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A Methodology for Integrated Conceptual Design of Aircraft Configuration and Operation to Reduce Environmental Impact

Andrew March[*], Ian Waitz[†], Karen Willcox[‡]
Massachusetts Institute of Technology, Cambridge, Massachusetts, 02139.

Significant reductions in environmental impact and operating costs are achievable when both aircraft configuration and operation are considered simultaneously at the early stages of aircraft design. The challenges with combining these disciplines are that the design space becomes larger, and each design evaluation requires coupled analyses. This paper presents a methodology in which a low-speed aerodynamic model and a trajectory simulation are integrated to study trades between aircraft performance, environmental impact, and cost. Four studies are conducted using this method to illustrate ways to reduce the environmental impacts of future airplanes in a future air-traffic system. First, a study of the departure procedure for the Boeing 747-200 shows that significant benefits are possible by modifying the current procedures without changing the aircraft. For instance, from the start of takeoff roll to 10,000 feet the following are mutually achievable: a 37% reduction in climb time, a 26% reduction in fuel consumption, a 26% reduction in 55 EPNdB noise exposure area, and a 2.6% reduction in operating costs. A second example analyzes trades between noise and operating cost and considers current noise taxation schemes. Then, the sensitivity of the takeoff and approach noise certification procedures are presented to show it is possible to simultaneously evaluate both configuration and operational changes. The results of these studies are that takeoff noise is insensitive to small configuration changes, but procedural modifications can have a significant impact. For approach, the noise can be significantly reduced through either configuration or procedural changes.

I. Introduction

Environmental impact is becoming an increasingly important aspect of aviation. Recently, 92% of the busiest commercial airports in the United States reported they are having more difficulty balancing environmental concerns with airport operations as compared with twenty years ago. They consider aviation noise the most serious environmental problem today, but anticipate that air quality will be a more significant concern in the future.[1]

For an aircraft departure there are tradeoffs between air pollution and noise. For a given airplane, a noise reduction may require an increase in the amount of fuel consumed and consequently additional air pollution will enter the atmosphere. Both air pollution and noise have been connected to increased risk of human health problems. Air pollution has been correlated with premature death due to a short-term exposure, decreased life expectancy due to chronic exposure, aggravation of respiratory and cardiovascular disorders, affected lung function after a short-term exposure, reduced lung function due to chronic exposure, and an increased rate of chronic respiratory conditions.[2] Studies have reported that aviation noise may cause hypertension, ischaemic heart disease, sleep disturbance, and poor school performance.[2] Perhaps the most pervasive impact of aviation noise however, is the annoyance it causes people, and studies have shown that aviation noise is more annoying to communities than other transportation noise sources even when they are at the same level.[2]

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[*] Graduate Student, Department of Aeronautics and Astronautics, MIT
[†] Professor and Department Head, Department of Aeronautics and Astronautics, MIT
[‡] Associate Professor, Department of Aeronautics and Astronautics, MIT

On a positive note, even with the significant growth in aviation over the last thirty-five years aircraft fuel efficiency has improved 60% and the number of people exposed to high levels of aircraft noise is estimated to have decreased.[3] The reduction in noise and fuel consumption are due to improved aircraft technologies; however, most of the older aircraft have been retired and the pace of technological improvements may have slowed. Additional measures to reduce noise, emissions, and fuel consumption are likely to result in design compromises, measures to reduce fuel consumption may require increased noise and nitrogen oxide emissions, and vice versa.[4]

Much research in reducing aircraft environmental impact has been focused on improving engine specific fuel consumption and aerodynamics. For instance, Antoine et al. perform a multidisciplinary optimization to create a preliminary design for a tube-and-wing aircraft with minimum operating cost, fuel burn, nitrogen oxide emissions, and noise. However, the optimization did not include many parameters for the aircraft operation, the only parameters were initial and final cruising altitude and cruise speed.[5] These three parameters are a very small subset of the operational design space which includes many more parameters that describe takeoff, climbing, cruise, descent and approach.

Another method to reduce environmental impact is to improve operational procedures. However, this is often treated in isolation from aircraft design, for instance, using changes to the standard departure procedure Clarke showed it is possible to reduce the 737-200 baseline departure noise.[6] The flight path simulator used in the work is a complete emulation of a 737-200 cockpit. However, the simulation entails high computational complexity, and attempting to use formal methods to optimize procedures for environmental impact would be challenging. In lieu of the full cockpit emulation Visser and Wijnen compute trajectories treating the airplane as a point mass moving along linear segments. For the same 737-200 they optimized arrival and departure trajectories for minimum population exposed to noise and aircraft fuel burn.[7–9] The primary results were that the airplane should fly around population centers; however, they did show that the population exposed to noise could be reduced by reducing the engine power when flying over the densely populated areas to compromise between fuel burn and noise exposure.

The Silent Aircraft Initiative (SAI) conducted a more integrated study of environmental impact in terms of both configuration and procedure. The SAI developed methods to analyze the aerodynamic performance of a blended-wing-body aircraft,[10] and study both the arrival[11] and the departure[12] procedures for that aircraft. For the arrival analysis, an airframe design code was combined with a landing simulation method in order estimate a Pareto front of fuel burn and approach noise. For the takeoff optimization the thrust during the takeoff roll and the angle during the initial climb phase were iterated until all takeoff requirements were met with an imposed maximum allowable noise level. The result of the work by the SAI is a conceptual design for a commercial aircraft that is economically feasible and that produces no perceptible noise outside of an airport boundary.

An important challenge to reducing the environmental impact of aircraft is that both operation and configuration need to be analyzed and designed simultaneously. This results in a large design space; to evaluate candidate designs requires determining the aerodynamic performance of the aircraft and simulating those capabilities on a candidate mission. Accordingly a parametrization is needed that can characterize configuration and procedure in as few variables as possible and a method is required which can balance model fidelity to both achieve a short solution time and provide accurate results. The work presented in this paper is the integration of a low-speed aerodynamic model and a trajectory simulation, which results in a method capable of computing the trajectory, time to climb, fuel burn, noise exposure, and estimated operational cost for a given configuration and set of operational procedures. The method has an accuracy similar to aircraft manufacturer conceptual design tools (cruise drag error about 1%), but the computational time is such that optimization is tractable.[13]

This paper describes a method to design for reduced aircraft environmental impact that considers both configuration and operation. Section II presents an overview of the method, which is separated into three parts: a high-level summary of the low-speed aerodynamic model in Section II.A; the components of the trajectory simulation in Section II.B; and the operational cost estimation model in Section II.C. The method will be demonstrated by optimizing the departure procedure for the Boeing 747-200 in Section III. The optimization will be formally posed in Section III.A, and the trajectory parametrization used is presented in Section III.B. A brief discussion of the selection of an optimization algorithm is given in Section III.C, followed by the optimization results in Section III.D. Section IV will present the sensitivity of the certification noise to both configuration and operational parameters, the takeoff sensitivity is in Section IV.A, and the approach sensitivity is in Section IV.B. The paper will conclude with a discussion of the importance of combining operation into aircraft design in a multidisciplinary design optimization framework.

