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**International Civil Aviation Organization  
UNDP/ICAO Regional Project RLA/98/003  
Transition to the CNS/ATM Systems in the CAR and SAM Regions**

**Fifth Meeting/workshop of Air Traffic Management (ATM) Authorities and  
Planners for RVSM, RNAV routes and RNP implementation in the CAR and SAM Regions  
(AP/ATM/5 RVSM-RNAV-RNP)**

(Panama, Panama, 18 to 20 June 2003)

**Agenda Item 4: Review of the issues related with RVSM Implementation in the CAR/SAM  
Regions**

**Summary of the Preliminary Cost-Benefit Analysis for the Implementation of RVSM in the  
CAR/SAM**

(Presented by the United States of America)

**Summary**

This paper presents the findings of a preliminary cost-benefit study to estimate the potential operator cost-savings resulting from the implementation of RVSM in the CAR/SAM Regions. This study finds that benefits will exceed costs by a ratio of nearly 4:1 for this airspace initiative.

**1. Introduction**

1.1 This paper presents the findings of a preliminary cost-benefit analysis to determine the potential benefits to CAR/SAM commercial aircraft operators from RVSM implementation.

**2. Discussion of Costs**

**2.1 Assumptions for Determination of Costs**

- Operators will upgrade all non-approved aircraft for RVSM operations

- Monitoring costs are estimated in this analysis as an additional operator cost
- Pilot training costs are not considered in this analysis, however, experience in prior implementations has shown that this has resulted in a nominal cost to operators
- System upgrade costs to ATS providers are not considered in this analysis

### 3. CAR/SAM RVSM Implementation Costs

3.1 The upgrade costs for the non-approved aircraft were determined by using current FAA RVSM upgrade cost estimates used in analysis to support the rulemaking effort for U.S. Domestic RVSM. These estimates represent the cost of the engineering work associated with bringing an aircraft into RVSM compliance or the airworthiness approval costs (Table 1).

**Table 1. CAR/SAM Commercial Aircraft RVSM Upgrade Costs**

TYPE	ESTIMATED COST	SOURCE OF ESTIMATE	TYPE	ESTIMATED COST	SOURCE OF ESTIMATE
A30B	****	Manufacturer (Visual inspection only)	B762	****	Manufacturer (Visual inspection only)
A310	****	Manufacturer (Visual inspection only)	B763	****	Manufacturer (Visual inspection only)
A319	****	Manufacturer (Visual inspection only)	B772	****	Manufacturer (Visual inspection only)
A320	****	Manufacturer (Visual inspection only)	CRJ1	****	Manufacturer
A321	****	Manufacturer (Visual inspection only)	CRJ2	****	Manufacturer
A332	****	Manufacturer (Visual inspection only)	DC10	\$2,200.00	OWG Survey 6/97
A342	****	Manufacturer (Visual inspection only)	DC8	\$150,000.00	Engineering design organization
A343	****	Manufacturer (Visual inspection only)	DC9	\$150,000.00	Engineering design organization
A346	****	Manufacturer (Visual inspection only)	E135	\$17,500.00	Manufacturer
B703	\$175,000.00	Engineering design organization	E145	\$17,500.00	Manufacturer
B721	\$130,000.00	Engineering design organization	F100	\$8,000.00	Operator Survey 6/01
B722	\$130,000.00	Engineering design organization	F28	\$50,000.00	Engineering analysis
B731	\$130,000.00	Engineering design organization	IL62	\$150,000.00	Engineering analysis
B732	\$130,000.00	Engineering design organization	IL76	\$150,000.00	Engineering analysis
B733	\$17,500.00	Operator Survey 1/01	J328	****	Manufacturer
B734	\$17,500.00	Manufacturer (Visual inspection only)	JCOM	\$150,000.00	Engineering design organization
B735	\$17,500.00	Manufacturer (Visual inspection only)	L101	\$25,000.00	Manufacturer, 1/01
B737	****	Manufacturer (Visual inspection only)	MD11	\$2,200.00	Engineering analysis
B738	****	Manufacturer (Visual inspection only)	MD80	\$33,300.00	Engineering analysis
B742	\$58,400.00	FAA Survey 12/97 and OWG Survey 6/97	YK40	\$150,000.00	Engineering analysis
B752	\$50,700.00	FAA Survey 12/97 and OWG Survey 6/97	YK42	\$150,000.00	Engineering analysis

