

# Evaluation of the Applicability of a Modern Aircraft Performance Model to Trajectory Optimization

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**Abstract**—Much of the research being performed as part of the current Air Traffic Management (ATM) modernization effort involves trajectory optimization. The trajectory computation tools required for this rely on aircraft performance models, but the validity of these models for optimization purposes has often not been demonstrated. As a first step towards filling this gap, this paper evaluates the accuracy of trajectory optimization results from a modern aircraft performance model (APM) designed for ATM applications, using reference data from a major aircraft manufacturer. The study focuses on cruise speed optimization and considers several aircraft types representative of jet airliner operations. A detailed evaluation of the APM presents the accuracy of its optimization results (cruise speed and fuel consumption) and underlying parameters (drag coefficient, specific range) for several cruise optimization criteria: maximum range, long range, and economy. Representative results are summed up to assess the suitability of this APM for cruise optimization in several types of applications: ATM simulations, environmental impact assessments, business and economic studies, and on-board applications.

**Keywords**—aircraft performance model, trajectory optimization, fuel consumption, air traffic management

## I. INTRODUCTION

Much of the research being performed as part of the current Air Traffic Management (ATM) modernization effort involves trajectory optimization [1,2]. The purpose of trajectory optimization is to determine the values of some flight parameters (e.g. flight route, cruise altitude, speed profile) that minimize (or maximize) one or several optimization criteria (e.g. trip cost, trip fuel, noise, emissions). The influence of such flight parameters on the optimization criteria is often determined by aircraft performances. The trajectory computation and simulation tools used for ATM trajectory optimization research rely on aircraft performance models (APM), such as BADA 3 [3,4], BADA 4 [2,5,6,7], Piano-X [8] or custom models [9]. The validity of these models for optimization purposes, however, has often not been demonstrated. Accuracy evaluations have been performed for some of these APM, using either manufacturer performance data (e.g. flight manuals) [10] or flight data recordings [4,11] as reference. Such evaluations only provide an estimation of a model's accuracy (e.g. fuel flow error) in given flight conditions, which is not sufficient to infer how accurate would be the determination of optimum flight conditions using this model. As a first step towards filling this gap, this paper

evaluates the accuracy of trajectory optimization results from a modern APM designed for ATM applications, using reference data from a major aircraft manufacturer. The evaluation focuses on cruise speed optimization and considers several aircraft types representative of current jet airliner operations.

This paper first describes the methodology adopted for the evaluation. A first set of results is then presented for point optimizations, followed by a second set of results for integrated optimizations. The final part of the paper discusses possible follow-ups to this study.

## II. METHODOLOGY

The cruise speed optimization considered in this study consists in the determination of the cruise speed that minimizes (or maximizes) a specific optimization criterion based on the fuel consumption, under given values of the remaining flight conditions (e.g. cruise altitude and aircraft weight). The results of this optimization consist of both the optimum cruise speed, and the value of the corresponding fuel consumption.

In order to evaluate the applicability of a modern APM to cruise speed optimization, this study compares:

- On the one hand, a set of reference cruise optimization results obtained from an aircraft manufacturer performance tool, which can be considered the most accurate source of performance data for each individual aircraft type.
- On the other hand, a set of candidate cruise optimization results estimated, in the same conditions as the reference data, by a candidate APM representative of modern APMs that can be used in ATM trajectory optimization applications.

The selected aircraft manufacturer is Boeing, who provided reference data for seven aircraft types that include twin- and quad-engine jets, as well as narrow- and wide-body airframes, in order to be representative of current jet airliner operations. The main characteristics of the selected aircraft types are summarized in Table I; the specific name of each type cannot be disclosed to preserve the confidentiality of the reference performance data. The reference optimization results were computed using the Boeing Performance Software (BPS). BPS combines a set of computational routines common to all of the performance calculations, with modules that are specific to different flight segments and performance databases that

represent unique airframe/engine combinations. BPS calculations of inflight performances are based on the equations found in [12].

TABLE I. MAIN CHARACTERISTICS OF THE SELECTED AIRCRAFT TYPES

Aircraft type	Engine type	Type of body
A1	Jet	narrow
A2	Jet	narrow
A3	Jet	narrow
A4	Jet	wide
A5	Jet	wide
A6	Jet	wide
A7	Jet	wide

The selected APM is the Base of Aircraft Data (BADA) [13], an aircraft performance model developed and maintained by EUROCONTROL as an enabler of a variety of ATM applications, including air traffic modeling and simulation, environmental assessment, and non-safety-critical decision support tools (DST) for air traffic control (ATC). BADA has been developed in close cooperation with aircraft manufacturers and operators, and is broadly considered as the international standard aircraft performance model for ATM [14]. BADA provides a means for aircraft manufacturers to supply accurate aircraft performance information to the ATM community, in a manner that protects their sensitive proprietary information, and within a framework validated and controlled by a neutral international entity. BADA comprises two model families, namely BADA 3 and BADA 4 [13]. Since BADA 3 has already been found non-suitable for trajectory optimization by previous research [15], only BADA 4 is considered in this study. The BADA optimization results were computed using the Trajectory Computation Infrastructure software [16].

