

Reducing Aviation’s Environmental Impact Through Large Aircraft For Short Ranges

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More than 90% of high-traffic scheduled flights are less than 1,500 nautical miles; however, the majority of aircraft used on these routes have design ranges considerably longer than 1,500 nm. We show that the impact of civil aviation on climate change can be reduced by using large aircraft designed specifically for the majority of flights — Large Aircraft for Short Ranges (LASR). The reduction in greenhouse gas emissions per passenger kilometer achieved by LASR aircraft is approximately 5% with respect to narrow body aircraft and 13% with respect to wide body aircraft. The LASR approach achieves this by a reduction in the operational empty weight afforded by a reduction in the maximum take-off weight. Since this approach does not require novel technology, it can be implemented immediately, yet remains complementary with future technological innovations.

I. Introduction

The possibility that human actions can warm the planet was debated throughout much of the twentieth century.¹ However, the mounting evidence for anthropogenic climate change is compelling; the international scientific consensus is that humanity is very likely (90–99%) causing global warming.² Climate change demands immediate action, and the airline industry is not exempt. While aviation contributes only 2% to the total anthropogenic carbon dioxide (CO₂) emissions, carbon dioxide emissions alone are misleading and do not represent the total radiative forcing from aviation, which is closer to 5%.³

Many technological and operational advances have been proposed to decrease aviation’s impact on climate change. Examples include alternative fuels,^{4,5} blended-wing-body configurations,⁶ and active-flow control.^{7,8} Each of these ideas has merit and should be investigated. However, they cannot be easily implemented in the short term.

More than 90% of high-traffic routes flown by airlines are less than 1,500 nm. This represents a significant proportion of aviation’s greenhouse gas emissions, so it makes sense to target the efficiency of aircraft used on these short routes.

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Using today’s technology, a potential solution is *Large Aircraft for Short Ranges (LASR)*. By designing aircraft for short ranges, a lower operational empty weight is realized. This, in turn, increases fuel efficiency and provides a simple yet effective means of reducing aircraft emissions. The objective of this paper is to demonstrate the merit of this approach. An aircraft conceptual design tool is used to determine the performance of a large, short-range aircraft and compare it with existing aircraft on the basis of performance, economics, and environmental impact.

II. Market Analysis

The goal of this section is to establish how many existing flights can be replaced by LASRs and to determine the overall market size for LASR aircraft, assuming LASRs will carry approximately 300 passengers in a two-class configuration.

The first step is to identify the airline sector to be targeted by LASRs. In order to limit our analysis to busy routes served by jet aircraft, two assumptions are made about the flight operations of LASRs:

Passenger Traffic: Only one-way, single-stage flights with passenger demand of at least 600 seats per day are considered

Minimum Aircraft Capacity: Only routes where the average aircraft size is at least 100 seats are considered.

The LASR approach is two-fold: first, combine two or more flights of smaller aircraft into a single LASR flight; second, replace the operation of traditional long-range aircraft operating on short, high-density routes with LASRs.

