ISSN 1330-3651 (Print), ISSN 1848-6339 (Online)
https://doi.org/10.17559/TV-20170125145236
Original scientific paper

Operational Aspects of Vertical Navigation during the Approach Phase of Flight: CDA vs. Conventional Step-Down Approach

Petar ANDRAŠI*, Doris NOVAK, Antonio RATKOVIĆ

Abstract: The continuous descent approach (CDA) is an operational technique used by aircraft when descending from cruise altitude; the aim is to minimize thrust and thereby avoid horizontal flight segments. CDA involves vertical navigation calculations that modify flight trajectory according to altitude; these procedures can reduce fuel consumption, emission of toxic exhaust gases, and noise due to the aircraft and its engines. In order to verify some of these benefits under field conditions in Croatia, the present study analysed fuel consumption, approach distance and approach duration during 44 landings by Croatia Airlines Dash-8 Q400 aircraft at the airport in Split, Croatia. CDA was performed at 426 km/h (230 knots) or at high speed, and these procedures were compared with the standard step-down approach involving a flight speed of 426 km/h (230 knots) and an18.5 km-long (10 NM) horizontal segment at an altitude of 914 m(3000 ft). The different approach conditions were compared in terms of fuel consumption. The results indicate that implementing CDA can provide small fuel savings on individual flights, and that these savings can be significant when calculated over an entire fleet on an annual basis. The significant reduction in fuel consumption should also mean a reduction in CO_2 emissions.

Keywords: Continuous descent approach (CDA); fuel management; vertical navigation

1 INTRODUCTION

The continuous descent approach (CDA) is a noise-reducing procedure in which the aircraft applies an optimal rate of descent towards the final approach fix, at which point the pilot can initiate instrumental approach. CDA involves calculating flight altitude as a function of distance from the runway, and this so-called vertical navigation minimizes or even eliminates the need for engine power corrections and allows the engine to work at minimum power from the beginning of the procedure. The result is continuous descent without horizontal flight segments. This procedure has been reported to reduce fuel consumption from cruising altitude (top of descent) to final approach 305 m (1000 ft) above ground. Since this flight segment can be as long as 56 km (30 NM) and last up to 20 minutes, vertical navigation can lead to significant fuel savings.

The environmental impact of air traffic, including noise and toxic emissions, has become a key factor limiting the expansion of many airports. The rapid growth of communities around airports and increasing awareness of the environmental pollution generated by airports conflict with annual growth in air traffic. The environmental impact of airport operations leads individuals and associations in the local community to file objections with local authorities or lawsuits in court. This negative publicity then makes it difficult to introduce new runways, exacerbating the already increasing congestion around major airports. This congestion leads, in turn, to higher fuel consumption and toxic emissions.

To reduce the environmental impact of air traffic on communities located near airports and to offset relatively high fuel prices, many airports have issued specially designed CDA procedures. At the same time, an increasing number of airlines have adopted these procedures for all types of aircraft in their fleets. Despite its growing global acceptance, CDA has not officially been introduced into aircraft operations in Croatian airspace. Therefore, the present work was undertaken to verify that CDA can be implemented in this region and that it can have positive commercial and environmental benefits for airlines and airports. We measured fuel consumption of Croatia Airlines Dash-8 Q400 aircraft during routine commercial flights, from the top of the descent to landing at the airport in Split, Croatia. Approaches were performed using either the "step-down" procedure or the CDA procedure at different flight speeds under various atmospheric conditions. We hypothesized that because CDA minimizes engine power corrections during descent, it would lead to lower fuel consumption than the standard step-down approach, regardless of wind effects or air traffic control restrictions.

Our results confirmed our hypothesis that CDA can be deployed in Croatian airspace, though it places significant demands on air traffic controllers, suggesting that implementation will require adaptation by staff and systems. Our results also confirmed our hypothesis that CDA leads to fuel savings: although the financial benefits are negligible for a single flight or approach, they are significant when considered on an annual basis for a larger number of aircrafts. In addition to these financial benefits, CDA implementation can substantially reduce CO_2 emissions, benefiting the environment and communities located near the airport.

The conducted research can serve airline companies to implement appropriate navigation and approach procedures that will have a positive impact on fuel economy, and therefore on the environment as well. With the reduction of the noise footprint of an aircraft during the approach, quality of life in the vicinity of the airport can be raised to a higher level.

2 BACKGROUND AND LITERATURE REVIEW

CDA procedures assist the aircraft crew in determining and implementing the optimal descent profile that minimizes fuel consumption, noise and toxic emissions. This involves calculations and operations that are collectively known as vertical navigation. In the CDA process, the aircraft remains at the highest possible cruise altitude for as long as possible and then descends according to an optimized profile that minimizes path corrections.

