "Safety Analysis of Upgrading to TCAS Version 7.1 Using the 2008 U.S. Correlated Enounter Model," MIT Lincoln Laboratory, Lexington, MA, Project Report ATC-349 (11 May 2009).