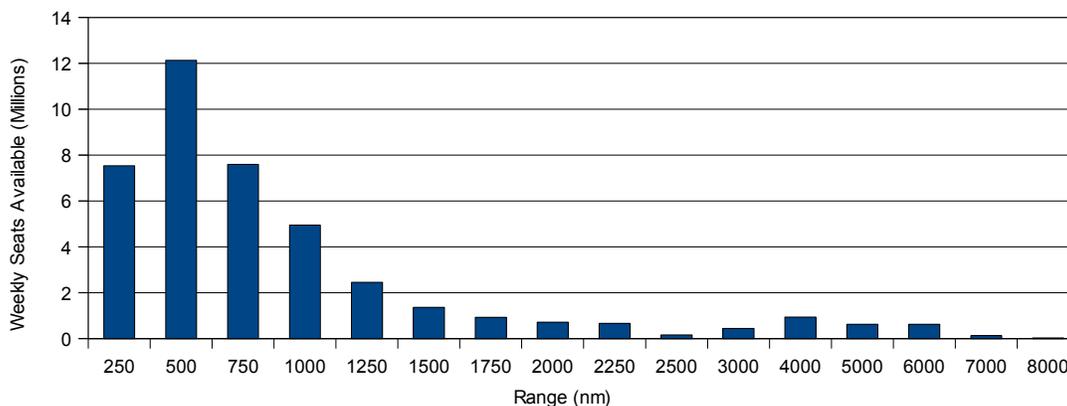


Figure 1. Distribution of flights by length

Using the services of OAG,⁹ all scheduled flights (worldwide, February, 2009) satisfying the above criteria were determined and are shown in Figure 1. The figure provides a picture of the stage length distribution for heavily travelled routes. The vast majority of flights (greater than 90%) occur at ranges under 1,500 nm; hence this will be used as our target design range. By summing the above chart up to 1,500 nm, we find there are approximately 41 million seats per week available. This can be used to gauge the total size of the market segment for LASRs.

III. Preliminary Assessment

The LASR aircraft concept is an example of a reduced range design. A related idea, multi-staging long haul flights, has been discussed by Green.¹⁰ The later concept is to break long flights into multiple stages, refueling at each stopover. This leads to significantly reduced take-off weight, and a lower total fuel burn. Since the results were first published, a correction addressing the omission of the reserve fuel requirement has been made.¹¹ The fundamental fuel saving mechanism is the same in both concepts: a reduction of aircraft operating empty weight achieved by a reduced maximum take-off weight requirement leading to

lower induced drag and hence fuel burn. Since the LASR concept is related to the reduced-range multi-stage aircraft design, a preliminary assessment of the LASR concept is conducted using the techniques used by Green as well as other authors (Nangia,¹² Hahn,¹³ and Creemers¹⁴). All of the above authors use the Breguet range equation for a jet aircraft in a cruise-climb profile:

$$R = \frac{V}{c} \frac{L}{D} \ln \left(\frac{W_1}{W_2} \right) = X \ln \left(\frac{W_1}{W_2} \right) \quad (1)$$

The parameter X is a combination of the aerodynamic efficiency ($\frac{L}{D}$) and the overall propulsive efficiency $\frac{V}{c}$, where V is the flight speed and c is the thrust specific fuel consumption. In broad sense, this can be thought of as a given technology level, with better aerodynamic efficiency and higher efficiency engines pushing X to higher values. W_1 and W_2 refer to the weight at the beginning and end of cruise respectively. For Green's analysis, a constant value of $X = 30,580$ km is assumed. The simple structural model from Küchemann¹⁵ is used in Green's analysis:

$$W_{TO} = c_1 W_{TO} + c_2 W_P + W_{MF} \quad (2)$$

where W_{TO} is the take-off weight, c_1 is a structural weight constant which represents the structural mass that varies with take-off weight, W_P is the payload weight, c_2 is the weight constant that determines the weight of the airframe that varies with payload weight, and finally W_{MF} is the mission fuel burned. We must also account for the reserve fuel, W_{RF} , and will express the operating empty weight (OEW) as

$$OEW + W_{RF} = W_{TO} - W_{MF} - W_P = c_1 W_{TO} + (c_2 - 1) W_P \quad (3)$$

A 4.5% approximation for the reserve fuel is used as discussed in Creemers.¹⁴

The concept of "lost fuel" refers to the fuel burned to accelerate the aircraft to cruise speed, climb to altitude and descend. A value of 2.2% of take-off weight⁸ is assumed. From the Breguet range equation, the fuel burned during cruise is:

$$W_{CF} = W_1 - W_2 = W_1 \left(1 - e^{-\frac{R}{X}} \right) \quad (4)$$

and thus the mission fuel is

$$W_{MF} = W_{CF} + 0.022 W_{TO} = W_{TO} \left(1 - 0.978 e^{-\frac{R}{X}} \right) \quad (5)$$

