Junior-level Jet Engine Design Project Incorporating Aircraft Performance, Cost, and Environmental Issues

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Abstract

Capstone design classes in aerospace engineering oftentimes employ a multi-disciplinary team-based approach to design projects. In discipline-specific non-capstone classes, the typical emphasis is to cover the necessary conceptual material, and the design project in such a class tends to consider optimization issues related to the discipline-specific topic. This paper discusses the author's attempt to incorporate aircraft performance, cost, and environmental issues in the turbojet engine design project of a junior-level propulsion course. Coverage of such issues is thought to better prepare students for the capstone design class where a multitude of multi-disciplinary topics are covered in a team-based approach.

Introduction and Background

Educating the 21st Century engineering student for success in an increasingly global environment requires nurturing the students to acquire a multitude of different skills and experiences. To ensure that students graduate with these desired skills, engineering programs must show that a series of outcomes-based criterions are met as part of the Accreditation Board for Engineering and Technology (ABET) requirements. In criteria "3c," which is one of the eleven criterions for accreditation in Aerospace Engineering, a program must show that students have the "ability to design a system, component, or process to meet desired needs within realistic constraints such as economic, environmental, social, political, ethical, health and safety, manufacturability, and sustainability."[1]

At Wichita State University, the Aerospace Engineering program includes the traditional mix of general engineering core, aerodynamics and propulsion, dynamics and control, and structures courses followed by a two-course capstone design sequence. In addition to the capstone design sequence, aspects of design are covered in a multitude of non-capstone classes starting in the sophomore year. Many of these non-capstone classes utilize a series of class assignments to consider an optimization-type design problem. Although the design assignments in non-capstone classes vary somewhat from year to year and from instructor to instructor, they tend to be individual assignments that emphasize discipline-specific topics. In order to bridge the gap with the capstone design sequence in the senior year, the author took what had been an individually assigned optimization design problem and modified it into a team-based multi-disciplinary project for the second semester junior year propulsion class.

The impetus for changing the propulsion design project came about as a result of the author’s experience gained in the Boeing Welliver Faculty Summer Fellowship program. This eight week summer program allows engineering faculty to interact with top executives, and to observe the activities of mid-level managers in their day-to-day activities. The program also introduces Faculty Fellows to interdisciplinary issues like economics and manufacturing which are encountered by design engineers in the Aerospace Industry today. At the end of the eight week period, Faculty Fellows report their lessons learned to Boeing executives through a team-based presentation. Probably the most significant experience of this program was gaining an insight into the strategic view and thinking of top level executives including Boeing’s CEO and President.

Several important lessons were learned by the author as a result of the Boeing Welliver Fellowship experience. First was the recognition that the Aerospace Industry has been undergoing some significant changes. In the past, the Aerospace field was considered to be at the forefront of technology, always pushing the state-of-the-art to fly "faster, higher, and farther" (i.e., to improve performance). Recently, cost issues have driven companies to bring products quicker to the market at lower cost. In the future, however, there may be some emphasis given to developing products which are environmentally clean and quiet. Thus, the "faster, higher, and farther" (i.e., "mean" in performance) mantra has changed to "quicker (to market), better, and cheaper" (i.e., "lean") to all of the above *plus* "cleaner, quieter, and safer " (i.e., "lean, mean, and green").[2] This suggests that issues besides the traditionally taught performance analysis concepts may need to be given increased coverage in the curriculum.

The second lesson learned from the Boeing Welliver Fellowship was recognizing the need for systems engineers.[2] As the Aerospace field has matured, many companies have taken on the systems integrator role where components or subsystems are bought from subcontractors who may be located across the country or overseas. Although each individual component or subsystem may be relatively simple and inexpensive, the "value-added" occurs when they are integrated into the vehicle or system to meet the requirements of the customer. Success as a systems integrator requires a good understanding about customer needs, design constraints, manufacturability, and operator life-cycle cost issues to name just a few examples. Successful systems engineers must therefore be able to communicate with and understand the issues that are dealt with by a multitude of different people such as marketing, design engineers, manufacturing technicians, and maintenance personnel. This suggests a need for introducing more multi-disciplinary concepts using a team-based approach to design problems in the Aerospace curriculum.