For each aircraft type, defined by its airframe/engine combination, the manufacturer tool and the APM were used separately to compute the reference and candidate optimum speed and fuel consumption for a variety of cruise altitudes, gross weights, and optimization criteria. Other parameters that may affect the optimum cruise speed, such as atmosphere temperature or wind, were set to nominal values (i.e. ISA conditions, no wind).

Three optimization criteria have been selected for this study:

- Maximum Range Cruise (MRC) corresponds to the speed that maximizes the cruise range [17,18,21]; this is equivalent to minimizing the fuel burnt over a given cruise distance.
- Long Range Cruise (LRC) corresponds to the speed above MRC that provides 99% of the maximum cruise range [18,21].
- Economy (ECON) corresponds to the speed that minimizes the flight cost, according to a given value of the Cost Index (CI) [19-21]. One value of the CI has been used for each aircraft type: this value was selected by Boeing in the range of typical values used by airlines operating each type [21].

While the combination of multiple aircraft types, altitudes, weights and optimization criteria generated hundreds of comparison points, this initial study favoured a qualitative analysis of the results, over a quantitative one. Rather than providing statistical measures computed over the full set of results, the next sections will focus on a selection of cases that illustrate the variety of behaviours observed among the results.

### III. POINT OPTIMIZATION RESULTS

The first set of results corresponds to the determination of the optimum speed under instantaneous aircraft cruise conditions, also called point optimization. Graphical and numerical comparisons have been performed between the reference and candidate values of the optimum cruise speed and the associated fuel flow. Vertical scales have intentionally been removed from the plots presented in this section, in order to preserve the confidentiality of the sensitive reference performance data. A measure of the consistency between the reference (labeled *REF* or *BPS*) and candidate (labeled *BADA 4* or *B4*) data is provided instead, in the form of the relative Root Mean Square Error (rRMSE) computed with respect to the reference data.

This section examines six study cases. Each study case presents the optimization results obtained for one combination of aircraft type, cruise altitude, and optimization criteria, over the range of aircraft weights compatible with the selected cruise altitude. In each study case, only one input condition has been modified compared to one of the other study cases, in order to highlight the sensitivity of the results to each input condition. The presentation of the study cases is followed by a more detailed analysis that highlights the key reason behind the variety of behaviours observed in the study cases.

#### A. Study case 1

Fig. 1 presents the results of the LRC speed optimization for aircraft type A7, a cruise altitude of 38,000ft, and a variety of aircraft weights; the associated LRC fuel flow is presented in Fig. 2. In this case, BADA 4 provides a very accurate estimate (0.1% rRMSE) of the LRC speed at low weights, but this accuracy decreases at medium to high weights (1.5% rRMSE), where BADA 4 underestimates the speed. The accuracy of the BADA 4 LRC fuel flow is more stable than the accuracy of the LRC speed across the range of weights, with an overall rRMSE of 1.37%.

#### B. Study case 2

Fig. 3 presents the results of the LRC speed optimization for aircraft type A7, a cruise altitude of 30,000ft, and a variety of aircraft weights; the associated LRC fuel flow is presented in Fig. 4. Compared to study case 1, only the cruise altitude differs in the inputs, but the trends of the outputs' accuracy are significantly different. In this case, BADA 4 provides a very accurate estimate (0.1% rRMSE) of the LRC speed at medium to high weights, but this accuracy decreases at low weights (1.4% rRMSE), where BADA 4 underestimates the speed. The accuracy of the BADA 4 LRC fuel flow increases with the aircraft weight, from a 3.1% rRMSE at the lowest weights to a 1.0% rRMSE at the highest weights.

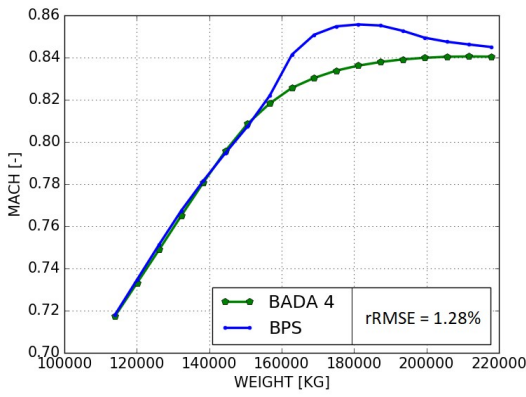


Fig. 1. LRC speed (A7, FL380)

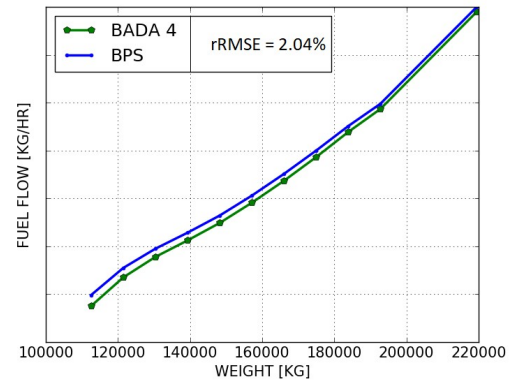


Fig. 4. LRC fuel flow (A7, FL300)