A simple iterative scheme is utilized to find a consistent solution for OEW , W_{MF} and W_{TO} based on the following equations:

$$W_{MF} = W_{TO} \left(1 - 0.978 e^{-\frac{R}{X}} \right) \quad (6)$$

$$W_{RF} = 0.045 W_{TO} \quad (7)$$

$$OEW = (c_1 - 0.045) W_{TO} + \frac{(c_2 - 1) W_{TO} \left(0.978 e^{-\frac{R}{X}} - c_1 \right)}{c_2} \quad (8)$$

$$W_{TO} = OEW + W_{MF} + W_{RF} + W_P \quad (9)$$

Using the structural weight constant values of $c_1 = 0.351$ and $c_2 = 2.6$ as suggested by Green,⁸ we obtain the results in Table 1. In contrast to Green, we keep the value of c_2 fixed, as changing its value would erroneously result in a decrease of the structural mass related to the fixed passenger payload of 293 people. We must ensure the fuselage and furnishings mass are identical between both aircraft to ensure the same capacity.

The first observation we can make is that splitting up a 6,400 nm journey into approximately four 1,500 nm legs with the *same aircraft* does not result in a substantial fuel savings. This implies that the fuel savings derived from multi-stage long range travel only occur on much longer routes or through aircraft redesign for the shorter range. The second observation is that for a redesigned LASR aircraft, the OEW has decreased by approximately 26% with a corresponding 22% reduction in fuel burn. Based on this preliminary analysis, it appears that the LASR concept warrants further investigation.

Table 1. Simple LASR aircraft analysis

Description	c_1	c_2	Range (nm)	Payload (tonne)	Fuel (tonne)	Reserve (tonne)	TOW (tonne)	OEW (tonne)	Fuel for 6,400 nm (tonne)	% OEW Change	% Fuel Burn Change
Airbus A330	0.351	2.6	6,400	27.97	78.2	10.5	232.5	115.9	78.16	-	-
Airbus A330	0.351	2.6	1,500	27.97	18.1	7.6	169.6	115.9	77.4	0.00%	-1.01%
LASR	0.351	2.6	1,500	27.97	14.4	6.0	134.1	85.8	61.18	-26.00%	-21.76%

IV. Detailed Analysis

In this section, the details behind the performance analysis of a LASR aircraft in comparison with selected aircraft are provided. The aim is to demonstrate that a large, short-range aircraft can provide significant fuel burn savings per passenger over both an existing aircraft of similar size flying at this shorter range and a current smaller aircraft designed for a range of 3,000 nm.

To investigate the fuel savings of operating a LASR aircraft in lieu of existing aircraft, a conceptual design tool was used. The design tool is based on pyACDT, an object-oriented framework for the design and optimization of aircraft.¹⁶ This framework uses object-oriented concepts to model the aircraft components, engine components, mission dependent characteristics, and disciplinary analyses to achieve the required scalability and extensibility required for multidisciplinary design. All necessary disciplines required at the conceptual design level are considered, with low to medium fidelity models being used to provide rapid execution and robustness.

The design tool was developed in part for use in multidisciplinary optimization, and as such, has the ability to allow the user to rapidly modify the selection of objective functions, design variables and constraints. Table 2 lists the design variables selected for the optimizations performed in this study.

Table 2. Optimization design variables

Sea-level Static Thrust
Cruise Altitude
Wing Reference Area
Horizontal Stabilizer Area
Vertical Stabilizer Area

The objective is to analyze the baseline aircraft and the LASR aircraft as accurately as possible to make comparisons. We wish to optimize the LASR for a specific range and then compare the LASR's performance to the performance of the reference aircraft at this design range. The Airbus A330-200 was selected as the large, long-range reference aircraft, since its two-class seating capacity is 293 seats, which is very close to our target aircraft size of 300 seats. The Airbus A330 Airplane Characteristics for Airport Planning document¹⁷ was used to obtain the reference aircraft weight and performance data listed in Table 3. Additionally, we compare the LASR performance with a smaller aircraft, the A320, which is often used on routes relevant to LASR.