Maximizing the length of the path for which the aircraft operates at the minimal ("idle") power setting can significantly reduce fuel consumption. Ideally, descent should start at a flight position (top of descent) determined by the flight management system, at which point the CDA procedure should also begin. Such maximization of idle power settings reduces not only fuel consumption but also noise. Aircraft noise comprises noise generated by the parts of the airplane as well as by the engine, so in CDA, with the engine at minimal noise, most of the remaining noise comes from the flaps, spoilers and landing gear [1]. The noise reduction achieved with CDA can be up to 5 dB compared to a conventional step-down approach [2], depending on the type of aircraft. The human ear clearly perceives differences of 5 dB, and in fact a drop of only 3 dB implies a halving of acoustic energy, since the decibel scale is logarithmic. Since aircraft and engine noise is perceptible primarily 15-50 km from the point of landing, CDA is well suited for reducing aircraft noise for communities located near airports. After the aircraft crosses the final approach fix, however, CDA and conventional step-down approach procedures produce similar noise [2]. Field measurements at Louisville International Airport in the US [4] suggest that CDA can reduce 60-dB noise contours relative to the step-down approach by 12% for a Boeing 757-200 equipped with Pratt & Whitney engines, 33% for a Boeing 757-200 equipped with Rolls-Royce engines and 17% for a Boeing 767-300.

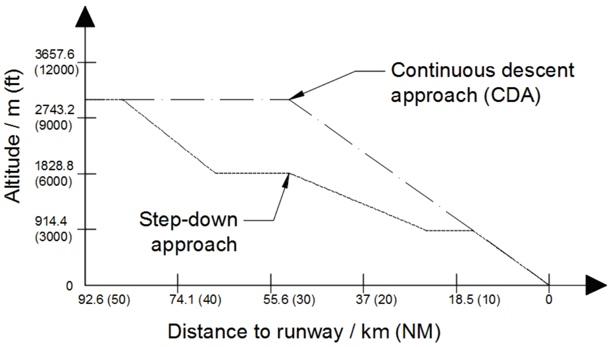

Figure 1 Comparison of descent and landing based on CDA or a conventional step-down procedure

By reducing fuel consumption, CDA has the additional benefit of reducing CO_2 emissions; aircraft emissions of this greenhouse gas are estimated to account for 2% of all man-made CO_2 emissions and 13% of all CO_2 emissions from transportation sources [3]. Reducing aircraft emissions of CO_2 and other toxic greenhouse gases has taken on financial significance with the introduction of emissions trading systems [3]. It also has environmental significance: complaints about respiratory difficulties in areas near airports primarily reflect high concentrations of CO_2, CO, NO_x and hydrocarbons. NO_x also contributes the most to global warming [1]. Airports typically monitor gas emissions above and below the boundary layer at 914 m (3000 ft) above the airport. Since both step-down and CDA procedures lead to only negligible differences in gas emissions above the boundary layer, research tends to focus on differences below the boundary layer, which can affect communities near the airport.

Key to the fuel efficiency of CDA is the fact that the aircraft is maintained as long as possible at cruise altitude, which prolongs the time during which ground speed can be maintained during the cruise phase of flight and thereby substantially reduces approach time. Field studies at Louisville International Airport reported average approach durations of 1808 sec with CDA and 1926 sec with the step-down procedure for a Boeing 757-200 [4], corresponding to a difference of 118 sec. Another field study measured an even larger difference of 147 sec for a Boeing 767-300 (1797 vs. 1944 sec) [4]. Simulation studies using the Future ATM Concepts Evaluation Tool (FACET) and a data set of 697 flights landing at Newark Liberty International Airport in the US suggest that CDA can shave an average of 2.42 minutes off each flight [5]. At the same time, the CDA procedure saves fuel: the FACET simulations suggest an average of 57 kg of fuel saved per flight. These simulations further suggest that CDA is more fuel- and time-efficient for nearly every type of civilian aircraft tested, though the amount of fuel savings depends on the type of aircraft. For this reason, the authors of the FACET study recommend that when prioritizing flights for descent and landing, air traffic controllers give priority to aircraft that will save more fuel during CDA, thereby maximizing overall efficiency of airport operations. To evaluate analytical relationship between speed, altitude and fuel burn a group of researchers in their study [6] simulated CDA approach using base of aircraft data total-energy model. Results showed that CDA procedure, if applied at low speed range, could consume more fuel than conventional approach. With that in mind authors propose CDA design guidelines based on observations attained during study. Another study [7] used FACET simulations to confirm that even in highly congested airspace where delays can obstruct complete execution of CDA, implementation of CDA procedure lead to a reduction of 23-43 kg of fuel per flight. Latest studies of CDA procedures [8,9] evaluate different aspect of CDA in terms of predictability, variability and operational feasibility and trade-off between trajectory predictability and potential fuel savings. Studies by EUROCONTROL suggest that implementing CDA at a minimum of 20% of European airports would save airlines 120 000 tons of fuel annually [10], which corresponds to approximately 100 million EUR and 400 000 tons of CO_2.