The third and final lesson learned was the new emphasis on reducing cost. This need goes beyond the traditional realm of reducing engineering and manufacturing costs (i.e., "lean" alone). In fact, the focus is the end user’s operating cost. Figure 1 illustrates such an operating cost comparison between three fictitious models labeled 1, 2, and 3 from two different manufacturers labeled A and B. Although the total trip cost along the horizontal axis is a function of the number of passengers carried by the aircraft, the primary driver for the horizontal axis is essentially the trip distance (i.e., range). Each aircraft model typically has several variants where fuselage extensions are added to increase the number of passengers and/or fuel tanks added to increase range. Thus, there are variations in cost per passenger and trip cost depending on the model variant. This is the

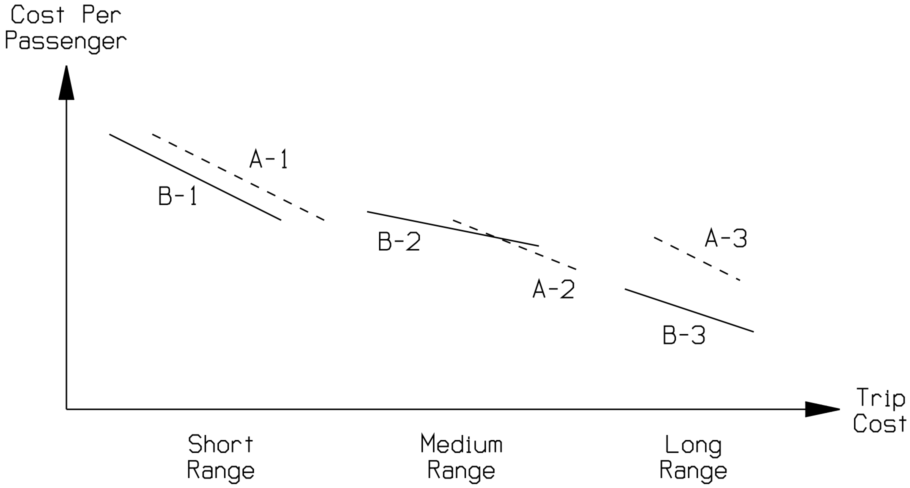

Figure 1 - Operating cost comparison between different aircraft (reference [3]).

reason why the figure consists of a series of curves, one curve for each model type rather than a single data point. By studying operating cost comparisons for real-life aircraft,[3] it becomes readily apparent why the long range model from manufacturer B outsells the long range model from manufacturer A. This also explains why manufacturer B is willing to spend significant funds (several billion dollars) to develop a new more efficient medium range aircraft.

Based on some of the lessons learned from the Boeing Welliver Fellowship experience, the author became motivated to change the second semester junior year propulsion design project. The goal was to change what had been an individually assigned optimization design problem into a team-based multi-disciplinary project while considering realistic constraints such as cost and regulatory issues. The major hurdle to this approach was obtaining cost information which is typically proprietary information for most manufacturers. Details about how this hurdle was overcome are detailed in the section which follows.

Project Evolution and Cost Estimate Process

The jet engine design project in the junior year propulsion class has changed significantly over the course of its fourteen year evolution. The project began as an individually assigned problem considering the effect of varying the compressor pressure ratio on the fuel efficiency of a turbojet engine. Only two fixed design points were considered back then: take-off thrust at sea level and maximum thrust operation for high subsonic flight speed at cruise altitude. Such a design assignment invariably led to the obvious end result of high compressor pressure ratio providing the most fuel efficient solution. Although there was very little learned in terms of "new concepts" by the students, the design project was nevertheless important in that significantly more work was involved compared to a typical homework assignment, and a final written report was also required. This jet engine design project was typical for a discipline-specific project where the engine was designed without ever considering its interactive effect when mated to an aircraft.