The aircraft conceptual design tool is a set of analyses which allow the modelling of aircraft geometry, structural weight breakdown, aerodynamics, propulsion and performance.¹⁸ The geometry of each aircraft component is derived from a set of primary physical attributes and additional geometric parameters.

The aircraft takeoff weight is calculated iteratively from main component weights that are estimated using statistical methods¹⁹⁻²¹ and from mission fuel requirements. The propulsion system weight includes engine, oil, thrust reverser, starting system and control systems weights, all of which are a function of takeoff thrust. The structural weight group includes wing, empennage, landing gear, fuselage and nacelle weights. Empennage weight is calculated from correlations based on maximum takeoff weight, lifting surface planform geometry and airfoil thicknesses. The nacelle weight is proportional to the engine geometrical size and the maximum takeoff thrust. The fuselage weight is solely based on its overall geometry, and the landing gear

Table 3. Baseline configurations

	A330-200	A320
Design Range (nm)	6,400	3,000
Passengers (2-class)	293	150
MTOW (kg)	233,000	77,000
OEW (kg)	116,740	41,345
Engine	CF6-80E1	CFM56-5B5
Payload Weight (kg)	27,215	14,288

weight is correlated to the aircraft maximum takeoff weight. Finally, the wing and control surface weights are proportional to an ultimate load factor, the wing planform geometry and the takeoff gross weight.²² The furnishings-group weights include elements such as seats, lavatories, windows, emergency systems and galleys. Operational items that are considered in this analysis include attendants and crew weights, unusable fuel weight and other operational items typical in commercial aircraft. The systems group weight is the summation of individual weights for systems such as anti-ice, avionics, air-conditioning, electrical, APU, fuel, hydraulic, flight control and instrumentation. Finally, the payload weight includes passenger and baggage weights, as well as any other cargo carried during flight. Table 4 lists all the major weight groups considered and the factors that influence the weight of each component in that group.

Aircraft lift and drag are calculated based on standard aerodynamic calculations used at the conceptual design stage. Induced, parasite, and wave drag calculations are considered. The induced drag is calculated using a panel method whereas parasite drag is calculated using a detailed component build-up. The propulsion module is a cycle analysis code used to model the engine at its design point and at all off-design conditions, including any combination of Mach number, altitude, and throttle setting. The performance model provides point performance calculations over a specified mission profile. Takeoff and landing distances, rates of climb, and range are calculated based on analytical expressions or numerical simulations.

To estimate the fuel consumed over an entire flight, the fuel burn of multiple segments are modelled using take-off weight (TOW) fuel fractions. This permits rapid estimations of fuel burn on secondary segments while taking into account the benefits of a lower TOW. The fuel usage during climb is estimated as a function of weight as well as final climb altitude. Finally, the reserve fuel is simply a small fraction of the aircraft MTOW.

With the above assumptions on fuel consumption, general aircraft geometry characteristics and engine cycle parameters, the A330-200 aircraft, in a 293 passenger 2-class configuration with two CF6-80E1 engines, was modelled with the design tool.

To make comparisons as accurate as possible, minor adjustments were made to the analysis to match its performance as closely as possible to the data in Table 3. Since detailed aerodynamic, propulsion and weight data is unavailable, it is difficult to predict specific sources of error. However, two modifications were implemented to ensure the model more closely matches published data. The first modification is adding a 5% weight increment to all structural components in the aircraft. The second modification is a 5% decrease in the aircraft thrust specific fuel consumption (SFC). Since all aircraft designed or optimized in this framework share the same engine cycle parameters, the slight tuning of the SFC will affect all in the same fashion. It is also quite difficult to correct this error without detailed information regarding engine component efficiencies and cycle parameters. Having applied these two modifications, the performance and weight data for the A330-200 and A320 are listed in Table 5 and are comparable to published data, thus supporting the accuracy of our model.