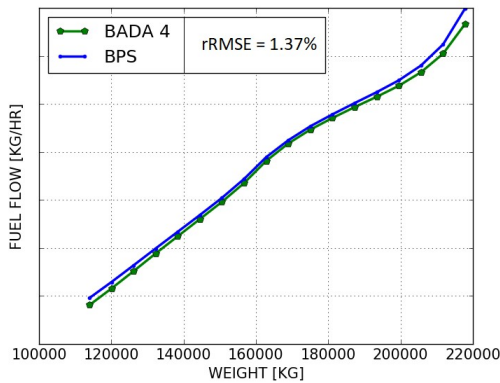


Fig. 2. LRC fuel flow (A7, FL380)

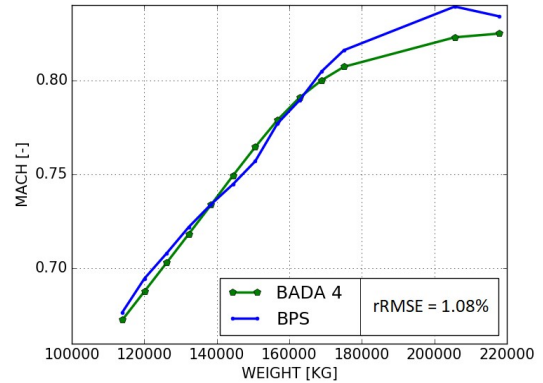


Fig. 5. MRC speed (A7, FL380)

### C. Study case 3

Fig. 5 presents the results of the MRC speed optimization for aircraft type A7, a cruise altitude of 38,000ft, and a variety of aircraft weights; the associated MRC fuel flow is presented in Fig. 6. Compared to study case 1, only the optimization criterion differs in the inputs, and the trends of the outputs' accuracy are similar. In this case, BADA 4 provides an accurate estimate (0.4% rRMSE) of the MRC speed at low to medium weights, but this accuracy decreases at high weights (1.6% rRMSE), where BADA 4 underestimates the speed. The accuracy of the BADA 4 MRC fuel flow is more stable than the accuracy of the MRC speed across the range of weights, with an overall rRMSE of 1.66%.

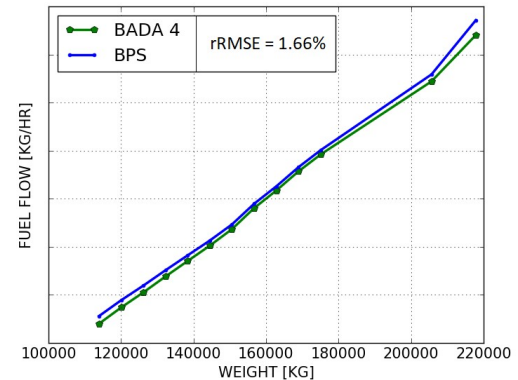


Fig. 6. MRC fuel flow (A7, FL380)

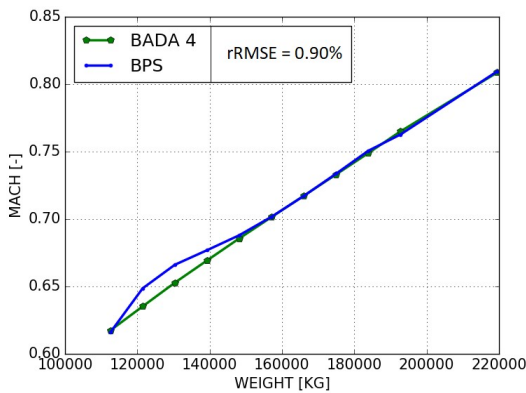


Fig. 3. LRC speed (A7, FL300)

### D. Study case 4

Fig. 7 presents the results of the ECON speed optimization for aircraft type A7, a cruise altitude of 38,000ft, and a variety of aircraft weights; the associated ECON fuel flow is presented in Fig. 8. Compared to study cases 1 and 3, only the optimization criterion differs in the inputs, but the trends of the outputs' accuracy are significantly different. In this case, the accuracy of the BADA 4 ECON speed increases with the aircraft weight, from a 4.2% rRMSE at the lowest weights to a 0.8% rRMSE at the highest weights, but BADA 4 underestimates the speed over the whole range of weights. The accuracy of the BADA 4 ECON fuel flow is more stable than

the accuracy of the ECON speed across the range of weights, with an overall rRMSE of 0.88%.

### E. Study case 5

Fig. 9 presents the results of the LRC speed optimization for aircraft type A5, a cruise altitude of 38,000ft, and a variety of aircraft weights; the associated LRC fuel flow is presented in Fig. 10. Compared to study case 1, only the aircraft type differs in the inputs, but the trends of the outputs' accuracy are significantly different. In this case, BADA 4 provides an accurate estimate (0.3% rRMSE) of the LRC speed at medium to high weights, but this accuracy decreases at the lowest weights (2.5% rRMSE), where BADA 4 underestimates the speed. The accuracy of the BADA 4 LRC fuel flow is more stable than the accuracy of the LRC speed across the range of weights, with an overall rRMSE of 2.73%. While BADA 4 slightly underestimated the fuel flow in all study cases for the A7 aircraft, it overestimates it in this study case for the A5 aircraft.