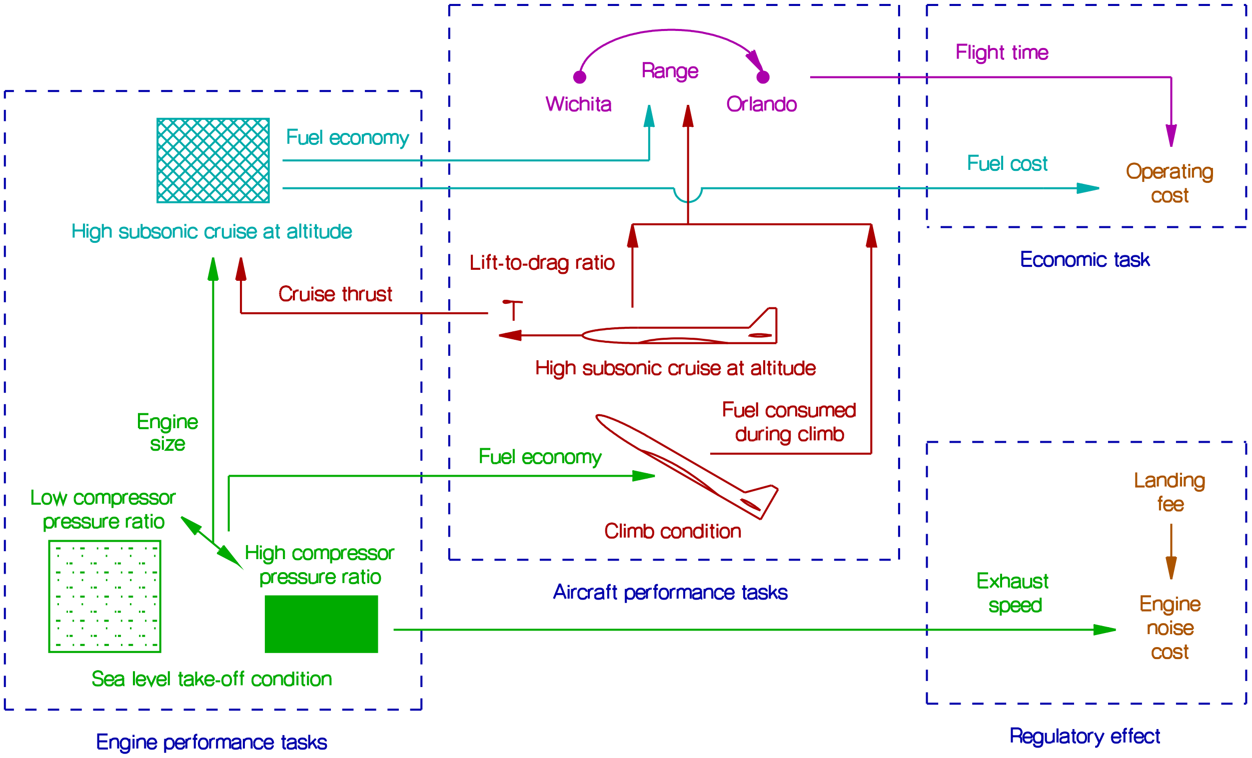

Figure 2 - Jet engine design project disciplinary tasks. Left: engine performance tasks. Center: aircraft performance tasks. Right: tasks associated with economic and regulatory issues.