3.2 A sample of all commercial turbojet aircraft types from the CAR/SAM registry was compiled using data from J&P Airline Fleets International. This sample of operator fleets was queried against the current FAA ACB-310 Unified NAT CMA/APARMO Database to determine the non-approved aircraft. The results of this analysis show that of the 1,265 commercial airframes registered to operators based in

the CAR/SAM, 94 currently possess RVSM approval leaving 1,171 airframes to upgrade. In addition, flights being conducted by the non-approved aircraft types of North American operators were identified in Enhanced Traffic Management System (ETMS) and OAG traffic samples. This resulted in 1,509 non-approved airframes flown by North American operators for a total count of 2,774 airframes to upgrade at a cost of \$134.45 million (Table 2).

**Table 2. CAR/SAM Fleet Upgrade Cost Estimate**

CATEGORY	FLEET	APPROVED	TO APPROVE	TO MONITOR	TOTAL COST
CAR/SAM COM	1,265	94	1,171	858	\$ 78,037,500.00
NORTH AMERICA COM*	1,509	-	1,509	273	\$ 56,417,200.00
<b>TOTAL</b>	<b>2,774</b>	<b>94</b>	<b>2,680</b>	<b>1,131</b>	<b>\$ 134,454,700.00</b>

\* This total reflects the number of non-approved North American operator-aircraft pairs currently operating in the CAR/SAM.

3.3 Through applying the monitoring requirements to the non-approved operator fleets, 1,131 aircraft were determined to require monitoring services. Utilizing an estimate of \$3,000.00 per airframe, a total monitoring cost of \$3.4 million was determined. Total upgrade and monitoring costs for the non-approved aircraft of operators conducting CAR/SAM operations is \$137.85 million (Table 3).

**Table 3. Commercial Aircraft RVSM Upgrade and Monitoring Costs**

COMMERCIAL AIRCRAFT RVSM UPGRADE COSTS					
YEAR	YEARLY UPGRADE COSTS	MONITORING COSTS	TOTAL COST	DISCOUNT RATE FACTOR	DISCOUNTED TOTAL
2003	\$68,925,000.00	\$1,696,500.00	\$70,621,500.00	0.9346	\$ 66,002,853.90
2004	\$68,925,000.00	\$1,696,500.00	\$70,621,500.00	0.8734	\$ 61,680,818.10
<b>TOTAL</b>	<b>\$137,850,000.00</b>	<b>\$3,393,000.00</b>	<b>\$141,243,000.00</b>		<b>\$ 127,683,672.00</b>

#### 4. Statistical Analysis of Historical Data

4.1 This section presents a statistical analysis of a 16-22 September 2002 traffic sample for the CAR/SAM obtained from OAG and ETMS data. The summaries of this statistical analysis were utilized to develop the cumulative distribution functions needed for generating flight events.

4.2 The statistical analysis commenced by determining the frequency of flights and the distributions of flight take-off times, aircraft types, origin-destination pairs and of tracks.

4.3 A cumulative probability distribution was then determined for each of these characteristics, though some distributions were not independent of one another. For example, each origin-destination pair had a separate distribution for the aircraft type used. Once the distributions were computed, a Fortran

program was used to create random numbers to determine which characteristics should be assigned to the flight events.

## 5. Flight Take off Times

5.1 As take off times were given in the OAG sample, no computation of these times was necessary. However, as take off times were not included in the given ETMS data, it was necessary to estimate these times from a given time and location in the airspace. The estimation of take off times was computed by using the amount of time that would be required for each flight to reach the point of origin from a given point. This value was determined through the use of spherical coordinates, the distance between the given point and the point of origin, as well as the aircraft's speed in Mach. Cumulative distributions were then determined for the entry times for each hour of the day according to the region and direction of the flight. The take off time was assigned by subtracting the time to reach the point of origin from the time at the given point.

5.2 Analysis of the 2002 data shows that 5530 flights represented 66% of the average daily traffic, with 26.96% being northbound, 23.18% eastbound, 26.82% southbound and 23.04% westbound.