II. Methodology

The method used to analyze aircraft configuration and operation is shown in Figure 1. The model is separated into two main subcomponents the low-speed aerodynamics model and the trajectory simulation. Both of these methods are briefly discussed in the following sections; more detail can be found in Ref. 13. This section concludes with an overview of the operational cost model.

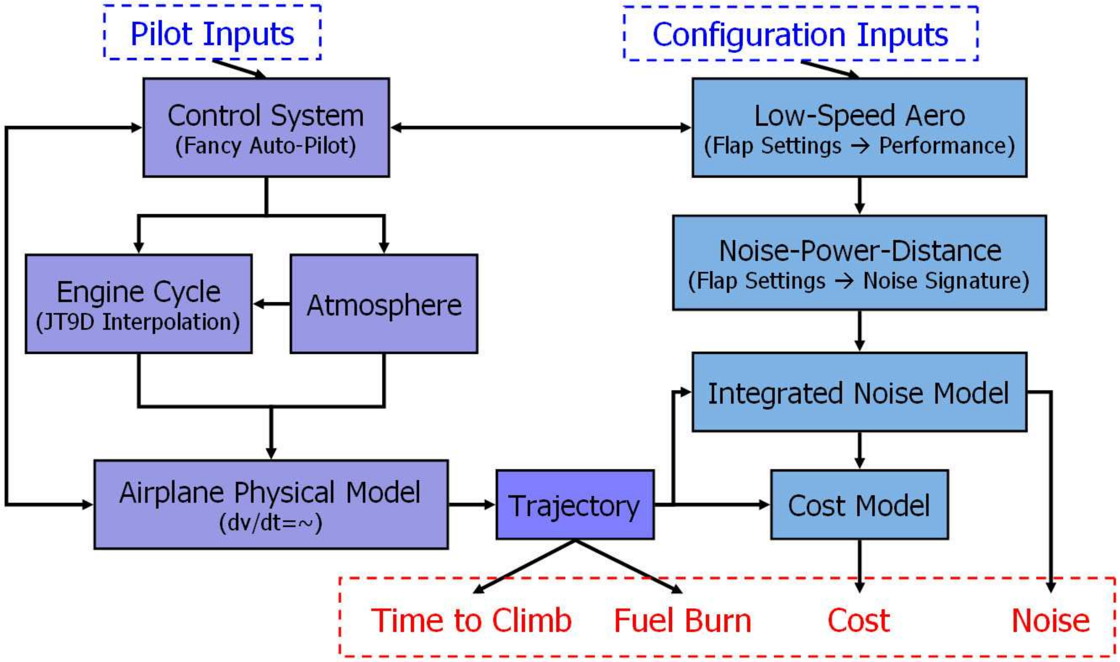


Figure 1. Flow chart outlining how configuration and procedure can be analyzed to estimate aircraft performance, operating costs, and environmental impacts.

II.A. Low-Speed Aerodynamics

The intent of the low-speed aerodynamics model is to estimate all important performance aspects of a typical current commercial aircraft with accuracy sufficient for conceptual design trade studies. The tool is capable of predicting the drag polars, lift-curve, and maximum lift coefficient for aircraft in both the cruise and high-lift configuration. A flow chart for the low-speed aerodynamic model is shown in Figure 2. The model uses a total of 60 parameters, and from that constructs a simple three-dimensional CAD model. Figure 3 shows the approximate level of detail used in the model. The CAD model is used to compute wetted areas and average thickness of each component. This information is then used to compute the profile drag of the airplane. The aircraft geometry information is also employed to construct a vortex lattice model which is used to compute the induced drag and lift curve slope for small angles of attack. The profile drag and induced drag are then summed to form the baseline aircraft drag polar.

If the aircraft does not have any flaps deployed, an adjustment is made to the drag polar shape to account for pressure drag and separation. In addition, an estimate of the maximum lift coefficient is made and the shape of the lift-curve is also modified to account for separation effects. If the flaps and/or slats are deployed, a set of largely empirical corrections is made to the baseline drag polar to compute the drag polars, maximum lift coefficient, and lift-curve. A comparison of drag polar estimates and flight test results for the Boeing 727-100 are presented in Figure 3(a) and a comparison of the estimates for the lift-curve and flight test results are presented for the Boeing 737-700 in Figure 3(b).

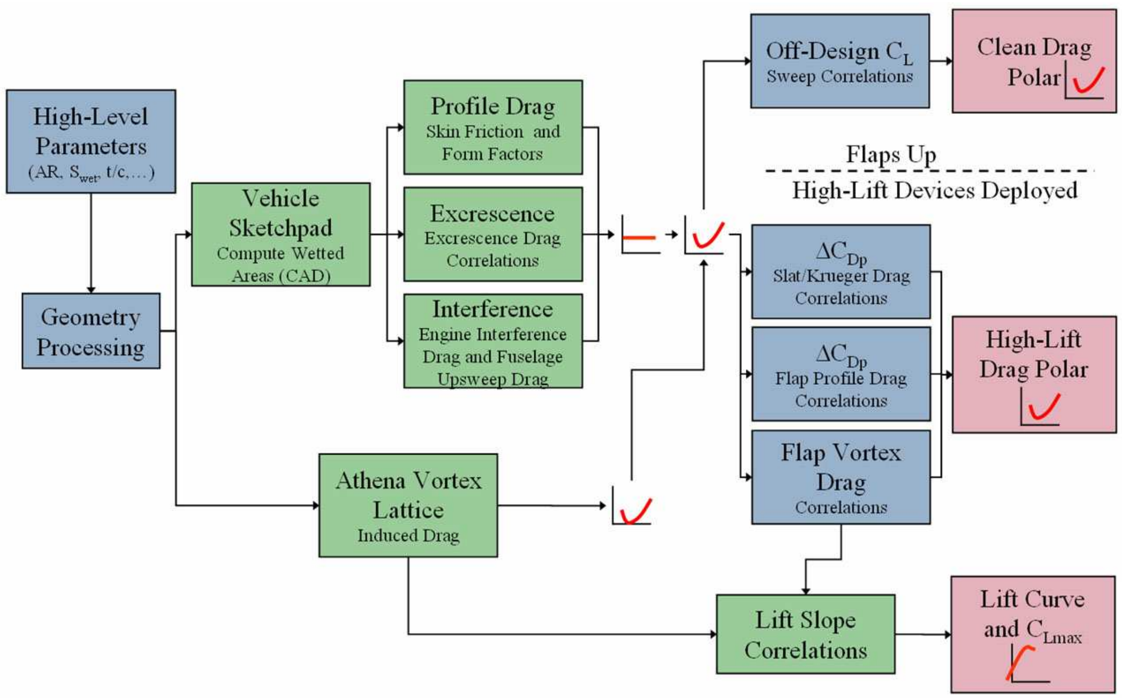
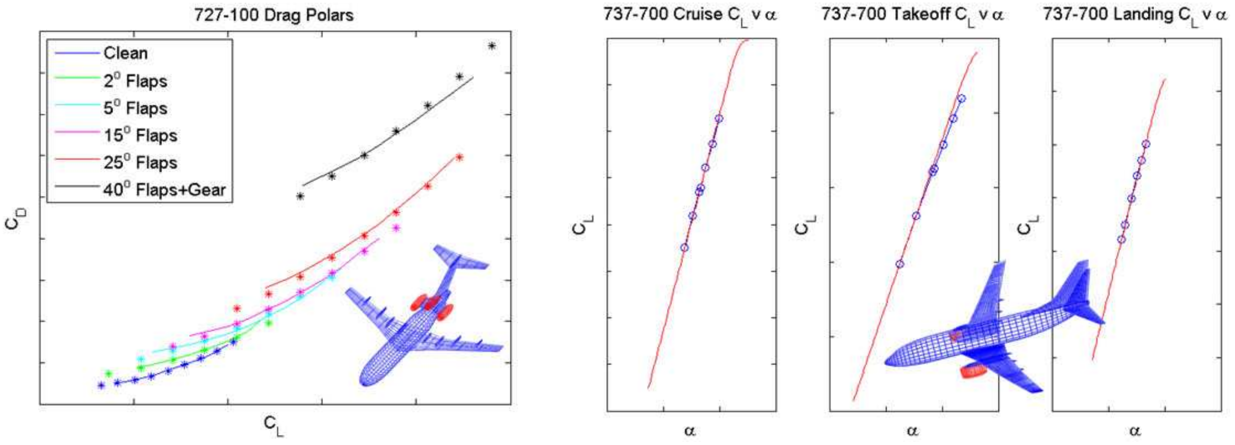