Eleven years ago, the design project was changed to incorporate the effect of mating the engine to an aircraft. In this case, four different major tasks are involved: (1) take-off *engine* performance, (2) climb and cruise *aircraft* performance, (3) cruise *engine* performance, and (4) overall *aircraft* performance. These four different major tasks are illustrated in the left-hand and center boxes of Figure 2. First, maximum take-off thrust at sea level is determined as a function of variations in compressor pressure ratio. Here, a high compressor ratio engine is represented by a "dense" engine (i.e., green-filled rectangle) while a low pressure ratio engine is represented by a "light" engine (i.e., green-shaded square). The "size" of the engine in terms of mass flow rate of air going through the engine is then varied in order to meet the take-off thrust requirement specified in the project assignment. This take-off thrust and sizing calculation is part of the engine performance calculations. The first part of the second task involves determining the fuel consumed during the climb to cruise altitude. The fuel consumed during climb will affect the amount of fuel available during cruise which will then be used later on in the fourth task's calculations. Also determined during the second task is the amount of thrust required to fly a specified aircraft at cruise altitude under high subsonic speed condition. Both of these calculations made during the second task (illustrated in red color) involves aircraft performance concepts which are covered in a sophomore year course which is a pre-requisite to the junior year propulsion class. The third task (illustrated in aquamarine color) is to throttle the engine down by burning less fuel and reducing the maximum cycle temperature. The engine must be throttled down because cruise at less than maximum flight speed requires less thrust than the maximum thrust capability of the engine. Indeed, determining the cycle temperature necessary to produce the engine thrust which matches the thrust required based on aircraft performance calculations is the variable result being sought in this third task. In the fourth and final task (illustrated in pink color), the maximum distance which can be traveled by the aircraft is calculated based on the Breguet range equation. Completing this final calculation requires information about the engine's fuel economy, which is itself dependent on the cruise thrust requirements, as well as the aircraft's lift-to-drag ratio and the amount of fuel available during cruise. It should be noted that the actual trip distance is less than the maximum achievable range since the Federal Aviation Administration requires a fuel reserve to reach an alternate airport. In the present design project, this was interpreted to be a range reserve of 400 miles.

As illustrated in Figure 2, one pair of tasks (i.e., first and third depicted in green and aquamarine colors) is the engine design calculations typically performed by the engine manufacturer while the other pair of tasks (i.e., second and fourth depicted in red and pink colors) is the aircraft performance calculations typically made by the aircraft manufacturer. This type of multi-disciplinary design optimization problem lends itself well to a team-based solution approach. Consequently, this turbojet engine design project has been assigned to three or four person teams since nine years ago. Furthermore, this approach dovetails well with the multi-disciplinary team-based approach sought under the ABET 2000 criteria.

After the Boeing Welliver Fellowship experience, the idea of incorporating cost issues to the design project (upper right box of Figure 2) was considered. Figure 3 illustrates a typical airline's costs for flight operations broken down according to major categories. In the past, fuel cost were less than 10% of the flight operation cost for an airline. However, recent significant increases in the price of fuel has raised this portion to 20-30% of the airline's flight operation cost.[4] Flight crew cost is typically on order of about a third of the flight operation cost.[5] Maintenance costs 10-30% depending on the age of the aircraft.[5] Other flight operation costs include insurance and debt,

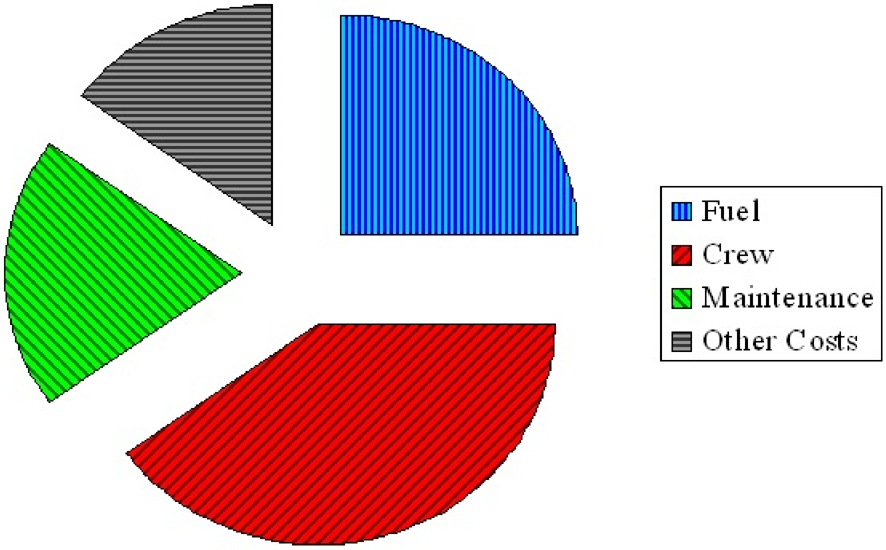

Figure 3 - Flight operation cost breakdown according to major categories.