## 6. Distribution of Aircraft Types

6.1 The region, direction, and origin-destination pair determined the type of aircraft assigned to a given flight. 11 aircraft types were described in Table 4. Using these classifications, cumulative distributions were created for aircraft type.

**Table 4. Classification of Aircraft Types**

<b>AC Type</b>	<b>Description</b>	<b>AC Type</b>	<b>Description</b>
AC1	B767-300	AC7	MD11
AC2	B747-200	AC8	B757
AC3	DC10	AC9	EA340
AC4	L1011	AC10	Business Jet
AC5	A310	AC11	B777
AC6	B747-400		

## 7. Distribution of Aircraft Speeds

7.1 The speed and take off weight of the aircraft were assigned according to type. The speed is represented in Mach ranging from 0.790 to 0.860. Most aircraft types use between three to five different speeds. Aircraft speed is dependent only on the type of aircraft. Table 5 shows the cumulative distributions of the speeds by aircraft type.

**Table 5. Cumulative distributions of aircraft speeds**

AC Type	0.790	0.800	0.810	0.820	0.830	0.840	0.850	0.860	Average
AC1	0.012	0.737	0.901	1.000					0.80350
AC2				0.026	0.085	0.792	0.953	1.000	0.84143
AC3		0.121	0.280	0.503	0.878	1.000			0.82218
AC4				0.047	0.721	1.000			0.83231
AC5	0.038	0.564	0.946	1.000					0.80452
AC6						0.063	0.612	1.000	0.85325
AC7				0.251	0.735	1.000			0.83014
AC8	0.098	0.929	1.000						0.79973
AC9			0.178	0.593	1.000				0.82228
AC10*	0.098	0.929	1.000						0.79973
AC11					0.075	0.929	1.000		0.83996

\* Because aircraft AC10 (business jets) considered many different models, the range of speeds was quite large. To simplify, we modeled AC10 as an AC8 (B757).

## 8. Distribution of Take-Off Weights

8.1 As take-off weight is dependent on the aircraft type, a triangular distribution was used to assign take-off weights. A triangular distribution uses the minimum and maximum values assigned for each aircraft while the most likely value depends on the length of the flight. The most likely value was determined using the distance between the origin and destination along with the maximum distance between the origin and destination pair. A flight that covers the maximum distance was assumed to use the maximum take off weight values given in *Jane's All the World's Aircraft (1996-1997)* while the other flights used a proportion of the maximum take off weight according to their distance. Table 6 shows the most likely (average) take-off weights for the aircraft types.

**Table 6. Average take-off weight values (in pounds)**

	AC1	AC2	AC3	AC4	AC5	AC7	AC8	AC9	AC10	AC11
Average take off weight (lbs.)	35985	692054	508086	418342	310219	544717	216978	501851	378086	483488
	9									

8.2 Table 7 shows the take-off weight distributions for select aircraft types. For the values based on the 2002 data, most likely take-off weights were rounded to the nearest one. For the values based on computations, take-off weights are rounded to the nearest thousand.

**Table 7. Sample Take-Off Weight Distributions**

AC 1			AC2		
Min	Likely	Max	Min	Likely	Max
312559	359859	418000	622712	692054	820000

9. **Generation of Flight Events**

9.1 Fortran 77 was utilized to complete the flight events generation, as it is a powerful computer programming language, simplifying the task of analyzing, organizing, and manipulating large quantities of data.

10. **Program Methodology**

10.1 This section describes the programs utilized with the original data to generate flight events.

10.2 **Preliminary Programs**

10.2.1 Prior to running the actual flight events generation program, the raw data collected from the OAG and ETMS was processed through several intermediate programs to convert the data files into the necessary format, and analyze them to obtain the essential information to complete flight events. Each line of the raw data consisted of several columns: call sign, aircraft type, origin, destination, time information, routing, and ground speed.

- The *uniquecarsam.for* program reads in the raw data, and compiles a list of the unique origin-destination (od) pairs into a master od file.
- The *dist\_cm\_od\_carsam.for* reads in the raw data and calculates the probability distributions linking the od pairs from the master od file with other flight factors, including aircraft type, and civilian/military designation.
- The *trackprob.for* program computes the probability of each track being utilized, and the probability of each aircraft type occurring on each track.
- The *timedist.for* program calculates the probability of a flight occurring during each hour of the day based on the heading of each flight. The numbers 1,2,3 and 4 were used to indicate North, East, South and West respectively.