Figure 2. Low-speed aerodynamic model flow chart.



(a) 727-100 Drag polar estimates (asterisks) and flight test results (solid lines).

(b) 737-700 Lift-curve estimates (red) and flight test results (blue).

Figure 3. Low-speed aerodynamic method sample results and wireframe sketches of geometric detail.

II.B. Trajectory Simulation

As shown in Figure 1, the trajectory simulation integrates a variety of models in order to compute the time to climb, fuel burn, cost, and noise exposure for a given aircraft procedure. The aerodynamic performance of the airplane is supplied by the low-speed aerodynamic model and is supplemented with an aircraft procedure parameterized by pilot inputs. The control system uses the estimated performance and pilot commands to fly the airplane. The control system includes a complete engine cycle for the JT9D-7A engine[14] so it properly models thrust lapse and throttle settings in addition to being able compute the required fuel flow into the engine. In lieu of a complete engine cycle, regression data for thrust lapse coefficients such as those from the Integrated Noise Model[15] (INM) can be used. The control system then determines if the airplane is capable of flying the supplied pilot inputs; if the inputs are safe, the control system will simulate the airplane as a point mass moving through space. The trajectory is divided into discrete segments that cannot exceed ten seconds, and along each segment the acceleration of the airplane is constant. All of the changes of the flap settings and throttle settings are assumed to change instantly between the flight segments. A higher fidelity model was used which included the pitch angle and maximum pitching rates and did not require constant acceleration segments. The results of the two trajectory models were quite similar, within 5% for both distance and time as a function of altitude. However, the higher-fidelity model takes over five minutes to run; whereas, the linear model takes less than twenty seconds, a 93% reduction in execution time.

The trajectory simulation includes a capability to estimate noise. The INM contains a database of Noise-Power-Distance (NPD) curves which contain the entire noise signature for an airplane with a constant configuration, for instance, all of the information needed to compute the noise from the airplane provided the flap, slat, and landing gear settings do not change. However, to thoroughly study the trajectory, the ability to change the flap and slat settings is mandatory, so a modified version of the Aircraft Noise Prediction Program[16] (ANOPP) is used to compute the change in the noise signature of the airplane. To save execution time, the noise signature of the airplane is assumed to be constant based on the initial flap and slat setting at takeoff, even if the flaps or slats change. This assumption causes an insignificant change in the estimated noise from the airplane as the engine noise for any current fleet airplane strongly dominates the airframe noise signature. For landing it is necessary to change the aircraft noise signature as the flap settings change because the thrust noise is of similar magnitude to the airframe noise. The exception to this is the noise certification procedure where the flap setting is kept constant so only one set of NPD curves needs to be used. The INM uses the computed NPDs and computed trajectory to estimate the noise emissions from the aircraft for the simulated flight procedure.

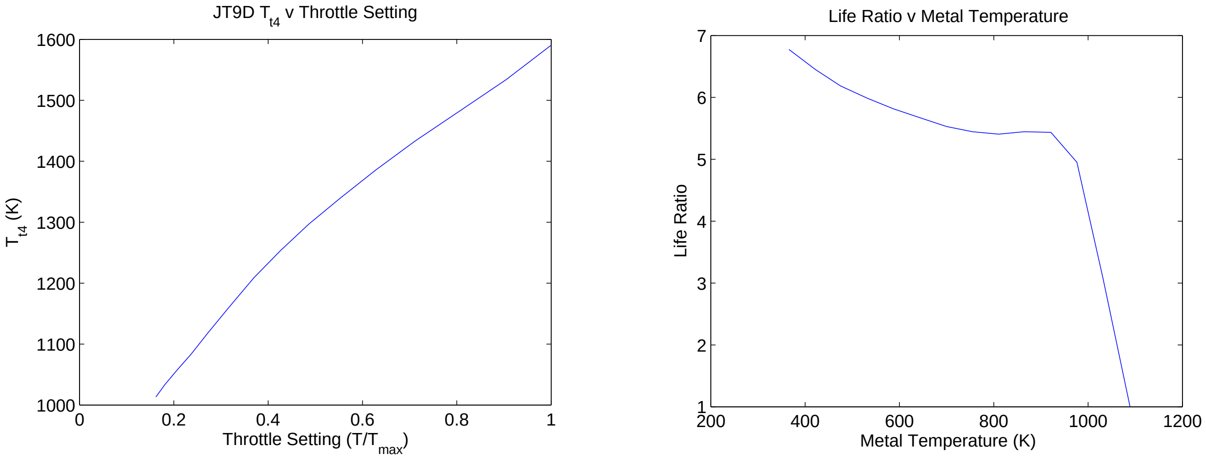
II.C. Cost Model

The cost model is based on the United States Department of Transportation Form 41 data for the year 2007. Form 41, Schedule P-52, Aircraft Operating Expenses,[17] contains all of the cost data for every major airline operating in the United States separated by aircraft type. Form 41, Schedule T-100, U.S. Air Carrier Traffic and Capacity Data (both international and domestic segments),[18] contains the aircraft usage statistics, such as block hours and flight segment lengths, for all major U.S. airlines by aircraft type. All of the operating costs are separated into three categories based on how the cost is accumulated, per flight, per block hour, and per year. For instance, fuel and crew costs are assumed to be accumulated at a fixed rate per block hour, taxes are assumed to be per flight, and depreciation is assumed to be per year. The block hour operational costs for the two airlines operating the 747-200 are quite similar, $15,800 for UPS and $14,200 for NWA. However, the per flight costs ($1,000 UPS and $1,700 NWA) and the annual costs ($18.4M UPS and $8.44M NWA) are significantly different, which is believed to be caused by the fact that UPS had a larger fleet and that NWA stopped operating the 747-200 for scheduled service midway through the year.