which can be on order of about 15-20%.[5] Finally, there are costs for cabin crew (flight attendants), in-flight services (e.g., beverages), airport landing fees, and ground handling which are not counted in the flight operation cost, but are nevertheless expenses against revenue generated. Detailed flight operation cost information such as those described above is available in the literature, but is limited to a single model type (Boeing 737) for pre-9/11 (i.e., spring 2001) cost data.[5] Airline operations have undergone significant changes since then. Consequently, a cost estimate based on more rudimentary information which might be generalized was sought.

Information about jet fuel prices paid by the airlines is available from the International Air Transport Association[6] and the Air Transport Association of America[7] while retail price information is available from AirNav.com[8]. It should be noted that fuel prices paid by the airlines may not include the cost of delivery (to the ramp-side by fuel trucks). On the other hand, retail prices which include such delivery costs vary in price from airport to airport. The cost of jet fuel paid by the airlines is currently about $2 per gallon while retail prices for jet fuel service provided at the ramp by a delivery truck range from under $3 per gallon in Kansas to over $6 per gallon in Southern California. A rough estimate of $3 per gallon was used in the recent turbojet engine design project. It should be noted that fuel costs have doubled since cost estimates were initially included in the design project five years ago, and these higher fuel prices were incorporated in this year's project.

Flight crew (i.e., Captain and First Officer) hourly pay rates are available from AirlinePilotCentral.com.[9] There is some variability (± 10%) in flight crew cost from airline to airline, but the average for the major airlines is $135 per flight hour for Captains with six years experience while it is $87 for First Officers. In comparison, flight crew cost on fractional ownership (corporate-type) business jets is about $100 per flight hour for Captains and $67 for First Officers. Cabin crew salary information is available from CabinCrewJobs.com[10] where a flight attendant with six years experience earns about $30,000 per year while working 75 flight hours per month. This translates to a pay rate of about $$33^1/_3$ per flight hour for flight attendants. Since a typical 100 passenger jet has four flight attendants, cabin crew costs are about $133 per flight hour. Thus, current flight and cabin crew costs total $355 per flight hour on a 100 passenger jet. This compares to a rate of $320 per flight hour which has been (and continues to be) used in the design project based on cost data obtained five years ago.

Based on Federal Aviation Administration data, maintenance cost for two-engine narrow-body passenger jets is $515 per flight hour.[11] Similar (i.e., 100+ passenger), but older three-engine narrow-body passenger jets have a cost of $712 per flight hour.[11] Since newer jets have lower maintenance costs,[5] a figure of $500 per flight hour was used in the design project.

London's Heathrow Airport is said to have one of the more expensive airport fees. Their regulations and fee schedule is available in the open literature.[12] The landing fee for a baseline passenger aircraft is £512.5 which corresponds to $1025 at the current exchange rate of $2 per British Pound Sterling (i.e., £1). A parking fee of about £10 ($20) per hour and a departure fee of £155 ($310) brings the total airport fee to $1,355. Information about other operating expenses such as in-flight services (e.g., beverages) and ground handling costs were not available. A rough estimate of $3,000 (total) per flight for the airport fee, in-flight services, and ground handling cost was made. This turned out to be a reasonable estimate when the result from direct operating cost calculation based on low fuel cost was compared against those in the literature for pre-9/11 cost values.[5,11]

It should be noted that there are landing fee penalties for increased engine noise. The landing fee at Heathrow Airport is increased to £768.75 ($1,538) for aircraft with moderately increased noise levels and £1537.5 ($3,075) for non-compliant stage 2 noise level aircraft.[12] This type of information can be used to calculate the effect of additional regulatory fees associated with flying a noisy aircraft as illustrated in the lower right box of Figure 2. In this case, a relative noise level is calculated based on the exhaust speed (i.e., exhaust Mach number cubed). Determining the effect of this noise regulation was considered to a limited extent in the design project assignment this year, and may be given expanded coverage in the future.