10.3 **Flight Events Generation Program**

- The *dists8\_carsam.for* program generates the flight events. The outputs calculated from the *dis\_cm\_odt\_carsam.for*, *trackprob.for*, and *timedist.for* were input into the program.

11. **Report of Flight Events**

11.1 The simulation program generated a report representing 5,530 flights, approximately one day's worth of flights. The file format consisted of eight columns for entry time, region, direction, origin-destination, aircraft type, take-off-weight, and percent payload, respectively.

11.2 Take off times ranged from zero to 2,357 minutes.

11.3 Direction was designated 1,2,3, and 4 for North, East, South and West respectively.

**Table 8. Direction designation**

<b>Direction</b>	<b>Number</b>
North	1
East	2
South	3
West	4

11.4 Aircraft type were designated as integers from one through eleven as shown in Table 9.

**Table 9. Aircraft type designation**

<b>AC Type</b>	<b>Number</b>
B767-300	1
B747-200	2
DC10	3
L1011	4
A310	5
B747-400	6
MD11	7
B757	8
EA340	9
B Jet	10
B777	11

11.5 A partial list of the simulated data for September 16-22, 2002 is given below (Figure 1).

**Figure 1: Flight Events**

1502	1601	1705	SBTE	SBFZ	84.93	42.82	86.22	38.32	2	8	0.80	136684	1705
921	1047	857	KJFK	MDSO	40.64	73.78	18.43	69.67	3	5	0.80	247193	857
1747	1813	1811	SBAX	SBRJ	74.33	46.93	67.08	43.17	3	10	0.80	195085	1811
805	931	927	SPIM	KATL	78.00	77.12	33.64	84.43	3	1	0.80	289687	927
1840	1907	1414	SBRB	KMAO	80.02	67.82	34.18	79.33	3	8	0.81	218860	1414
923	1050	1432	SBRF	SBGR	81.87	34.93	67.00	47.03	3	5	0.81	275659	1432
1432	1558	1766	SAWH	SAVC	35.18	68.32	44.22	67.47	1	10	0.80	217267	1766
1232	1354	899	KLAX	MMMX	33.94	118.41	19.44	99.07	2	5	0.80	202236	899
1608	1734	228	SBBR	SBCT	74.13	47.92	64.47	49.18	3	8	0.80	216975	228
1242	1342	595	SBFZ	SBTE	86.22	38.32	84.93	42.82	4	8	0.80	221615	595
2128	2252	1367	TTPP	KJFK	10.47	61.40	40.64	73.78	1	8	0.80	201324	1367
821	914	388	SACO	SAME	58.68	64.20	57.50	68.80	4	8	0.80	176889	388
947	1013	1183	KMIA	SLVR	25.71	80.29	72.37	63.13	1	8	0.80	215218	1183
816	903	195	SKBO	SKMR	4.70	74.15	8.82	75.85	1	8	0.80	134613	195
1802	1948	1322	SBBH	SBSP	70.15	43.95	66.37	46.65	3	8	0.80	147563	1322
1642	1708	466	SBCT	SBBR	64.47	49.18	74.13	47.92	1	8	0.80	144407	466
2121	2247	1451	MMRX	MMMX	26.02	98.23	19.44	99.07	3	8	0.80	144144	1451
617	704	1445	SBRF	SBSV	81.87	34.93	77.10	38.33	3	5	0.81	256765	1445
1645	1703	1981	MGGT	SAWJ	14.58	90.53	40.69	67.80	1	8	0.80	220681	1981
1306	1432	1431	SBRF	SBGL	81.87	34.93	67.18	43.25	3	5	0.80	341026	1431

## 12. Flight Planning

12.1 The flight-planning algorithm was utilized to determine the optimum flight plan for the generated flights. The optimum plan included the flight levels over the region of study that minimized fuel savings.

12.2 Flight-planning was performed by dividing the flights into segments and analyzing each segment separately, therefore it was considered as a dynamic programming problem. The following sections give a description of a Greedy Algorithm followed by descriptions of the algorithms that were analyzed in order to determine the optimal flight paths.