For the cost optimization it is assumed that changes in the departure time reduce the total number of block hours flown but are insufficient for the carrier to increase the number of flights. Accordingly, the airlines schedule is assumed constant for the year. Another assumption is that any changes to the operational procedure are possible at all airports and during all seasons. This enables the per block hour costs and per flight costs to be aggregated to a per year basis to match the units of depreciation. In addition, all cost changes are assumed to be linear, so if a departure saves two minutes, the airline saves two minutes of its block hour rate for each flight of the year. A yearly-averaged fuel price of $2.57 per gallon was used for all analyses.

The final significant cost that can change by altering the departure procedures is the maintenance cost.

Engine maintenance is critically dependent on the temperatures in the hot section, for instance the turbine inlet temperature T_{t4}. Accordingly, an engine cycle model was built to match the engine performance tables being used.[14] The results of this model for turbine inlet temperature as a function of throttle setting (or equivalently, engine derate) are shown in Figure 4(a). Engine maintenance cost information is especially hard to obtain, and crude estimates are made based on a Boeing study of water injection into a 1980's 747-400 engine–similar to the engine on the 747-200. A 67 K reduction in T_{t4} increases engine life 29% and that translates into a maintenance cost reduction of $22 per block hour per engine.[19] It is estimated for the JT9D-7A that the turbine metal temperature is 63% of the gas temperature. This estimate is used in conjunction with metal life estimates for standard turbine materials from Ref. 19 to match the 29% expected engine life improvement. The modified engine life expectations are shown in Figure 4(b). Accordingly, to estimate the cost benefit of derating an engine, the reduced turbine inlet temperature is computed and the expected life improvement is computed using Figure 4(b). The cost savings is then scaled linearly with the life improvement assuming a 29% life improvement yields a $22 per hour per engine maintenance cost savings.



(a) JT9D-7A engine T_{t4} as a function of the throttle setting generated from the cycle model.

(b) Estimated JT9D turbine life increase due to reduced turbine inlet temperature modified from Ref. 19.

Figure 4. Functional relationships used to estimate the cost benefit of a derated takeoff.

III. Trajectory Design Space Exploration

This section demonstrates the trajectory simulation capabilities by exploring the trajectory design space with various optimization techniques. The problem formulation is given, followed by the parametrization used. The optimization techniques attempted and reasons for selecting a genetic algorithm are then given. Finally, the results of two optimization studies are presented, first a multi-objective optimization to find the best trajectories for minimum time to climb, fuel burn, noise exposure, and cost, second, an optimization to find the minimum cost departure for trajectories subjected to different noise taxation schemes.

III.A. Optimization Formulation

The purpose of this optimization is to find the Boeing 747-200 departure trajectory that minimizes four objectives: time to climb, fuel burn, noise exposure area, and operating costs, as shown in equation (1). There are numerous constraints that must be enforced to ensure this trajectory is safe, feasible, and in compliance with federal regulations. For instance, the airplane's velocity must be higher than the stall speed for the aircraft. Accordingly, the airspeed, V, must be greater than or equal to the square root of twice the aircraft weight, W, divided by the air density, ρ, multiplied by the maximum lift coefficient, C_{Lmax}, aircraft planform area, S, and the cosine of the flight path angle, γ, as shown in equation (2). The airspeed must also be less than the smooth air penetration speed, a velocity set by a maximum dynamic pressure, equation (3). The throttle setting, $\%F$ also has bounds which are 7% (engine idle) and 100% (full power), equation (4), the initial throttle setting needs to be greater than 75%, equation (6), but in addition to those bounds a throttle setting that ensures a positive rate of climb is required, equation (5). Some constraints on the operational procedure are that the aircraft flap setting must always be decreasing, equation (7), the final flap setting must be flaps up, equation (8), and the flap setting selected must be available on that airplane, equation (9). The Federal Aviation Regulations require that the pilots not make any control inputs below an altitude of 684 ft for a four-engine aircraft, equation (10), and require the initial climb to be at a speed between $V_2 + 10kts$ and $V_2 + 20kts$ (a speed based on the aircraft stall speed).[20] In addition, because airline transport pilots are only required to maintain airspeed to within $\pm 5kts$ the initial climb speed is set to $V_2 + 15kts$, equation (11). As discussed in the parametrization section many of the constraints are handled explicitly through the parameter definitions used.

$$\min_x J(x) = \begin{bmatrix} \text{time to climb (s)} \\ \text{fuel burn (lbm)} \\ \text{55 EPNdB noise exposure area (mi}^2\text{)} \\ \text{operating cost (\$)} \end{bmatrix} \tag{1}$$

$$\text{s.t.} \quad V \geq \sqrt{\frac{2W}{\rho C_{Lmax} S \cos\gamma}} \tag{2}$$

$$\frac{1}{2}\rho V^2 \leq 270psf \tag{3}$$

$$0.07 \leq \%F \leq 1 \tag{4}$$

$$\gamma \geq 0 \tag{5}$$

$$\%F_{\text{initial climb}} \geq 0.75 \tag{6}$$

$$\text{Flap}_i \geq \text{Flap}_{i+1} \tag{7}$$

$$\text{Flap}_5 = 0^\circ \tag{8}$$

$$\text{Flap}_i \in \{0^\circ, 5^\circ, 10^\circ, 20^\circ\} \tag{9}$$

$$A_{\text{initial climb}} \geq 684ft \tag{10}$$

$$V_{\text{initial climb}} = V_2 + 15kts \tag{11}$$

III.B. Parametrization

The design space needs to include all feasible departure trajectories for the Boeing 747-200. The departure procedure is considered to be from the start of the takeoff roll until the airplane passes through an altitude of 10,000 ft above field elevation. For a two-dimensional climb (horizontal and vertical position only) the pilot can only change the pitch angle, throttle setting, and flap setting. To do so, he or she only has instruments that measure the altitude, airspeed, and rate of climb. In addition, as is fairly standard with flight under instrument flight rules, it is assumed the pilot can only perform either a constant velocity climb or an acceleration at a constant rate of climb. Accordingly, the departure procedure is separated into five sub-procedures, each of which includes a constant rate of climb acceleration and a constant velocity climb segment. Each sub-procedure has four design variables, the flap setting, throttle setting, airspeed, and end altitude. The breakdown of the trajectory is shown graphically in Figure 5. In addition, there is one additional design variable that applies to all five segments, which is the fraction of maximum climb rate the airplane should use during is constant rate of climb acceleration steps. To reduce the number of parameters it is assumed the airplane will always use a fixed fraction of the maximum possible rate of climb it could have at a given altitude to accelerate. For example, with a power fraction of 0.5 then at an altitude of 1,000 ft the airplane has a maximum rate of climb of 3,500 feet per minute (fpm) so it will climb at 1,750 fpm; however, at 10,000 ft the maximum rate of climb will have decreased to 2,200 fpm, so the airplane will only climb at 1,100 fpm. Some of the constraints have been included directly into the parametrization, for instance the initial climb speed and final flap settings are fixed. Therefore there is a total of 18 design variables used to describe the departure trajectory.