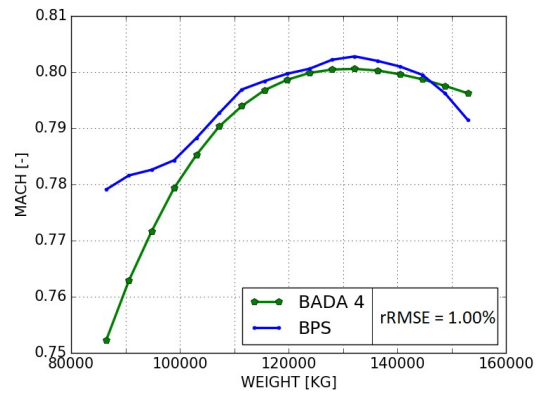


Fig. 9. LRC speed (A5, FL380)

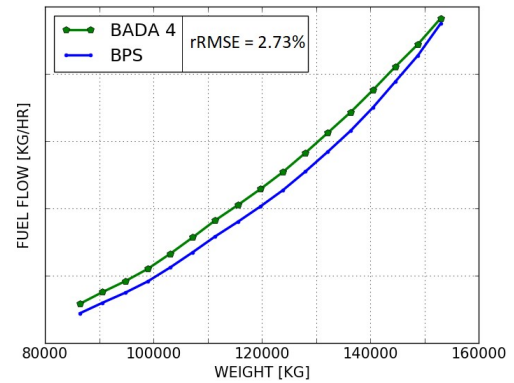


Fig. 10. LRC fuel flow (A5, FL380)

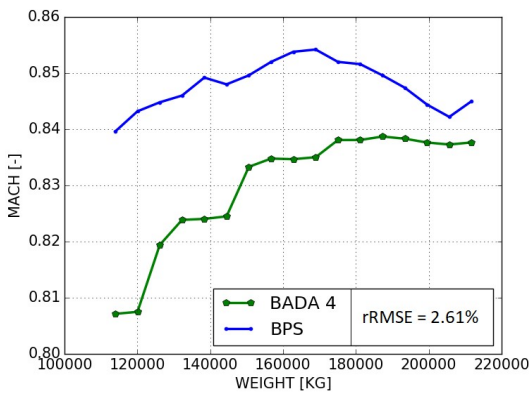


Fig. 7. ECON speed (A7, FL380)

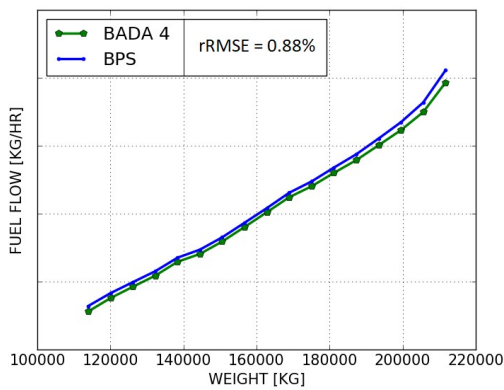


Fig. 8. ECON fuel flow (A7, FL380)

### F. Study case 6

Fig. 11 presents the results of the LRC speed optimization for aircraft type A6, a cruise altitude of 38,000ft, and a variety of aircraft weights; the associated LRC fuel flow is presented in Fig. 12. Compared to study cases 1 and 5, only the aircraft type differs in the inputs, but the trends of the outputs' accuracy are significantly different. In this case, BADA 4 provides an accurate estimate (0.25% rRMSE) of the LRC speed at medium to high weights, but this accuracy decreases at low weights (1.6% rRMSE), where BADA 4 overestimates the speed. While BADA 4 tended to underestimate the speed in all study cases for the A7 and A5 aircraft, it overestimates it in this study case for the A6 aircraft. The accuracy of the BADA 4 LRC fuel flow is more stable than the accuracy of the LRC speed across the range of weights, with an overall rRMSE of 0.41%.

### G. Understanding the results

The selected optimization criteria are all related to the fuel consumption. The fuel consumption of jet engines depends on the engines' thrust, which can be considered as equal to the airframe drag during cruise at constant speed and altitude [22]. Since the candidate APM is based on a kinetic approach, which models the forces acting on the aircraft, the accuracy of the drag and fuel flow models of the candidate APM are therefore paramount to the accuracy of the APM cruise speed optimization results.