While awareness of the financial and environmental benefits of CDA has boosted its worldwide acceptance by airlines and airports alike, the procedure is not widely applied in all member states of the ICAO. This reflects primarily the need to implement simultaneously enablers and operational procedures that ensure effective use of CDA [11]. Implementation of CDA also requires safety evaluations that aim to predict all possible scenarios that can threaten flight safety and to recommend appropriate response procedures. Thus, CDA implementation requires significant commitment from stakeholders and a suitably favourable cost-benefit analysis. Even though Croatia announced in 2008 its intention to implement CDA [12], we are unaware that such analysis has been attempted.

Therefore, the present study analyses all relevant factors to show that CDA can be implemented in Croatia as a standard operating procedure for daily air traffic, suggesting that this approach procedure can be applied more widely across the Balkans and globally. Since our data were obtained using commercial aircraft in routine operation for the national airline, we believe our findings provide a strong basis for implementing vertical navigation in Croatia.

3 METHODS

The goal of this work was to compare average fuel consumption and approach duration for Croatia Airlines Dash-8 Q400 aircraft operated at different flight speeds and under various atmospheric conditions over a 6-month period at Split Airport (IATA, SPU; ICAO, LDSP). Three approach procedures were compared:

- CDA at a speed of 426 km/h (230 knots)
- high-speed CDA
- standard step-down approach at 426 km/h (230 knots).

Measurements of fuel consumption and approach durations were measured between flight levels (FL) 200 and 100 and between FL 200 and landing, reflecting the fact that cruising altitudes varied between FL 200 and 250. The approach angle was 3° in all three procedures, and deceleration to configure the aircraft for landing began 22 km (12 NM) away from the runway threshold. Flaps were first adjusted by 5° at a distance of 18.5 km (10 NM), while the final landing configuration occurred at 11 km (6 NM) from the runway threshold. The position of the flaps was 15° for all measurements taken during final approach and landing.

Measurements were carried out over a 6-month period under various conditions of temperature, pressure, aircraft mass, wind direction and wind speed. Volumes of fuel consumed were converted into estimates of greenhouse gas emissions using the conversion that 1 kg of fuel spent during flight equals 3.149 kg CO_2 released into the atmosphere [13]. Results were analyzed statistically, and the following descriptive statistics were reported: arithmetic mean (X), standard deviation (σ) and coefficient of variation (CV).

3.1 CDA at a Speed of 426 km/h (230 knots)

In this procedure, the approach began at the top of descent as calculated by the vertical navigation system, and speed was maintained at 426 km/h (230 knots) until the moment of deceleration to configure the aircraft for landing (Fig. 2 approach (2)).

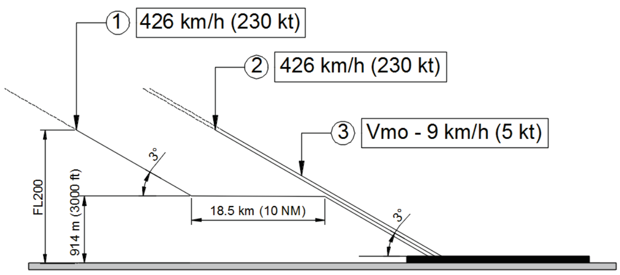

Figure 2 Standard step-down approach (1) CDA at 426 km/h (230 knots) (2), High-speed CDA (3)

The average wind component at the top of descent was 9.44 km/h (5.1 knots) of headwind, and variation with respect to the outer air temperature was 12.3 °C (ISA DVN).

3.2 High-speed CDA

In this procedure, flight speed was maintained at 9 km/h (5 knots) below the maximum operating speed (VMO) until the moment of deceleration to configure the aircraft for landing (Fig. 2 approach (3)). The maximum speed of the Dash-8 Q400 aircraft depended on altitude (Tab. 1).

Table 1 Maximal operating speeds for the Dash-8 Q400 aircraft as a function of altitude [14]

Altitude /m (ft)	V_{MO} /km/h (KIAS)
0 - 2438 (8000)	454 (245)
3048 (10 000)	522 (282)
5486 (18 000)	530 (286)
6096 (20 000)	509 (275)
7620 (25000)	459 (248)

3.3 Standard Step-down Approach at 426 km/h (230 knots)

In this procedure, both the descent from cruising altitude and the final approach were controlled by an instrument landing system but with a horizontal segment of 18.5 km (10 NM) inserted at 914 m (3000 ft) (Fig. 2 approach (1)).

4 RESULTS

4.1 CDA at a Speed of 426 km/h (230 knots)

Average fuel consumption (kg), distance travelled and duration were measured for 15 flights between FL 200 and FL 100 and between FL 200 and ground during CDA at 426 km/h (230 knots) (Tab. 2).