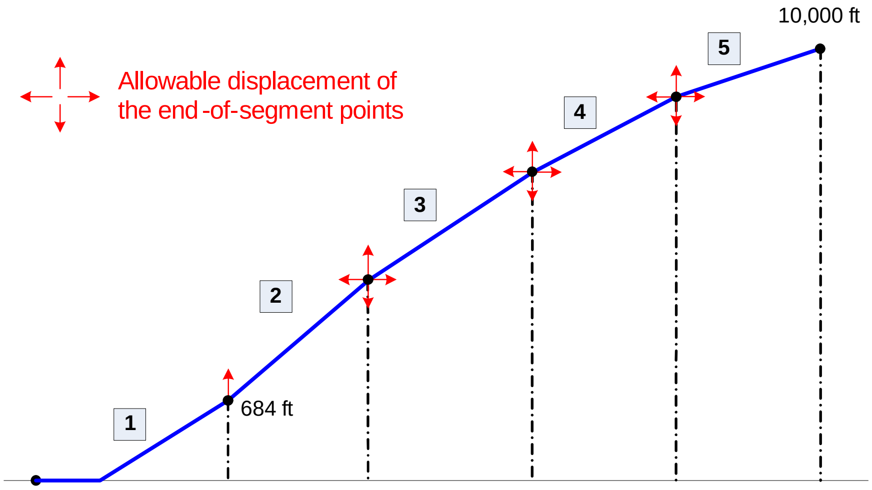


Figure 5. Schematic showing divisions of the departure trajectory into five non-overlapping procedures.

III.C. Design Space Exploration Methods

The trajectory design space has five aspects that make optimization difficult. First, the problem has only islands of feasibility; most design vectors will lead to a trajectory that the airplane cannot fly. Second, this problem has many local minima. Considering only fuel burn, a local minimum exists when flying at full power and minimizing time to climb, and another local minimum exists for a lower power setting where the aircraft takes longer to climb but the rate of fuel burn is considerably lower. This can be shown by that fact that there are certain speed and altitude combinations where the specific fuel consumption increases with throttle setting and others where it decreases with throttle setting.[14] Third, this is a mixed discrete continuous optimization problem. The flap settings are discrete, but the altitudes and velocities are continuous. Fourth, the design variables have scales that vary over a wide range; this is probably the easiest problem to resolve as the parameters can be scaled. Finally, the function evaluation time is over two minutes (Pentium 4 processor) and most optimization methods will require hundreds or thousands of function evaluations.

Four optimization methods were used on this problem: sequential quadratic programming (SQP), Nelder-Mead direct search, particle swarm optimization, and a genetic algorithm. Both SQP and direct search are susceptible to getting stuck at local minima and not finding the global optima. The two heuristic methods, particle swarm optimization and the genetic algorithm do not have any convergence guarantees, but tend to be less susceptible to getting trapped in local minima. The genetic algorithm is especially good at handling mixed discrete-continuous problems, however, there is no bound for how long the genetic algorithm will take to converge. Results for a sample trajectory optimization for time to climb are presented for all four algorithms in Table 1. The genetic algorithm was selected for design space exploration largely because it can handle the mixed discrete-continuous problem and because it found the best point out of all of the methods. Accordingly, computation time was sacrificed with the intent of improving result quality.

	Sequential Quadratic Programming	Direct Search	Particle Swarm	Genetic Algorithm
Time to Climb	312 s	319 s	319 s	308 s
Run Time	4-6 hrs	4-6 hrs	8-12 hrs	12-20 hrs

Table 1. Design space exploration method results and run times for a dual-core 32-bit personal computer with a 3.2 GHz processor.

III.D. Results

The results of the 747-200 departure optimization are presented for both a 725,000 and 565,000 lbm takeoff weight in Table 2 and Figure 8. The 725,000 lbm results show that the genetic algorithm has not converged and that the minimum time to climb trajectory outperforms the minimum fuel burn and minimum noise trajectories. Perhaps the most important result, however, is that there is one trajectory that is uniformly better than the current standard ICAO B baseline trajectory. The minimum time to climb trajectory saves 178 seconds in climb time (37%), 1,700 lbm of fuel (26%), 123 mi^2 of 55 EPNdB noise exposure (26%) and $1,800 in operating costs (2.6%). Similarly for the 565,000 lbm takeoff weight the savings are 95 seconds (30%), 731 lbm (17%), 49 mi^2 (16%), and $1,000 (1.4%).

725,000 lbm TOW	Climb Time	Fuel Burn	Noise Exposure	Cost
Baseline	486 s	6,820 lbm	478 mi^2	$70,000
Minimum Time to Climb	308 s	5,080 lbm	354 mi^2	$68,200
Minimum Fuel Burn	316 s	5,130 lbm	358 mi^2	$68,200
Minimum Noise	319 s	5,140 lbm	357 mi^2	$68,200

565,000 lbm TOW	Climb Time	Fuel Burn	Noise Exposure	Cost
Baseline	319 s	4,340 lbm	313 mi^2	$69,800
Minimum Time to Climb	223 s	3,610 lbm	264 mi^2	$69,000
Minimum Fuel Burn	237 s	3,600 lbm	265 mi^2	$68,700
Minimum Noise	267 s	3,610 lbm	265 mi^2	$68,800

Table 2. Anchor points for the pareto front of climb time, fuel burn, and 55 EPNdB noise exposure area for the 747-200 with 725,000 and 565,000 lbm takeoff weights.

An important note must be made about the noise results and the 55 EPNdB noise contour. The trajectory analyzed is from start of takeoff roll to 10,000 ft above field elevation and many airplanes, the 747-200 included, can generate more than 55 EPNdB on the ground at this altitude. Accordingly, if this trajectory were continued to a higher altitude the noise contour would be larger. However, the optimization results for this operational procedure show that the 747-200 ground track has reduced nearly 19 miles and that there is a significant reduction in the 55 EPNdB contour. Although the contour area has been reduced, a higher thrust setting is used and the actual flight path flown is initially closer to the ground than the baseline ICAO B departure. This means the noise near the airport and at the certification point, a point overflown by the airplane that is about 21,000 ft from the start of the takeoff roll, will increase. This causes an issue as most noise penalization schemes tax airlines for exceeding noise requirements at this point. For instance, at Heathrow if an airplane exceeds 97 EPNdB at this point the airline is charged £500 ($1,000), and if the exceedence is 3 or more EPNdB the airline is charged £1,000 ($2,000). Another penalization method that could easily be examined is violation of the stage III noise certification values, which are a function of the aircraft gross weight.