Simulations were run to estimate the fuel burn of these aircraft at ranges other than their design range. The initial cruise altitude was selected parametrically by optimizing for minimum mission fuel consumption. The selection was a balance between cruise-efficiency and climb-fuel requirements, while ensuring that the aircraft had an adequate maximum thrust-to-drag ratio at that altitude.

The framework was then used to redesign and optimize aircraft with the same capacity for the shorter ranges. The cruise Mach number was kept constant at 0.78 to ensure that all aircraft under comparison would maintain similar block times. Constraints were also imposed on the optimized aircraft, including

Table 4. Components considered in weights and c.g. module

Weight Group	Component	Dependencies
Structural	Wing	Geometry, Load Factor, MTOW ^a
	Horizontal Tail	Geometry, MTOW
	Vertical Tail	Geometry, MTOW
	Nacelle	Geometry, MTOT ^b
	Fuselage	Geometry
	Landing Gear	MTOW
Propulsion	Engine	MTOT
	Oil	MTOT
	Thrust Reverser	MTOT
	Starting System	EW ^c , nEng ^d
	Control System	MTOT
Systems	Anti-ice	Wing ,Nacelle, Fuselage Geometry
	Avionics	MTOW
	Air-conditioning	Fuselage Volume, nCrew ^e , nAttd ^f , nPax ^g
	APU	Fuselage Geometry, nCrew, nAttd, nPax
	Electrical	Fuselage Geometry, nEng, nCrew, nPax
	Fuel System	nEng, Fuel Volume, nTanks ^h
	Hydraulics	nEng, CSA ⁱ
	Flight Control	CSA
Instruments	nCrew, MTOW, MTOT	
Furnishings	Seats	nCrew, nAttd, nPax
	Lavatories	nPax
	Galleys	nPax
	Emergency Systems	nCrew, nAttd, nPax, MTOW
	Windows	nPax
Operational	Attendants	nAttd
	Crew	nCrew
	Unusable Fuel	Wing Area, MTOT, nTanks, FW ^j
	Cargo	Baggage and Cargo Weight, nCont ^k
Payload	Passengers	nPax
	Baggage, nPax	
Fuel	Fuel Weight	MTOW, Mission

^aMTOW – Maximum Takeoff Weight

^bMTOT – Maximum Takeoff Thrust

^cEW – Engine Weight

^dnEng – Number of Engines

^enCrew – Number of Crew

^fnAttd – Number of Attendants

^gnPax – Number of Passengers

^hnTanks – Number of Fuel Tanks

ⁱCSA – Control Surface Areas

^jFW – Fuel Weight

^knCont – Number of Cargo Containers

Table 5. Accuracy of reference model

Variable Name	Actual Data	A330-200	Actual Data	A320
MTOW (kg)	233,000	232,888	75,499	76,567
OEW (kg)	116,739	115,951	41,243	42,114
FW (kg)	88,166	88,814	19,967	20,135
Payload (kg)	28,123	28,123	14,288	14,288

takeoff field length, second-segment engine-out climb gradient and cruise maximum thrust-to-drag ratio. Table 6 indicates performance, weight, and aerodynamic data for the two reference aircraft, and the optimized aircraft for flights of 1,500 nm, 1,000 nm and 500 nm. Planform views of the A330 and the LASR are shown in Figure 2.

From the table, we find that on a flight of 1,500 nm, the LASR can offer up to 13% reduction in fuel burn per passenger in comparison to the A330-200 and 5% compared to the A320. The savings relative to the A330-200 are even larger at the shorter ranges.