Table 2 Distance travelled, duration and fuel consumed during CDA at 426 km/h (230 knots)

Flight	From FL 200 to FL 100			From FL 200 to ground		
	Distance /km (NM)	Time /mm: ss	Fuel used /kg	Distance /km (NM)	Time /mm:ss	Fuel used /kg
1	55.6 (30.0)	06:52	72	55.6 (30.0)	16:58	168
2	56.1 (30.3)	06:05	52	56.1 (30.3)	14:57	131
3	56.1 (30.3)	06:25	55	56.1 (30.3)	16:11	153
4	55.7 (30.1)	06:22	57	55.7 (30.1)	15:52	152
5	56.7 (30.6)	06:04	49	56.7 (30.6)	15:18	133
6	57.2 (30.9)	05:55	50	57.2 (30.9)	14:27	130
7	59.3 (32.0)	07:16	77	59.3 (32.0)	16:38	158
8	56.7 (30.6)	06:24	54	56.7 (30.6)	15:09	135
9	55.7 (30.1)	06:23	53	55.7 (30.1)	16:23	155
10	57.6 (31.1)	06:43	62	57.6 (31.1)	15:32	145
11	58.0 (31.3)	05:51	46	58.0 (31.3)	14:06	125
12	58.0 (31.3)	06:39	57	58.0 (31.3)	15:33	141
13	57.4 (31.0)	06:35	58	57.4 (31.0)	16:09	150
14	58.2 (31.4)	06:44	59	58.2 (31.4)	15:56	151
15	58.3 (31.5)	06:18	53	58.3 (31.5)	15:17	141
X	57.0 (30.8)	06:26	56.9	57.0 (30.8)	15:38	144.5
σ	0.58	00:22	8.00	0,33	00:46	11.74
CV	1.89%	5.69%	14.0%	0.5%	4.9%	8.1%

4.2 High-speed CDA

The same three parameters were measured for 17 flights from FL 200 to FL 100 and from FL 200 to landing for high-speed CDA (Tab. 3). The average wind component at the top of descent was 7 km/h (3.8 knots) of headwind, and variation with respect to the outer air temperature was 13.7 °C (ISA DVN).

Table 3 Distance travelled, duration and fuel consumed during high-speed CDA

Flight	From FL 200 to FL 100			From FL 200 to ground		
	Distance /km (NM)	Time /mm: ss	Fuel used /kg	Distance /km (NM)	Time /mm: ss	Fuel used /kg
1	58.2 (31.4)	05:17	64	113.9 (61.5)	13:40	143
2	58.3 (31.5)	04:54	69	115.8 (62.5)	13:09	144
3	57.6 (31.1)	05:45	72	113.9 (61.5)	14:32	142
4	59.6 (32.2)	05:36	65	114.8 (62.0)	14:13	144
5	57.2 (30.9)	05:10	54	113.3 (61.2)	13:29	132
6	58.2 (31.4)	05:02	52	113.7 (61.4)	13:55	135
7	58.0 (31.3)	06:04	75	113.2 (61.1)	15:35	175
8	57.4 (31.0)	06:12	71	112.8 (60.9)	14:35	153
9	57.4 (31.0)	05:58	74	114.3 (61.7)	15:16	168
10	56.3 (30.4)	05:49	63	112.4 (60.7)	14:05	144
11	57.6 (31.1)	05:39	68	112.8 (60.9)	14:08	150
12	57.8 (31.2)	05:32	70	112.8 (60.9)	14:11	160
13	57.2 (30.9)	05:46	69	113.0 (61.0)	14:16	161
14	55.7 (30.1)	04:58	54	113.2 (61.1)	13:23	132
15	58.5 (31.6)	05:36	71	113.3 (61.2)	14:24	159
16	57.8 (31.2)	05:30	61	114.1 (61.6)	16:21	174
17	57.4 (31.0)	05:27	67	112.8 (60.9)	13:45	145
X	57.6 (31.1)	05:33	65.8	113.5 (61.3)	14:17	150.6
σ	0.83 (0.45)	00:22	6.83	0.83 (0.45)	00:48	13.17
CV	1.44%	6.63%	10.37%	0.74%	5.55%	8.74%

4.3 Standard Step-down Approach at 426 km/h (230 knots)

Finally, the same three parameters were measured for 12 flights from FL 200 to FL 100 and from FL 200 to landing for a step-down approach at 426 km/h (230 knots) (Tab. 4). The average wind component at the top of descent was 2.2 km/h (1.2 knots) of headwind, and variation with respect to the outer air temperature was 12.8 °C (ISA DVN).

The values for a step-down approach from FL 200 to FL 100 overlap with the corresponding values for CDA at 426 km/h (230 knots) (Tab. 2). In this altitude regime, both procedures involve the same actions. In contrast, the distance travelled from FL 200 to landing is longer for the step-down approach because of the 18.5-km (10-NM) horizontal segment. As a result, the step-down approach takes longer and consumes more fuel.