Table 3 presents the results of optimizing departure trajectories for cost given the two taxation schemes considered. The objective is to minimize the sum of the total departure cost and the noise tax applied for the different taxation strategies. The optimal trajectories are also shown graphically in Figure 9. For the 725,000 lbm takeoff weight the baseline does not violate the stage III noise certification, but the cost optimum trajectory without tax does. With the penalty applied the airplane will fly a different trajectory so it avoids paying the $1,000 fine, but the cost of the trajectory will still be $500 higher than the tax-free minimum cost trajectory. The 747-200 is either incapable of meeting the 97 EPNdB requirement at Heathrow or it is too costly, so in this case the optimum departure is to pay the $2,000 fine and fly the tax-free minimum cost trajectory. At the lower takeoff weight of 565,000 lbm, the tax-free minimum cost trajectory does not violate the stage III certification noise; however, it does violate the Heathrow noise requirement. In this case the cost optimum departure is 99.7 EPNdB, which still violates the 97 EPNdB level, but does not exceed 100 EPNdB where the fine doubles. The interesting finding from these studies is that the noise at one location has dropped, but the total noise exposure area increases. Therefore, this regulation strategy will be effective in areas where the population is in clusters around an airport with large areas of unpopulated spaces; however, if the airport is in a city center with a uniformly distributed population the number of people affected by peak noise may or may not decrease but the overall number of people exposed to moderate aircraft noise will increase.

725,000 lbm TOW	Climb Time	Fuel Burn	Noise Exposure	Cost per Flight	Flyover Noise
Baseline (No Tax)	486 s	6,820 lbm	478 mi^2	$70,000	104.8 EPNdB
Minimum Cost (No Tax)	326 s	5,180 lbm	361 mi^2	$68,200	106.9 EPNdB
Certification Tax (105.1)	335 s	5,500 lbm	372 mi^2	$68,700	104.7 EPNdB
Heathrow Tax (97.0)	326 s	5,180 lbm	361 mi^2	$70,200	106.9 EPNdB

565,000 lbm TOW	Climb Time	Fuel Burn	Noise Exposure	Cost per Flight	Flyover Noise
Baseline (No Tax)	319 s	4,340 lbm	313 mi^2	$69,800	97.4 EPNdB
Minimum Cost (No Tax)	223 s	3,600 lbm	265 mi^2	$68,600	103.3 EPNdB
Certification Tax (103.6)	223 s	3,600 lbm	265 mi^2	$68,600	103.3 EPNdB
Heathrow Tax (97.0)	235 s	3,720 lbm	271 mi^2	$69,700	99.7 EPNdB

Table 3. Results of trajectory cost optimization for the 747-200 with a 725,000 lbm and a 565,000 lbm takeoff weight with different noise penalization methods. Numbers in parenthesis indicate the threshold flyover noise when the £500 tax is added, £1,000 will be added at that number plus 3 EPNdB.

IV. Aircraft Configuration Sensitivity Studies

Two sensitivity studies were conducted to show that it is possible to analyze both configuration and operation using this methodology. The noise certification procedures for takeoff and approach are selected because the aircraft configuration is constant for the entire procedure, so the aerodynamic performance and noise signature only needs to be computed for one flap and slat setting to analyze a flight operation.

IV.A. Takeoff

A model of the Boeing 777-200ER was used to conduct a sensitivity study of takeoff noise to aircraft configuration. The takeoff certification procedure requires the airplane to takeoff with full power and upon reaching a minimum altitude, 984 ft for the 777, the airplane is allowed to reduce power. However, throughout the entire procedure a constant configuration must be maintained, so the flap and slat setting cannot be altered during the procedure. The certification noise is recorded at two points, at the flyover point 21,325 ft from the start of the takeoff roll and the maximum noise recorded on a line parallel to the flight path but displaced 1,476 ft. The certification values published are for the procedure that produces the minimum sum of these two measurements.[21] Figure 6 shows the noise estimated at the flyover and sideline locations as a function of cutback altitude for the baseline 777-200ER. Figure 6 demonstrates there is a cutback altitude at which the sum of the flyover and sideline noise is a minimum; accordingly, for each configuration studied the cutback altitude will have to be optimized. This sensitivity study shows that there is a coupling between the operational procedure and the configuration.

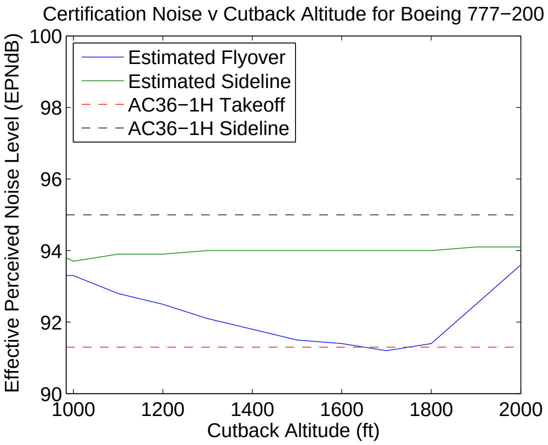


Figure 6. Estimated change in the flyover and sideline noise as a function of the cutback altitude for the Boeing 777-200ER noise certification procedure, and the published value.[22]

An initial screening test was performed to select the low-speed aerodynamic model parameters that have a significant impact on the drag polar or the lift curve. These parameters were then tested at the ±10% levels to determine the sensitivity of noise to configuration. An important note is that the changes to the configuration are assumed small enough that the airframe weight will not change significantly, the validity of this assumption depends substantially upon the design objective for the airplane studied. The computed sensitivity of takeoff noise to airframe configuration is quite small. The maximum percent change in the sum of the flyover and sideline noise is presented for the three most sensitive parameters in Table 4. The reason the highest sensitivity of takeoff noise is so small, 0.19% for a 10% change, is that takeoff noise is thrust dominated for the 777-200ER, and most other tube and wing configurations. When the airframe noise is estimated using ANOPP, the combination of engine and airframe noise is 22 EPNdB higher than the airframe noise alone. This means the airframe noise is insignificant compared to the engine noise. The airframe changes are able to alter the noise through changes in the airplane's climb performance. For the three significant parameters, the aspect ratio changes the induced drag, the planform area changes the lift coefficient, and the wing tip thickness to chord ratio changes the maximum lift coefficient which changes the airspeed at which the airplane is required to climb.

Parameter	Parameter Change	Noise Sensitivity
Aspect Ratio	-10%/+10%	-0.14%/+0.19%
Planform Area	-10%/+10%	-0.11%/+0.18%
Wing tip t/c	-10%/+10%	-0.01%/+0.15%

Table 4. Parameters with the highest takeoff noise sensitivity.