Figure 2. Planform view of LASR (left), A330 (center) and A320 (right)

V. Economic Analysis

Economic justification of a new aircraft such as the LASR is vital to its adoption by the airline industry. The following analysis considers the economic performance of the LASR in comparison with the Airbus A320 and A330-200.

Table 7 provides a per-trip breakdown of total cash operating cost (COC) for a LASR in comparison with two A320's (to provide a 300 seat capacity compared to the 293 seat capacity LASR) and one A330-200 over a range of 1,500 nm. The 'Change Per Seat' column represents the change in cost presented by the LASR on a per seat basis relative to the two A320's and the A330-200, respectively. From this table, we can see that the LASR provides significant cost savings over these aircraft; the most significant savings are from fuel costs: the LASR reduces this expense by more than \$4 US and \$8 US per passenger relative to the two A320's and A330-200, respectively. In the situation where fuel prices increase beyond the assumed \$3 US/gallon, the potential savings presented by the LASR are obvious. The second most significant savings over the two alternatives are those from the Navigation, Landing and Handling fees. These savings come mainly from the MTOW-savings presented by the LASR since both Navigation and Landing fees are assumed to depend on this value. Given that landing fees can also include carbon taxes and the fuel burn savings presented by the LASR, the advantage the LASR has over these aircraft can only increase. Overall, one LASR results in almost 12% per trip savings over two A320's and almost 13% per trip savings over one A330-200. On a COC per seat basis, the LASR presents savings of roughly 9% and 13% relative to the A320 and A330-200, respectively.

Table 6. Performance analysis results

Variable Name		Airbus A320	Airbus A330-200	LASR [†]
Passengers (2-class)		150	293	293
Design Range	(nm)	3,000	6,400	1,500
	(km)	5,556	11,853	2,778
Design Mach		0.76	0.82	0.78
Analysis Mach		0.78	0.78	0.78
Cruise Alt	(ft)	35,000	39,000	37,370
	(m)	10,668	11,887	11,390
Payload (kg)		14,288	28,123	28,123
1,500 nm				
TOW (kg)		68,591	171,212	138,923
Fuel Burn (kg)		8,797	18,749	16,253
Fuel Burn (kg/pkm)*		0.0211	0.0230	0.0200
L/D		16.25	20.39	18.5
% Fuel Burn Change (A330 Reference)		–	–	–13.3%
% Fuel Burn Change (A320 Reference)		–	–	–5.4%
1,000 nm				
TOW (kg)		66,011	166,021	134,264
Fuel Burn (kg)		6,344	13,812	11,823
Fuel Burn (kg/pkm)		0.0228	0.0255	0.0218
L/D		16.0	20.13	18.3
% Fuel Burn Change (A330 Reference)		–	–	–14.4%
% Fuel Burn Change (A320 Reference)		–	–	–4.6%
500 nm				
TOW (kg)		63,448	160,866	129,678
Fuel Burn (kg)		3,906	8,911	7,462
Fuel Burn (kg/pkm)		0.0281	0.0328	0.0275
L/D		15.64	19.84	18.07
% Fuel Burn Change (A330 Reference)		–	–	–16.2%
% Fuel Burn Change (A320 Reference)		–	–	–2.2%

[†] LASR aircraft with 1,500 nm range

* pkm = passenger-km

Table 7. Total per trip Cash Operating Cost (COC) breakdown in USD for range of 1,500nm

	Two A320s	A330-200	LASR		
	Cost	Cost	Cost	Change Per Seat w.r.t.	
				Two A320s	A330
Fuel (\$3 US/gallon)	17,354	18,493	16,031	−\$4.41	−\$8.40
Maintenance	2,275	2,275	1,970	−\$1.02	−\$1.04
Flight Crew	2,800	1,750	1,663	−\$3.79	−\$0.30
Cabin Crew	1,400	1,260	1,260	−\$0.47	\$0.00
Catering, Reservation and Lounge	3,420	3,537	3,537	+\$0.39	\$0.00
Navigation, Landing and Handling	7,791	8,192	6,532	−\$4.20	−\$5.67
Total Cash Operating Costs	35,040	35,506	30,993	−\$13.49	−\$15.40
% Change per seat				−9.43%	−12.7%

VI. Environmental Analysis

In this section, we consider the environmental impact of LASR using the total emissions per passenger on a 1,500 nm flight.