Table 4 Distance travelled, duration and fuel consumed during a step-down approach at 426 km/h (230 knots)

Flight	From FL 200 to FL 100			From FL 200 to ground		
	Distance / NM	Time /mm: ss	Fuel used /kg	Distance / NM	Time /mm:ss	Fuel used /kg
1	59.4 (32.1)	06:39	58	133.5 (72.1)	18:10	202
2	59.6 (32.2)	06:36	59	133.9 (72.3)	17:48	194
3	57.8 (31.2)	07:17	66	132.4 (71.5)	18:20	207
4	58.7 (31.7)	07:23	69	133.9 (72.3)	19:03	223
5	58.3 (31.5)	06:57	65	132.0 (71.3)	18:43	199
6	57.8 (31.2)	06:05	49	131.3 (70.9)	17:33	179
7	58.0 (31.3)	06:10	49	133.7 (72.2)	18:02	184
8	55.7 (30.1)	05:54	45	132.2 (71.4)	17:22	175
9	59.3 (32.0)	06:28	59	132.4 (71.5)	18:11	201
10	58.7 (31.7)	06:43	64	132.6 (71.6)	18:13	202
11	58.7 (31.7)	06:20	52	133.9 (72.3)	18:15	191
12	58.9 (31.8)	06:09	49	132.6 (71.6)	18:12	185
X	58.3 (31.5)	06:33	57.0	133.0 (71.8)	18:09	195.2
σ	1.00 (0.54)	00:27	7.68	0.83 (0.45)	00:26	12.82
CV	1.70%	6.87%	13.48%	0.63%	2.41%	6.57%

4.4 Comparison of Different Approach Conditions

For flights relying on the high-speed CDA or step-down approach, the average deviation of the actual temperature from the standard temperature based on International Standard Atmosphere conditions at flight altitude was 12.5 °C, while it was slightly less in the case of CDA at 426 km/h (230 knots) because two flights occurred under colder conditions in October. As a result, variability was moderate to very strong ($\sigma \approx 4.5$ °C) for this approach condition. Flights for the other two approach conditions were conducted during the summer, so variability was slight ($\sigma \approx 2$ °C)

The average wind component at the top of descent varied within the range 1.3-9.4 km/h (0.7-5.1 knots) of headwind. Individual wind component values varied from 91 km/h (49 knots) of tailwind to 124 km/h (67 knots) of headwind; these strong deviations from central values explain the high variability at cruising altitudes and FL 200 ($\sigma \approx$ 37 km/h (20 knots)) as well as at FL 100 ($\sigma \approx$ 18.5 km/h (10 knots)). The data reveal that the wind speed component increased with flight altitude.

Tab. 5 describes the weather conditions for the various test flights.

Average values for specific ground range [SR(GND)] and specific air range [SR(AIR)], both measured at the top of descent, varied over the range 0.632-0.646 km/kg (0.341-0.349 NM/kg) per torque, corresponding to approximately 55% variation. At FL 200, high-speed CDA was associated with average SR(GND) and SR(AIR) of approximately 0.963 km/kg (0.52 NM/kg) with relatively slight variability and a standard variation of measurement of 0.20 km/kg (0.11 NM/kg); the other two approach procedures were associated with average SR(GND) and SR(AIR) values near 1.20 km/kg (0.65 NM/kg) with extremely low variability and a standard variation of 0.11 km/kg (0.06 NM/kg). For all three approach conditions, the specific range, which averaged 0.98 km/kg (0.48 NM/kg) at FL 100, decreased during descent. Differences in specific range between high-speed CDA and CDA at 426 km/h (230 knots) were smaller at FL 100 than at FL 200, as a direct result of deceleration in order to achieve 444 km/h(240 knots) at FL 80; achieving 444 (240 knots) requires only slightly more torque than maintaining 426 km/h (230 knots).

The average torque value during approach at 426 km/h (230 knots) was 16% of the torque during the entire approach. During high-speed CDA, average was 35.8% of the torque during the entire approach at FL 200. At FL 100, average torque was 23.6% during the entire approach. The large dispersion of measured values around the central values reflects frequent torque adjustment in order to maintain the desired speed and avoid exceeding v_{MO}.

Average rate of fuel consumption during CDA at 426 km/h (230 knots) was approximately 480 kg/h at FL 200, and it increased progressively during descent, reaching approximately 570 kg/h at FL 100. Conversely, the rate of fuel consumption during high-speed CDA decreased during descent, going from 705.3 kg/h at FL 200 to 677.1 kg/h at FL 100. Our results showed CDA to be fuel-efficient, even though the desired speed was 9 km/h (5 knots) less than V_{MO} (277 knots at FL 100; Tab. 1). This efficiency reflects the optimized start of deceleration to achieve a speed of 444 km/h (240 knots) at an altitude of 2438 m (8000 ft). Interestingly, high-speed CDA was more fuel-efficient than conventional CDA, even though it consumed more fuel at lower altitudes due to greater air density.

Average target vertical speed for CDA or the step-down approach at 426 km/h (230 knots) was 8.488 m/s (1671 ft/min) at FL 200 and approximately 7.239 m/s (1425 ft/min) at FL 100. In contrast, target vertical speed was higher for high-speed CDA: 9.601 m/s (1890 ft/min) at FL 200 and 8.173 m/s (1609 ft/min) at FL 100.

The standard deviation in the distance needed for an aircraft to land from FL 200 and FL 100 was 0.83 km (0.45 NM) in all three approach conditions. This most likely reflects measurement error, since average air pressure was equal to the standard pressure of 1013.25 hPa with only small deviations from the central value of 4 hPa.