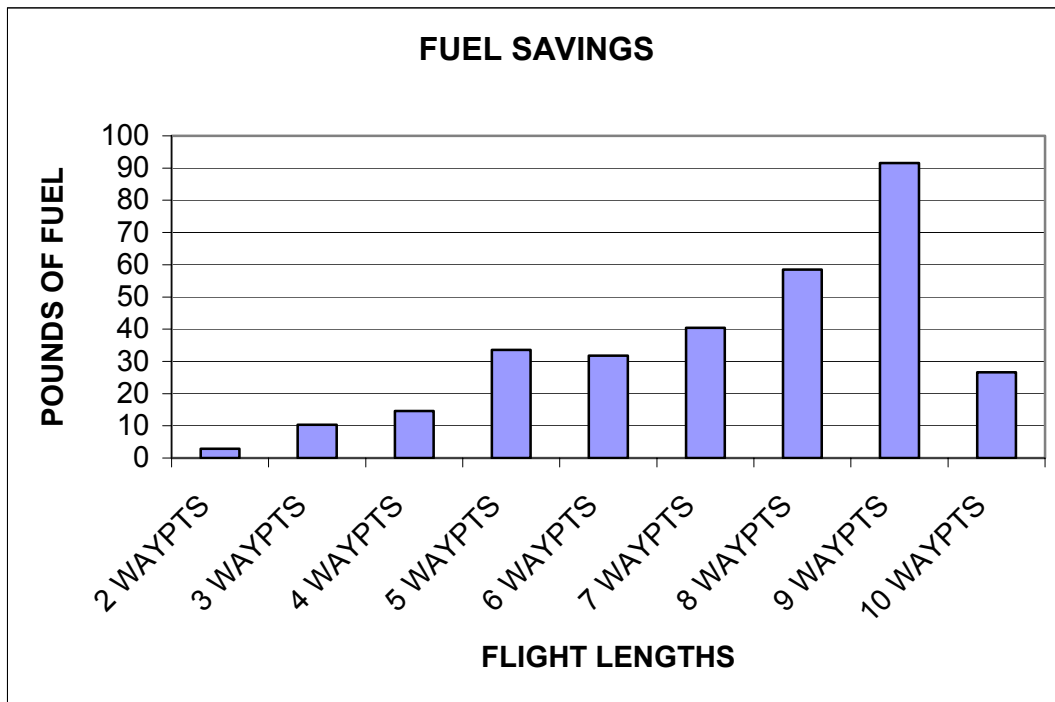
## 13. Greedy Algorithms

13.1 Greedy algorithms analyze a problem in stages making a decision based on what is best for a given stage. As flight planning also analyzes the problem in stages by choosing the best solution for each individual stage, different greedy algorithms were investigated to determine if they return comparable results to complete enumeration. It was determined that Greedy Algorithm 4 was the most appropriate.

14. **Comparison of BASE and RVSM with Greedy Algorithm**

14.1 In order to compare the amount of fuel used under the BASE scenario used for CVSM as compared to RVSM, flight plans were created for the 5,530 flights. The following figure illustrates the average amount of fuel saved using RVSM for the day studied. The weighted average amount of fuel saved for the first day was 10.53 lbs. per flight. In Figure 2 the average amount of fuel saved is shown with respect to flight length. As discussed earlier, the flights were broken up into segments called waypoints.

**Figure 2. Fuel Savings with respect to flight length.**



15. **Flight Tracking**

15.1 Flight tracking was used to analyze the optimal flight plans to determine if there were any conflicts between flights traveling in the same area at any given time. Conflicts can occur when multiple flights are traveling on the same or crossing tracks at the same flight levels. When conflicts arose it was necessary to alter one of the flights paths.

16. **Analysis of Data**

16.1 In analyzing the data, the flight-tracking algorithm was used to determine when conflicts arose. The conflicts were detected by comparing the flight plans and determining those flights using the same tracks and levels at the same time within a 15-minute time interval.

**17. Flight Tracking Algorithm**

17.1 Conflicts were detected by comparing all of the flight-plan segments. The algorithm determined if conflicts existed at the first waypoint. Appropriate steps were taken to resolve existing conflicts. Each flight plan was then flown to the beginning of the next segment using the speed and distance to determine the time that each flight would reach the next segment. The flights were then analyzed to determine if conflicts existed during the second segment. The algorithm continued in this manner until all of the flights reached their destination.