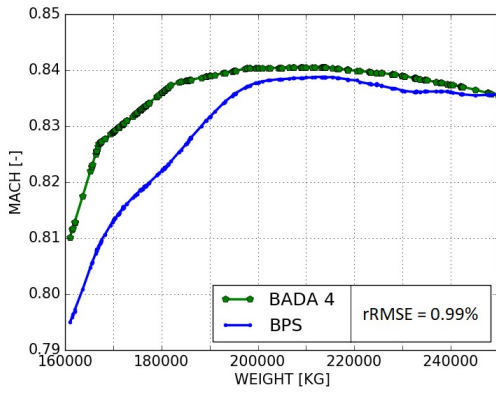


Fig. 11. LRC speed (A6, FL380)

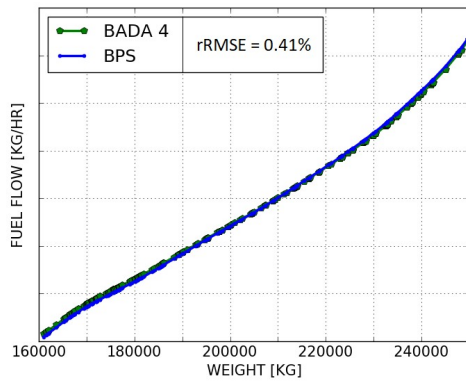


Fig. 12. LRC fuel flow (A6, FL380)

The MRC and LRC criteria in particular are based on the notion of specific range (SR). The SR can be defined as the instantaneous value of distance covered per unit quantity of fuel consumed under given flight conditions (i.e., altitude, speed and aircraft weight) [18]. Under the assumptions of this study, the SR (in NM/kg) can be expressed as:

$$SR = \frac{V}{FF} \quad (1)$$

where  $V$  is the true airspeed (in knots) and  $FF$  is the fuel flow (in kg/h). The integration of the SR over a given flight segment returns the distance flown with a given amount of fuel consumed. MRC corresponds to the speed that maximizes the SR, while LRC corresponds to the speed above MRC that provides 99% of the maximum SR.

In order to understand the apparent lack of consistency among the results of the study cases presented above, more detailed comparisons have been performed between the reference and candidate values of the key parameters involved in the MRC and LRC optimization process, namely the aircraft drag (represented by the drag coefficient  $CD$  [18,22]),  $FF$ , and  $SR$  (derived from  $FF$  using (1)).

Fig. 13 presents the values of  $CD$ ,  $FF$  and  $SR$  obtained from the reference data and from the BADA 4 APM for aircraft type A6, a cruise altitude of 30,000ft and a medium aircraft weight, over the full range of speeds flyable under those conditions. For all three parameters, the curve shapes are similar between the BADA 4 and reference values, and the  $SR$  rRMSE over the whole speed range is lower than 2%; the  $SR$  rRMSE in particular is only 1.31%. The relative error in the MRC (resp. LRC) speed estimated by BADA 4, however, reaches -2.6% (resp. -2.3%).

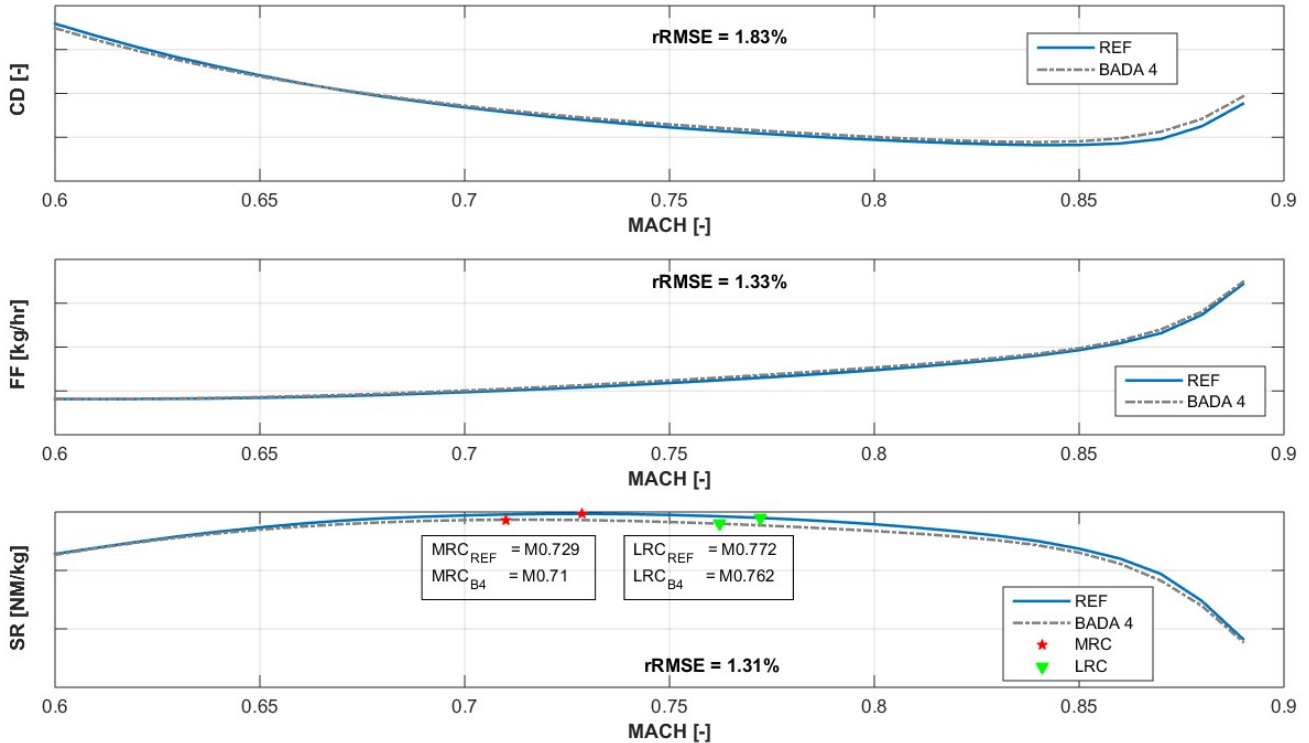


Fig. 13. MRC and LRC estimation (A6, FL300, medium weight)