Table 5 Atmospheric conditions during the test flights

Flight	TOD			At FL 200		At FL 100		At ground	
	FL	ISA Dev / °C	Wind / km/h(kt)	ISA Dev / °C	Wind / km/h(kt)	ISA Dev / °C	Wind / km/h(kt)	Temperature / °C	Air pressure / hPa
CDA at 426 km/h (230 knots)									
1	240	12	124.1 (67)	9	75.9 (41)	5	59.3 (32)	27	1017
2	250	13	−16.7 (−9)	13	−13.0 (−7)	13	−22.2 (−12)	25	1014
3	220	15	3.7 (2)	12	5.6 (3)	12	7.4 (4)	32	1016
4	240	15	37.0 (20)	14	25.9 (14)	14	−14.8 (−8)	25	1015
5	250	14	−18.5 (−10)	14	−18.5 (−10)	14	−14.8 (−8)	26	1012
6	220	15	−40.7 (−22)	15	−31.5 (−17)	13	−38.9 (−21)	34	1011
7	230	13	42.6 (23)	11	35.2 (19)	12	44.4 (24)	30	1012
8	250	14	−3.7 (−2)	13	9.3 (5)	5	22.2 (12)	30	1010
9	200	15	40.7 (22)	14	50.0 (27)	13	−13.0 (−7)	32	1012
10	240	15	50.0 (27)	14	40.7 (22)	10	14.8 (8)	21	1012
11	230	16	−64.8 (−35)	15	−63.0 (−34)	13	−25.9 (−14)	25	1015
12	250	9	25.9 (14)	9	22.2 (12)	9	7.4 (4)	31	1011
13	220	14	5.6 (3)	14	13.0 (7)	9	11.1 (6)	23	1017
14	250	2	−14.8 (−8)	2	−7.4 (−4)	−1	7.4 (4)	20	1006
15	250	3	−27.8 (−15)	2	−27.8 (−15)	0	−24.1 (−13)	17	1020
X		12.3	9.4 (5.1)	11.4	7.8(4.2)	9.4	1.3 (0.7)	26.5	1013.3
σ		4.19	44.41 (23.98)	4.11	34.65 (18.71)	4.79	26.24 (14.17)	4.79	3.34
CV		34%	467%	36%	445%	51%	1932%	18.04%	0.33%
High-speed CDA									
1	250	14	−33.3 (−18)	14	−27.8 (−15)	15	−9.3 (−5)	31	1010
2	240	15	29.6 (16)	15	20.4 (11)	14	−9.3 (−5)	32	1007
3	220	13	31.5 (17)	11	31.5 (17)	13	25.9 (14)	33	1011
4	230	13	22.2 (12)	11	7.4 (4)	12	16.7 (9)	33	1010
5	230	13	−90.7 (−49)	12	−81.5 (−44)	9	−31.5 (−17)	31	1016
6	250	12	−77.8 (−42)	12	−74.1 (−40)	12	−27.8 (−15)	31	1015
7	240	13	64.8 (35)	13	75.9 (41)	9	29.6 (16)	20	1023
8	220	14	63.0 (34)	12	59.3 (32)	8	55.6 (30)	14	1022
9	240	12	51.9 (28)	10	40.7 (22)	11	40.7 (22)	23	1011
10	220	15	22.2 (12)	14	13.0 (7)	15	13.0 (7)	28	1009
11	240	13	51.9 (28)	12	31.5 (17)	11	−5.6 (−3)	20	1018
12	230	14	9.3 (5)	13	7.4 (4)	13	5.6 (3)	27	1015
13	220	14	−1.9 (−1)	14	3.7 (2)	13	3.7 (2)	32	1014
14	250	14	−42.6 (−23)	14	−25.9 (−14)	13	−5.6 (−3)	27	1013
15	240	13	18.5 (10)	13	18.5 (10)	14	5.6 (3)	30	1019
16	220	15	−22.2 (−12)	14	−18.5 (−10)	14	7.4 (4)	27	1016
17	220	16	24.08 (13)	15	24.08 (13)	15	−1.85 (−1)	28	1014
X		13.7	7.04 (3.80)	12.9	6.30 (3.40)	12.4	6.67 (3.60)	27.5	1014.3
σ		1.07	44.89 (24.24)	1.41	40.45 (21.84)	2.12	21.85 (11.80)	5.20	4.34
CV		8%	634%	11%	651%	17%	329%	18.94%	0.43%
Step-down approach at 426 km/h (230 knots)									
1	250	8	29.6 (16)	14	40.7 (22)	14	20.4 (11)	17	1013
2	250	14	20.4 (11)	13	22.2 (12)	13	−3.7 (−2)	32	1015
3	220	14	63.0 (34)	13	53.7 (29)	14	38.9 (21)	32	1010
4	250	12	44.4 (24)	11	63.0 (34)	12	59.3 (32)	30	1012
5	240	16	51.9 (28)	15	42.6 (23)	14	25.9 (14)	21	1013
6	250	14	−48.2 (−26)	13	−38.9 (−21)	15	−9.3 (−5)	37	1014
7	230	10	−50.0 (−27)	10	−38.9 (−21)	6	−16.7 (−9)	30	1013
8	250	9	−77.8 (−42)	9	−66.7 (−36)	8	−37.0 (−20)	27	1014
9	240	14	−1.9 (−1)	13	3.7 (2)	16	−5.6 (−3)	27	1018
10	220	16	18.5 (10)	14	18.5 (10)	15	11.1 (6)	36	1015
11	250	15	−14.8 (−8)	14	−22.2 (−12)	15	−3.7 (−2)	30	1015
12	250	11	−9.3 (−5)	11	−18.5 (−10)	11	−18.5 (−10)	22	1014
X		12.8	2.22 (1.20)	12.5	5.00 (2.70)	12.8	5.19 (2.80)	28.4	1013.8
σ		2.59	42.23 (22.80)	1.76	39.98 (21.59)	2.92	25.91 (13.99)	5.74	1.86
CV		20%	1954%	14%	810%	23%	509%	20.19%	0.18%