IV.B. Approach

The approach noise certification procedure does not have the same freedom as the takeoff procedure. The airplane is required to fly a 3° glide slope to the landing point at an airspeed of $V_{ref} + 10kts$ (a speed based on the airplane's stall speed). The approach noise is then the noise measured at a point 6,562 feet before the landing threshold.[21] However, because the procedure is completely defined by those two parameters they will also be considered in the sensitivity study. Figure 7 is a tornado plot which shows the results of the approach sensitivity study. The approach sensitivities are significantly higher than the takeoff sensitivities, which is expected since the configuration changes will alter both the aerodynamic performance and the noise signature of the airplane. For instance, increasing flap deflection increases the amount of noise generated by the airframe, but increases the lift coefficient and enables the airplane to fly slower. Similarly, increasing the approach speed (defined as $KV_{stall}, K \approx 1.3$) increases the amount of noise the airframe generates, but reduces the thrust required to fly the approach and therefore decreases the engine noise.

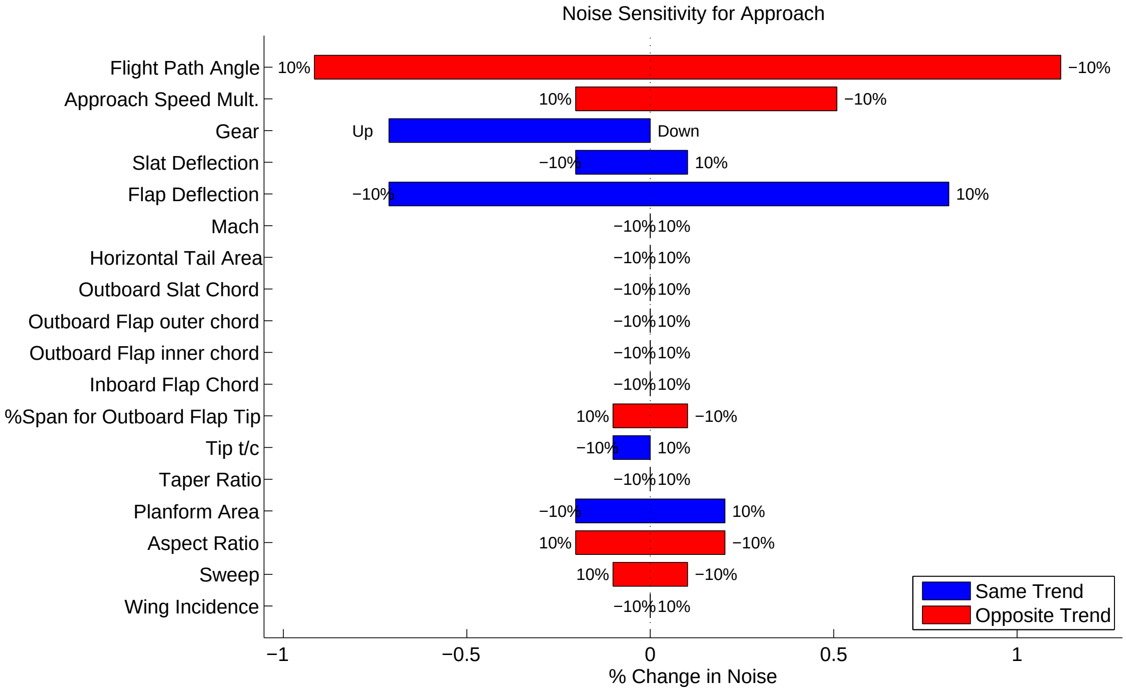


Figure 7. Tornado plot of the approach noise sensitivities, blue bars indicate an increase in the variable increases noise and red indicates a decrease.

With all of these couplings a second sensitivity study was conducted to determine which combination of parameters causes the largest change in the noise emissions. A full-factorial combination of the four parameters with the highest sensitivities—flight path angle, approach speed, slat deflection, and flap deflection—was analyzed. The best combination for reducing noise was the baseline airplane flying a 10% steeper approach 10% faster, which reduced noise 1.1 EPNdB (1.12%). This combination keeps the airplane higher above the ground and reduces the thrust the airplane requires. As a point of reference the Boeing 777-200ER requires about 30,000 lbf of thrust to fly a 3° approach at $1.3V_{stall}$. At that thrust level the engine and airframe noise is about 3 EPNdB higher than the airframe noise alone when the airplane overflies the approach noise measurement point. The 3 EPNdB difference means the engine dominates the noise, although the airframe noise is still significant, so increasing the aerodynamic performance of the airplane will be more effective at reducing airplane noise than will reducing the airframe noise signature.

V. Conclusion

Significant opportunities exist to reduce environmental impact and operational cost of future aircraft. Synergies between both configuration and operation can be exploited but this requires analysis of a large coupled model. This paper has presented one possible approach to study future aircraft configurations and ways to tailor departure and approach procedures to get the maximum benefit out of the new aircraft. It was demonstrated for an aircraft typical of those in the current fleet that safe procedures, which satisfy the Federal Aviation Regulations, exist that concurrently reduce time to climb, fuel consumption, noise exposure, and operational cost. Similarly, sensitivity studies of noise to aircraft configuration showed the significant coupling between configuration and operation, and that this method is capable of analyzing both design spaces simultaneously. The methodology presented in this paper may be useful for conceptual design of future aircraft and air-traffic systems to benefit both the environment and air carriers.

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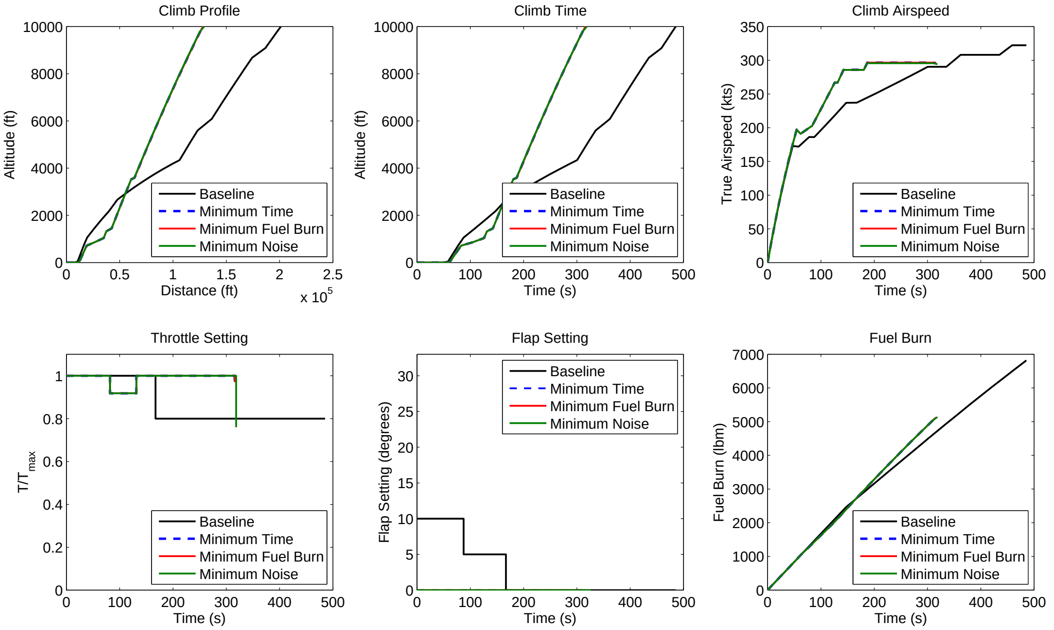