The explanation for the relatively large error in the optimum speed compared to the error in SR lies in the specific shape of the SR curve. The MRC conditions correspond to the peak of this curve. As can be seen in Fig. 13, the SR curve is nearly flat around its peak: even a small difference in the shape of the SR curve can therefore lead to a significant difference in the horizontal location of its peak. The LRC conditions are linked to MRC: they correspond to the point on the right-hand side of the peak whose SR is 1% lower than the maximum SR. Since this point is also located in the flat part of the SR curve, its estimation suffers from the same sensitivity to small modelling errors in the CD and FF parameters. Because of the flatness of the SR curve in the vicinity of the MRC and LRC conditions, however, even marked deviations between BADA 4 and reference optimum speeds have no significant impact on the estimated fuel consumption: the difference in BADA 4 SR between the reference and estimated MRC (resp. LRC) speeds is only 0.2% (resp. 0.3%). Most of the error in the BADA 4 optimum fuel consumption comes from the error inherent to the CD and FF models, rather than the error in optimum speed: the relative error in the MRC (resp. LRC) SR estimated by BADA 4 is -1.3% (resp. -1.4%), which is consistent with the SR rRMSE of 1.31%.

Fig. 14 presents the values of CD, FF and SR obtained from the reference data and from the BADA 4 APM for the same conditions as Fig. 13, except a higher aircraft weight. Despite a slightly higher rRMSE in all three parameters compared to Fig. 13, the relative error in the MRC (resp. LRC) speed estimated by BADA 4 is much lower, with a value of 0.1% (resp. 0.4%). This demonstrates that the accuracy of the optimum speeds estimated by an APM cannot be inferred from standard APM accuracy metrics such as the RMS error in CD or FF.

#### IV. INTEGRATED OPTIMIZATION RESULTS

The second set of results corresponds to the determination of the optimum speed over the whole cruise phase, also called integrated optimization. As the aircraft consumes fuel along the cruise, its weight decreases, which modifies its optimum cruise speed as seen in the previous section. Numerical comparisons have been performed between the reference and candidate values of the total elapsed time (ET) and fuel consumption (FC) over a cruise segment flown at the optimum cruise speed (re-estimated every 10NM). For each aircraft type, one combination of cruise distance, cruise altitude and initial cruise weight was selected by Boeing as representative of typical operations of that aircraft type. Additionally, two optimization criteria were evaluated:

- ECON with a CI equal to zero ( $CI_0$ ), which is equivalent to MRC [19,21]
- ECON with a CI that approximates LRC ( $CI_{LRC}$ ) under the selected cruise conditions [21].

According to [21], the typical values of CI used by airlines are comprised between  $CI_0$  and  $CI_{LRC}$ . Table II presents the elapsed time and fuel consumption results obtained for all the considered scenarios, together with the following BADA 4 error metrics computed with respect to the reference values: aETE (in s) is the absolute error in ET, aFCE (in kg) is the absolute error in FC, rETE (in %) is the relative error in ET, and rFCE (in %) is the relative error in FC.

The impact of the errors introduced by an APM in the integrated cruise optimization results will depend on the type of application. The following subsections analyse the results of Table II from the perspective of four categories of applications.