As we expected, high-speed CDA gave the fastest approach of 14:17 minutes from FL 200 to landing and 5:33 minutes from FL 200 to FL 100. The corresponding times for CDA at 426 km/h (230 knots) were slightly longer at 15:38 and 6:26 minutes. Even longer were the corresponding times for the standard step-down approach at 426 km/h (230 knots), 16:19 and 6:33 minutes (Fig. 3). Even though the first two CDA procedures occurred at 426 km/h (230 knots), the standard step-down procedure was still 40 seconds longer. This is because the speed during the horizontal segment at 914 m (3000 ft) was lower than the speed during the corrective segment at FL 200. The duration of approach was similar from FL 200 to FL 100 for all three conditions, reflecting the fact that they involved the same operating technique. The results show that the approach time from FL 100 to landing was longer than the approach from FL 200 to FL 100, reflecting the slower flight speed at lower altitudes and the deceleration regime to achieve a final approach speed for landing.

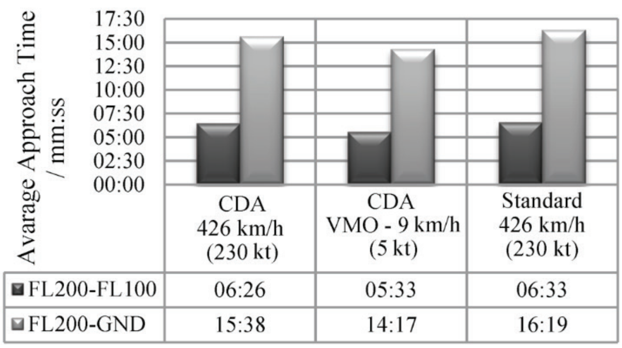

Figure 3 Average approach time under three approach conditions

The smallest fuel consumption during descent from FL 200 to FL 100 was 57 kg, measured during CDA and the step-down approach at 426 km/h (230 knots) (Fig. 4). The greatest fuel consumption between FL 200 and FL 100 (65.8 kg) was observed during high-speed CDA. Between FL 200 and landing, CDA at 426 km/h (230 knots) gave the smallest average fuel consumption (144.5 kg), compared to 150.6 kg for high-speed CDA. The greatest consumption between FL 200 and landing was 164.2 kg during the step-down approach. In all three-approach conditions, much more fuel was consumed when descending from FL 100 to landing, than when descending from FL 200 to FL 100.

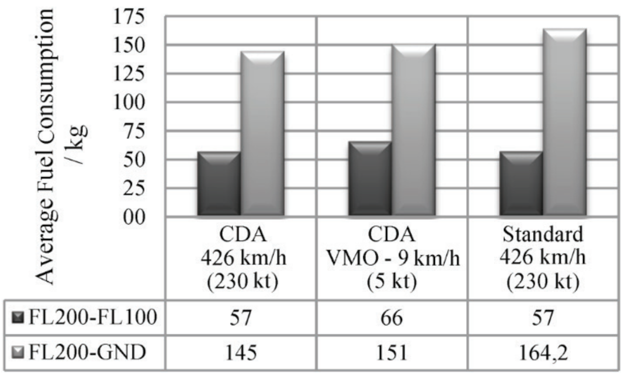

Figure 4 Average fuel consumption for three approach conditions

Comparison of the two CDA procedures shows that high-speed CDA lasted 1:20 minutes less (8,6% reduction), while CDA at 426 km/h (230 knots) consumed approximately 6 kg less fuel (4% reduction). Comparison of CDA at 426 km/h (230 knots) with the standard step-down approach shows that CDA was an average of 40 seconds shorter (4.2%) and consumed an average of 20 kg less fuel (12%). Taking into account the ratio of fuel consumed between FL 200 and landing to fuel consumed during the entire approach and landing (Tab. 6), we conclude that CDA can cut the total amount of fuel required for one flight by up to 3%. These results apply only to aircraft with turbo-prop engines.