Other Implementation Issues, Feedback, and Future Work

Each team was required to submit a final written report which was used as the primary basis for each student's grade. The report consisted of four separate self-contained chapters covering the four different major tasks, where range and operating cost calculations were combined as the fourth task. Each chapter consisted of an explanation of the task objective, technical approach used, results in tabular and graphical form, discussion, and summary. In order to encourage students to be succinct in their writing, a maximum page length limit of five pages per task, including tables and figures, while using 12 point font text and 1" margins was imposed. Students were warned about the need to include properly labeled table headers and graph axes labels including appropriate dimensional units. In the results discussion, emphasis was placed on explaining the technical behavior rather than simply describing the results. It should be noted that the optimal solution in one task did not necessarily agree with the optimal solution in another task. For example, the compressor pressure ratio and cruise altitude for minimum thrust required calculated in the second task was different from the compressor pressure ratio and cruise altitude for best fuel economy calculated in the third task. Although students worked on specific tasks and chapters individually, they checked one another's work because each student's grade was a composite of the individual's score and the average of the team's score. Furthermore, students were encouraged to contribute towards the success of the entire team by employing an "autorating" peer evaluation technique.[13] The peer evaluations were then used as a weighting factor to multiply against the individual plus team average composite score.

Six different versions of the project has been (or will be) assigned to students on a rotating basis. The project is calculated with metric units in odd-numbered years while English units are used in even-numbered years. Every third year, a 100 passenger jet is considered as the baseline aircraft, followed by a mid-sized business jet the next year and then a very light jet. Each aircraft type results in a different optimization point although students are not informed about this issue in advance. The use of different units and aircraft type on a six-year rotation ensures that the results and written report from an earlier year has limited informational value to students in subsequent years. Each year, the project is preceded by a homework assignment where a turbojet engine cycle calculation is performed in the same units (metric or English) as the project being assigned. This hand calculation homework assignment provides a solution for a single condition to compare against as the student teams create a "large" software code to solve the full design problem. Students are free to choose the type of software used to solve the design problem. Indeed, some teams utilize a couple of different software packages (e.g., Excel with FORTRAN or Maple or Mathcad or Matlab) in their project.

Feedback about the propulsion class and the design project were obtained from two sources. The Department Chair conducts an exit survey of graduating seniors, and their feedback over the years about the course appears to be very positive. The capstone design course instructor has mentioned that students who perform an expanded jet engine design investigation usually do a good job in that task. These comments provide some anecdotal evidence that the propulsion design project provides a positive benefit which bridges the gap with the senior year capstone design course. However, obtaining some quantitative feedback information from the students may be warranted as part of some future work.

Propulsion textbooks which are available typically tend to emphasize the propulsion specific topics. On the other hand, aircraft performance textbooks tend to consider the thrust and fuel economy information for a fixed (specific) engine. Consequently, textbooks in these two different disciplines typically do not consider the interactive effect of a "rubber" (i.e., size varying) engine on an aircraft under varying flight conditions. Thus, the interactive effect between the left-hand and center boxes of Figure 2 are typically not covered by textbooks in the propulsion or aircraft performance disciplines. Although the Aerospace Industry considers the interactive effect on a regular basis in their aircraft design studies, this information is not widely available in the literature. This is probably due to the proprietary nature of the work performed by the aircraft manufacturers. In order to document this interactive effect, the author has conducted a couple of investigations on this topic. In the first paper, the effect of varying the cruise flight condition on a turbojet powered mid-sized business jet was considered.[14] In the second paper, the effect of fan pressure ratio variations on a turbofan powered mid-sized business jet was considered.[15] Although the design project was initiated because of a desire to improve student learning, it has led to some technical lessons learned for the author as well.