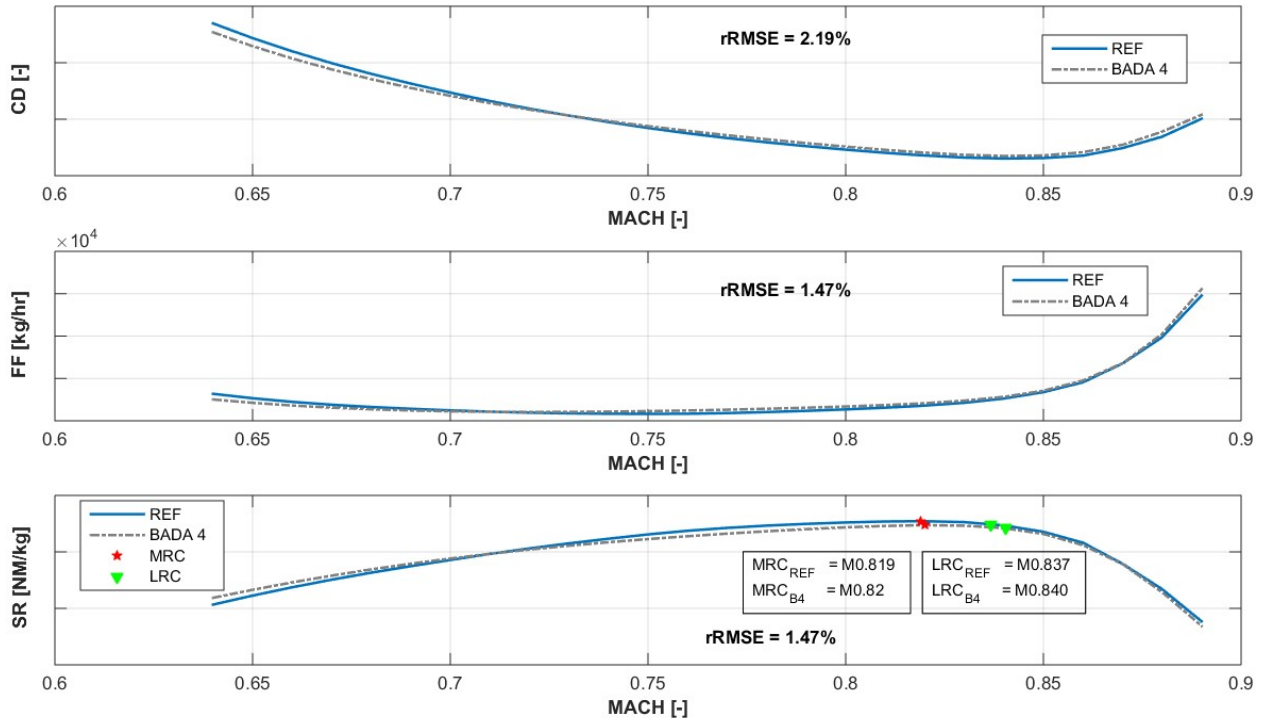


Fig. 14. MRC and LRC estimation (A6, FL300, high weight)

TABLE II. INTEGRATED TIME AND FUEL CONSUMPTION RESULTS

Aircraft type	CI	Reference		BADA 4		aETE [s]	aFCE [kg]	rETE [%]	rFCE [%]
		ET [s]	FC [kg]	ET [s]	FC [kg]				
A1	0	8728	5402	8944	5391	216	-11	2,47	-0,20
	≈LRC	8293	5453	8369	5485	76	32	0,92	0,59
A2	0	8818	5689	9087	5642	269	-47	3,05	-0,83
	≈LRC	8284	5740	8612	5703	328	-37	3,96	-0,64
A3	0	8395	6082	8791	6137	396	55	4,72	0,90
	≈LRC	8009	6143	8179	6229	170	86	2,12	1,40
A4	0	38357	108947	38867	110269	510	1322	1,33	1,21
	≈LRC	36772	109931	36406	112321	-366	2390	-1,00	2,17
A5	0	41050	43837	40991	44440	-59	603	-0,14	1,38
	≈LRC	39362	44227	39203	44999	-159	772	-0,40	1,75
A6	0	40646	76299	40776	77142	130	843	0,32	1,10
	≈LRC	38641	76998	37539	78565	-1102	1567	-2,85	2,04
A7	0	38231	49104	38852	48570	621	-534	1,62	-1,09
	≈LRC	36989	49553	36867	50303	-122	750	-0,33	1,51

### A. ATM simulations

ATM encompasses all the activities required to provide the capabilities to ensure safe and ordered air traffic operations. The ATM functions include Air Traffic Control (ATC), Air Traffic Flow Management (ATFM), and Airspace Management (ASM). For all these functions, the main trajectory information required to ensure safe operations and an efficient traffic flow is the aircraft position and speed, which will be used to determine future aircraft positions and its interactions with surrounding traffic. Errors in the optimum speed calculations will thus negatively impact the capability of an ATM simulation tool to accurately predict the evolution of a single flight or an entire traffic sample, while errors in the optimum fuel flow typically do not have relevance in such applications. Among the metrics of Table II, the rETE is therefore the most important to evaluate the applicability of BADA 4 to cruise speed optimizations in ATM simulations.

The average rETE over all scenarios is 1.13%, indicating that BADA 4 would tend to underestimate the optimum cruise speed and thus overestimate the cruise time. This trend is more pronounced for narrow-body aircraft (average rETE of 2.87%), while wide-body aircraft show an opposite trend (average rETE of -0.18%). With a maximum rETE below 5% and an average rETE below 2%, BADA 4 can be considered suitable for cruise speed optimization in the context of ATM simulations.

### B. Environmental impact assessments

Environmental impact assessments (EIA) in aviation aim at quantifying the contribution of aircraft to the global warming, climate change and disturbances around airports due to the noise and emissions (gaseous or particulate matter) generated by the aircraft. Aviation emissions in particular can be modeled as a function of the fuel consumed by the aircraft. Among the metrics of Table II, the rFCE is therefore the most important to evaluate the applicability of BADA 4 to cruise speed optimizations in EIA tools.

The average rFCE over all scenarios is 0.81%, indicating that BADA 4 would tend to overestimate the fuel consumption during optimum cruise. This trend is more pronounced for wide-body aircraft (average rFCE of 1.26%) compared to narrow-body aircraft (average rFCE of 0.20%). With a

maximum rFCE well below 5% and an average rFCE below 2%, BADA 4 can be considered suitable for cruise speed optimization in the context of EIA.