Table 6 Fuel consumed during descent from FL 200 to landing as a percentage of fuel consumed during the entire flight

Flight	High-speed CDA			CDA at 426 km/h (230 knots)			Step-down approach		
	Consumed during descent / kg	Consumed during entire flight / kg	%	Consumed during descent / kg	Consumed during entire flight / kg	%	Consumed during descent / kg	Consumed during entire flight / kg	%
1	143	1094	13.1	168	1303	12.9	202	1525	13.3
2	144	891	16.2	131	1739	7.5	194	1487	13.1
3	142	676	21.1	153	710	21.6	207	727	28.5
4	144	1258	11.5	152	641	23.7	223	1582	14.1
5	132	1037	12.7	133	1412	9.4	199	696	28.6
6	135	1115	12.1	130	589	22.1	179	953	18.8
7	175	643	27.2	158	751	21.1	184	1554	11.8
8	153	720	21.2	135	1227	11.0	175	1143	15.3
9	168	666	25.2	155	1567	9.9	201	2242	8.9
10	144	650	22.1	145	1205	12.0	202	630	32.1
11	150	1235	12.1	125	888	14.1	191	1175	16.3
12	160	661	24.2	141	1211	11.6	185	1361	13.6
13	161	656	24.5	150	672	22.3	-	-	-
14	132	1222	10.8	151	1214	12.4	-	-	-
15	159	635	25.1	141	1102	12.8	-	-	-
16	174	683	25.5	-	-	-	-	-	-
17	145	621	23.4	-	-	-	-	-	-
X	150.7	850.8	19.3	144.5	1082.1	14.9	195.2	1256.3	17.9
σ	13.17	240.5	5.8	11.7	345.1	5.3	12.8	447.3	7.3
CV	8.7%	28.3%	30.3%	8.1%	31.9%	35.6%	6.6%	35.6%	40.6%

Average fuel savings of 20 kg per flight relative to the conventional step-down approach correspond to a reduction in CO_2 emissions of approximately 63 kg. This reduction, if we assume 15 000 Dash Q400-type flights in Croatian airspace each year, would translate to a total annual reduction of 944.7 tons.

Our results establish that CDA can provide fuel, time and emissions benefits over the conventional step-down approach for smaller commercial aircraft in Croatia. Future research should directly measure noise levels and toxic gas emissions for the different types of approach conditions. Such studies should also consider a wider array of weather conditions. Our measurements were restricted to a few altitudes: 6096 m (20000 ft), FL 200 (1013.25 hPa), FL 100, and landing. Our results point to a significant effect of wind on fuel consumption: a greater head wind component prolongs approach, which consumes more fuel. We also noticed that differences in aircraft weight and variations in temperature and pressure did not significantly affect fuel consumption, though further studies are needed to quantify these effects.

Future studies should also examine the practical feasibility of implementing CDA procedures in Croatian airspace, given that it places substantial additional demands on air traffic management [8]. For example, it may not be feasible to implement CDA in terminal areas, where air traffic density is high. Further work should address this question, as well as the effects of CDA on flight safety, flight delays and other aspects of air traffic.

5 CONCLUSION

Although the Air Navigation Service Provider and other operators in Croatian airspace have not implemented CDA, our study suggests that doing so would bring significant financial and environmental benefits. Although CDA with vertical navigation reduces the total amount of fuel needed for one flight/approach by only 1-3%, these savings become substantial when calculated over the entire number of flight operations and all aircraft in a fleet. This fuel reduction translates to a reduction in CO_2 emissions.

The present study was restricted to commercial two-engine turbo-prop aircraft and it involved measurements only of approach distance, duration, and fuel consumption. It was proved that airline companies can apply CDA procedures within their normal operations even though they are still not implemented as part of standard operating procedures. Future studies should measure directly the emission of greenhouse gases during descent as well as the noise perceived by communities near the airport. Despite the limitations in our data, we were able to show that strong headwind lengthens the approach and therefore increases fuel consumption. In addition, differences in aircraft mass or in air temperature or pressure do not appear to significantly affect fuel consumption, though further work is needed to quantify these effects precisely. This work will require specialized equipment and calculation of aerodynamic coefficients. In addition to these specialized questions about CDA, studies should also examine its optimal implementation by airlines and airports and its effects on air traffic management, including safety, delays and other performance parameters.

Nevertheless, positive effect of CDA in aircraft operations during approach have beneficial outcome on airline business management in terms of fuel savings, thus having significant positive ecological impact.

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Contact information:

Petar ANDRAŠI, mag. ing. aeronaut.
(Corresponding author)
University of Zagreb,
Faculty of Transport and Traffic Sciences
Vukelićeva 4, 10 000 Zagreb, Croatia
petar.andrasi@fpz.hr

Doris NOVAK, prof. dr. sc.
University of Zagreb,
Faculty of Transport and Traffic Sciences
Vukelićeva 4, 10 000 Zagreb, Croatia
doris.novak@fpz.hr

Antonio RATKOVIĆ, capt.
Croatia Airlines d.d.
Bani 75b, 10010 Buzin, Croatia
antonio.ratković@croatiaairlines.hr