**18. Comparison of BASE and RVSM with the Flight Tracking Algorithm**

18.1 In comparing the amount of fuel used under the BASE scenario as compared to RVSM, the average fuel savings for the first day was 104.43 lbs. (1.63%) per flight. The increase in fuel savings was caused in part by the smaller height deviation and the fact that RVSM provides more flight levels thereby reducing conflicts.

**19. Conclusions**

19.1 As only 66% of the daily flights were modeled, the average fuel savings for 100% of operations was estimated through extrapolation. The fuel savings were then converted to dollars using an FAA fuel cost estimate of \$0.67/gal. A forecasted growth rate of 3.8% for total CAR/SAM operations was provided by the IATA Miami office and was used to forecast savings over the 15-year period 2003-2017.

19.2 The total costs for CAR/SAM commercial operators to upgrade and monitor their non-approved airframes is \$137.8 million, or \$127.7 million discounted. The estimated 15-year fuel savings from this initiative is estimated at \$538.0 million or \$312.1 million discounted. The ratio of benefits to cost for commercial CAR/SAM operators is nearly 4.0:1 or 2.4:1 discounted. This value is comparable to benefit-cost ratio estimates calculated for U.S. DRVSM and the Pacific. The findings of this study are presented below in Tables 10 and 11. The meeting is invited to consider the findings of this study.

**Table 10. CAR/SAM Commercial Aircraft Fuel Savings**

<b>YEAR</b>	<b>SAVINGS</b>	<b>FACTOR</b>	<b>DISCOUNTED</b>
<b>2003</b>	<b>\$ -</b>	<b>0.9346</b>	<b>\$ -</b>
<b>2004</b>	<b>\$ -</b>	<b>0.8734</b>	<b>\$ -</b>
<b>2005</b>	<b>\$ 32,767,375.18</b>	<b>0.8163</b>	<b>\$ 28,619,025.49</b>
<b>2006</b>	<b>\$ 34,012,535.44</b>	<b>0.7629</b>	<b>\$ 27,764,432.68</b>
<b>2007</b>	<b>\$ 35,305,011.79</b>	<b>0.713</b>	<b>\$ 26,934,193.49</b>
<b>2008</b>	<b>\$ 36,646,602.24</b>	<b>0.6663</b>	<b>\$ 26,129,027.39</b>

2009	\$ 38,039,173.12	0.6227	\$25,345,501.05
2010	\$ 39,484,661.70	0.582	\$24,587,098.84
2011	\$ 40,985,078.84	0.5439	\$23,853,315.89
2012	\$ 42,542,511.84	0.5083	\$23,138,872.19
2013	\$ 44,159,127.29	0.4751	\$22,446,084.40
2014	\$ 45,837,174.13	0.444	\$21,777,241.43
2015	\$ 47,578,986.74	0.415	\$21,125,070.11
2016	\$ 49,386,988.24	0.3878	\$20,495,600.12
2017	\$ 51,263,693.79	0.3624	\$19,880,060.45
<b>TOTAL</b>	\$ <b>538,008,920.35</b>		<b>\$312,095,523.54</b>

Table 11. Comparison of RVSM Costs and Benefits

COMPARISON OF RVSM COSTS AND BENEFITS						
Initiative	Cost	Benefit	Ratio	Disc. Cost	Disc. Benefit	Ratio
PAC	\$ 21,700,000.00	\$ 120,000,000.00	5.53	\$ 19,500,000.00	\$ 83,800,000.00	4.30
WATRS	\$ 26,200,000.00	\$ 34,200,000.00	1.31	\$ 23,400,000.00	\$ 18,400,000.00	0.79
<b>CAR/SAM</b>	<b>\$141,243,000.00</b>	<b>\$ 538,008,920.35</b>	<b>3.81</b>	<b>\$ 127,683,672.00</b>	<b>\$ 312,095,523.54</b>	<b>2.44</b>
DRVSM	\$866,500,000.00	\$ 4,900,000,000.00	5.65	\$ 762,800,000.00	\$ 3,000,000,000.00	3.93