### C. On-board applications

On-board applications (OBA) refer to the Flight Management System (FMS) or Electronic Flight Bag (EFB) capabilities related to the optimization of the trajectory according to actual aircraft performance and flight conditions [23]. In such applications, both the optimum speed and fuel consumption need to be accurately estimated so that the actual trajectory and fuel burn match the predictions done by the OBA. Among the metrics of Table II, the rETE and rFCE are therefore the most important to evaluate the applicability of BADA 4 to cruise speed optimizations in OBA.

The maximum values of the rETE and rFCE, in particular, need to be low enough to satisfy the tight accuracy requirements of OBA. With a maximum rETE exceeding 2% for most of the aircraft types, BADA 4 cannot be considered suitable for cruise speed optimization in the context of OBA.

### D. Business and economic studies

Business and economic studies (BES) look into the operating costs of an airline. A relevant information for such studies would be the evolution of flight time (which influences time costs) and fuel consumption (which influences fuel costs) when the CI is modified. As an example, the changes in cruise time and fuel consumed that occur between  $CI_0$  and  $CI_{LRC}$  can be determined from the results of Table II. The absolute and relative (with respect to  $CI_0$ ) changes computed from the reference and BADA 4 data are presented in Table III:

- $a\Delta ET$  (in s) is the absolute change in ET,
- $a\Delta FC$  (in kg) is the absolute change in FC,
- $r\Delta ET$  (in %) is the relative change in ET,
- $r\Delta FC$  (in %) is the relative change in FC.

TABLE III. CHANGES IN TIME AND FUEL CONSUMPTION UPON CHANGE OF CI

Aircraft type	Reference				BADA 4			
	$\alpha\Delta ET$ [s]	$\alpha\Delta FC$ [kg]	$r\Delta ET$ [%]	$r\Delta FC$ [%]	$\alpha\Delta ET$ [s]	$\alpha\Delta FC$ [kg]	$r\Delta ET$ [%]	$r\Delta FC$ [%]
A1	-435	51	-4,98	0,94	-575	94	-6,43	1,74
A2	-534	51	-6,06	0,90	-475	61	-5,23	1,08
A3	-386	61	-4,60	1,00	-612	92	-6,96	1,50
A4	-1585	984	-4,13	0,90	-2461	2052	-6,33	1,86
A5	-1688	390	-4,11	0,89	-1788	559	-4,36	1,26
A6	-2005	699	-4,93	0,92	-3237	1423	-7,94	1,84
A7	-1242	449	-3,25	0,91	-1985	1733	-5,11	3,57

What is important from the perspective of the BES is to assess if the changes in cruise time ( $r\Delta ET$ ) and fuel consumption ( $r\Delta FC$ ) estimated using BADA 4 are similar to the values provided by the reference data. The results from Table III indicate that for most aircraft types, BADA 4 significantly overestimates the change in cruise time (e.g. BADA 4: -7.94% vs reference: -4.93% for A6) and the change in fuel consumption (e.g. BADA 4: +1.84% vs reference: +0.92% for A6) between  $CI_0$  and  $CI_{LRC}$ . Therefore, BADA 4 cannot be considered suitable for the kind of analyses performed in the context of BES.

## V. DISCUSSION AND FUTURE WORK

In this study, the reference data used to evaluate the candidate APM were computed from a performance engineering software, considered by the aircraft manufacturer as the most accurate source of performance data. The optimum cruise speed actually flown by an aircraft, however, is determined by the on-board FMS, and this FMS may use performance databases and optimization algorithms that differ from the manufacturer performance tools, resulting in different optimization results. Using the methodology presented in this paper with FMS optimization results as a reference would therefore provide a useful complement to the present study. The collection of FMS optimization results for a variety of aircraft types and flight conditions may prove challenging however, considering the need to access real aircraft.

According to the results presented in this paper, BADA 4 can be considered as a suitable APM for cruise speed optimizations in ATM simulations or environmental impact assessments, but it may not yet satisfy the accuracy requirements of other applications. The authors, who participate to the development of BADA 4, intend to use the insight gained from this study to guide the next evolutions of this APM. Further improvements of the drag and fuel flow models, in particular, will be considered in order to improve the accuracy of the SR estimation and the resulting cruise optimization results.

## VI. CONCLUSIONS

This paper has evaluated the accuracy of trajectory optimization results from a modern APM designed for ATM applications, using reference data from a major aircraft manufacturer. The study focused on cruise speed optimization and considered several aircraft types representative of jet airliner operations. A detailed evaluation of the APM presented the accuracy of its optimization results (cruise speed and fuel

consumption) and underlying parameters (drag coefficient, specific range) for several cruise optimization criteria: maximum range, long range, and economy. Larger errors have been observed in the speed estimation compared to the fuel estimation, which could be explained by the flatness of the specific range curve in the vicinity of the MRC and LRC optimum speeds. From the errors measured in integrated optimization results (average: 2%, maximum: 5%, on both speed and fuel), the evaluated APM was deemed suitable for cruise speed optimization in ATM simulations and environmental impact assessments, and not suitable for on-board applications and business and economic studies. The results from this study will guide future evolutions of this APM, such as improvements of its drag and fuel flow models.

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