What is the environmental impact of a 300 passenger aircraft during a 1,500 nm flight? This is a difficult question, but, if we want to compare aircraft, an approximate answer is given by the total mass of greenhouse gases (GHG’s) emitted during the flight. Emissions of a particular GHG are estimated using the following equation:

$$E_i = e_i W_{\text{fuel}}, \quad (10)$$

where E_i is the mass of species i emitted, e_i is the emissions index for species i , and W_{fuel} is the mass of fuel burned. The greenhouse gas species considered are carbon dioxide (CO_2), water (H_2O), sulfate, soot, and nitrogen oxide (NO_x). The emissions indices for these species are listed in Table 8. Note, the emission index for nitrogen oxide varies with altitude, Mach number, and fuel-flow rate. We use the DLR fuel-flow-correlation model (see Ref. 23, for example) to estimate the emission index for nitrogen oxide.

Table 8. Emissions indices for various greenhouse gas species

	CO_2	H_2O	sulfate	soot	NO_x
e_i (g/kg)	3,160	1,230	0.2	0.04	0.013 – 0.017

We compare the GHG emissions of an A330-200, an A320, and a LASR over a 1,500 nm flight. The LASR aircraft has been optimized for the chosen range, but all three aircraft use similar technology. For example, we assume the LASR and A330-200 are equipped with two General Electric CF6-80E1A2 engines, while the A320 is equipped with two CFM56-5B5 engines. The necessary engine emission data is obtained from the ICAO databank.²⁴

Table 9 lists the GHG (kg per passenger) for the three aircraft on a 1,500 nm flight. On a per passenger basis, the LASR reduces CO_2 , H_2O , sulfate, and soot emissions by 13.3% relative to the A330-200, and 5.4% relative to the A320. These are significant improvements considering that no new technology is required. In terms of nitrogen oxide emissions, the LASR produces 28% less NO_x than the A330-200, and has similar emissions to the A320.

VII. Conclusions and Recommendations

We have shown that large aircraft designed for short ranges can reduce the environmental impact of aviation while offering economic advantages. On a 1,500 nm flight, a LASR aircraft designed for 1,500 nm

Table 9. Comparison of emissions per passenger for the A320, A330-200, and LASR over a 1,500 nm flight

	A320	A330-200	LASR
passengers	150	293	293
fuel burned (kg)	8,797	18,749	16,253
emissions (kg/pass.)			
CO ₂	185	202	175
H ₂ O	72.1	78.7	68.2
sulfate	0.0117	0.0128	0.0111
soot	0.00235	0.00256	0.00222
NO _x	0.785	1.08	0.776

reduces CO₂ emissions per passenger by 5.4% and 13% relative to an A320 and an A330-200, respectively. The LASR concept improves aircraft efficiency using existing technologies, so it can be implemented quickly to help mitigate aviation’s climate impact. Moreover, the concept is not tied to a specific technology, so its advantages will extend to future technologies and operations, including blended-wing bodies, active flow control, all-composite structures, continuous-descent landing, and multi-stage long-range flights.

In order to achieve these benefits, the following disadvantages must be accepted. The first is the reduction in flight frequency on busy routes, which restricts an airline’s ability to compete with more frequent flights on other airlines. The second is the burden placed on airlines to manage a less flexible fleet of aircraft. A short continental flight followed by a long-haul inter-continental flight is no longer possible with the same aircraft. Overall, however, we believe the benefits of reduced cost and emissions are sufficient to outweigh these disadvantages.

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