Summary

A turbojet engine design project employing a multi-disciplinary team-based approach which considers aircraft performance, cost, and environmental issues was developed. This project matured into its present form as a result of tailoring to meet ABET 2000 requirements and accounting for the evolving needs of the Aerospace Industry. Estimates for fuel, crew, and maintenance costs were obtained from the open literature in order to perform direct operating cost calculations as a part of this design project. A comparison with direct operating cost information available in the literature suggested that these estimates were made correctly. Feedback from students who participated in this design activity has been positive. Thus, this design project acts as an excellent learning tool which bridges the gap between discipline-specific engineering science courses and the senior-year capstone design sequence.

References

[1] "Criteria for Accrediting Engineering Programs: Effective for Evaluations During the 2006-2007 Accreditation Cycle," October 29, 2005, Accreditation Board for Engineering and Technology, Baltimore.

[2] J.H. McMasters and J.M. Cummings, January-February 2004, "From Father, Faster, Higher to Leaner, Meaner, Greener: Further Directions in Aeronautics," *Journal of Aircraft*, Vol. 41, No. 1, pp. 51-61.

[3] J. Roundhill and P. Radloff, July 2003, "The Future of Commercial Aviation - Building on Our Legacy," AIAA Paper 2003-2552, AIAA/ICAS International Air and Space Symposium and Exposition: The Next 100 Years, Dayton, OH.

[4] "Fuel 101: From Well to Wing," Air Transport Association of America (ATA), www.airlines.org/economics/energy/fuel+101.htm (website accessed May 2007).

[5] "Flying Boeing's Workhorse, the B-737, Scorecard 3," R2A Consulting (Unisys), www.unisys.com/transportation/insights/articles/articles.htm?insightsID=88374 (website accessed May 2007).

[6] "Jet Fuel Price Monitor," International Air Transport Association (IATA), www.iata.org/whatwedo/economics/fuel_monitor (website accessed May 2007).

[7] "Jet Fuel Cost and Consumption Report," Air Transport Association of America (ATA), www.airlines.org/economics/energy/MonthlyJetFuel.htm (website accessed May 2007).

[8] "Local Fuel Prices," AirNav.com, www.airnav.com/fuel/local.html (website accessed May 2007).

[9] "Legacy Airline Profiles," AirLinePilotCentral.com, www.airlinepilotcentral.com/airlines/legacy (website accessed May 2007).

[10] "Flight Attendant Salary Comparison Chart," CabinCrewJobs.com, www.cabincrewjobs.com/salarycomparison.html (website accessed May 2007).

[11] W. Tsai, "The Economics of Maintenance," 2002, *The Standard Handbook for Aeronautical and Astronautical Engineers*, M.R.D. Davies editor, McGraw-Hill, New York.

[12] "Heathrow Airport Conditions of Use," 14 February 2007, Heathrow Airport Limited (also online at www.boeing.com/commercial/noise/heathrowconditionsofuse2007.pdf).

[13] D.B. Kaufman and R.. Felder, 2000, "Accounting for Individual Effort in Cooperative Learning Teams," *Journal of Engineering Education*, Vol. 89, No. 2, pp. 133-140 (also online at www.ncsu.edu/felder-public/Papers/Kaufmanpap.pdf).

[14] R. Myose, T. Young, and G. Sim, September 2005, "Comparison of Business Jet Performance Using Different Strategies for Flight at Constant Altitude," AIAA paper 2005-7326, 5th AIAA Aviation, Technology, Integration, and Operations Conference, Arlington, VA.

[15] R.Y. Myose, T. Young, and I. Heron, September 2006, "Effect of Fan Pressure Ratio and Bypass Ratio on Business Jet Range Performance," AIAA paper 2006-7706, 6th AIAA Aviation, Technology, Integration, and Operations Conference, Wichita, KS.