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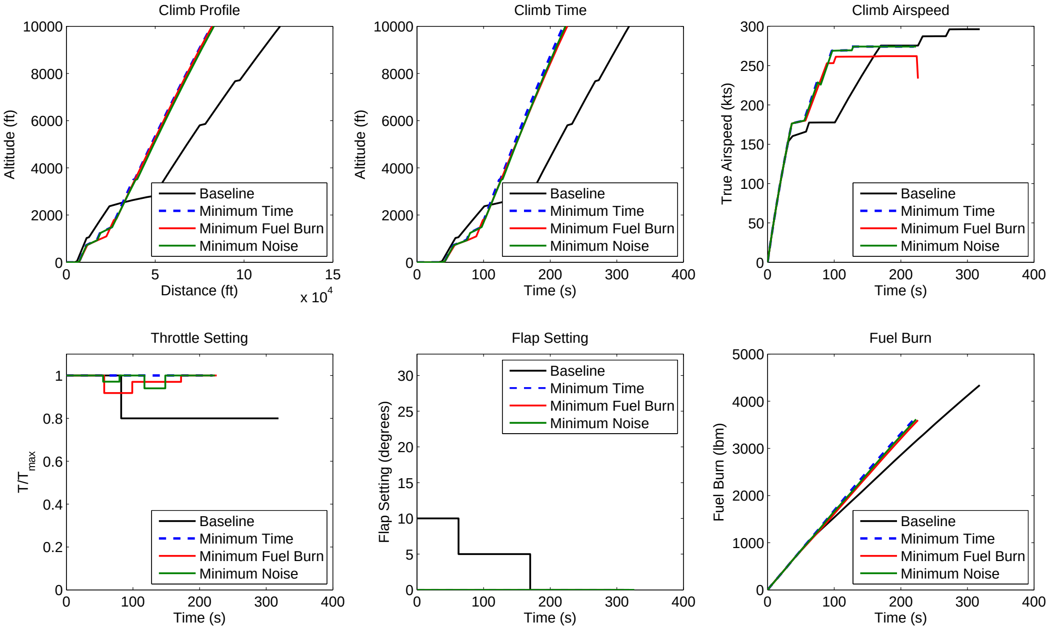
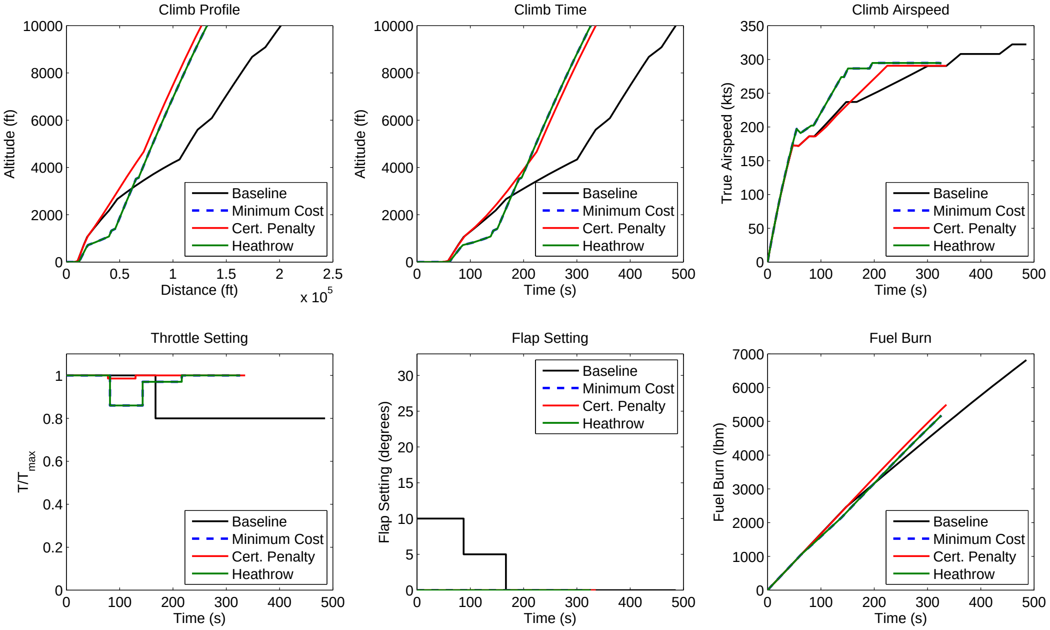


(b) 565,000 lbm.

Figure 8. Plots comparing the trajectories for minimum time to climb, minimum fuel burn, and minimum noise for different takeoff weights.



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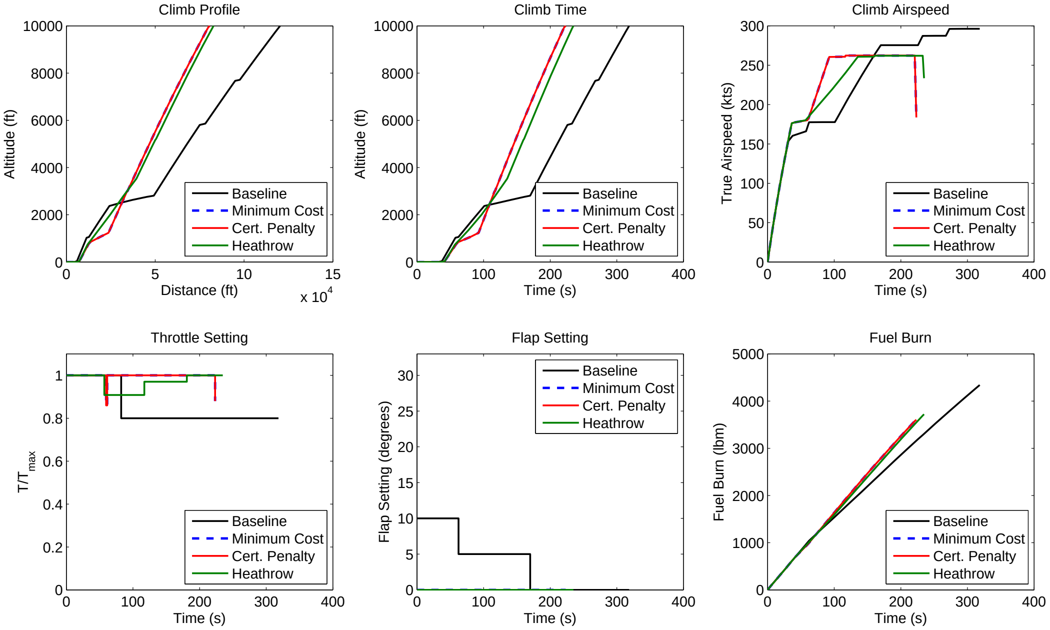

(b) 565,000 lbm.

Figure 9. Plots comparing the trajectories for cost with three different noise penalization schemes.