Impact Of Parametric Aerothermal Variability On Aircraft Engine Operating Cost

by

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Abstract

A comparative probabilistic maintenance reliability and economic analysis is presented with the object of quantifying the potential economic impact of aircraft engine component parameter aerothermal variability. A representative parametric aerothermodynamic cycle-deck is established for the Pratt & Whitney JT8D-9 model engine and utilized throughout the study. Open literature degradation data on this exemplar is employed in establishing functions of the second moment characteristics of the dependent parameter of interest, thrust specific fuel consumption (TSFC). Mean degradation data on component performance parameters are also presented in the literature and an approach is introduced to derive their variabilities from that of the dependent parameter. The practicality of a matching *off-design* analysis, as opposed to the *design-point* approach, is also validated and adhered to while using a commercially available gas turbine thermodynamic cycle analysis software, GASTURB. Maintenance criteria are established based on industry practices of exceeding predetermined TSFC and/or exhaust gas temperature (EGT) margins. By varying the second moment chararcteristics of the component performance parameters, the response of fleet operating maintenance reliability and economics is studied.

Thesis Supervisor: David L. Darmofal
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A miracle is in actuality the manifestation of presently *incomprehensible science, which is why ignorance is so blissful; of that which one is ignorant,* ***everything is a miracle.***

– RozzTz

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confidence and friendship and anxiously look forward to attending his defense. I am thankful to **Vince** in more ways than one. He has generously imparted his industry experience in answering most of my questions pertinent to gas turbine operation and in fact it was he who provided the initial impulse that set things in motion for this thesis work. **Tolu**, my primary nocturnal comrade provided benefic Latex assistance in the latter days prior to his departure and late night/early morning discussions with **Sudeep**, my secondary nocturnal comrade, exposed me to yet another host of issues from a truly different perspective. I am also very pleased to have become acquainted with several other congenial individuals in the lab: **Alex**, a very pleasant individual, **Guillame**, one of my first French contact; **Jerome**, my fellow Robust comrade; **Keith**, a person of great morals; **James**, the quiet genius, and the newer guys, **Michael**, **Garrett** and **Yann**.

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Nomenclature

ACRONYMS

Abbreviation	Description/Definitions
BLD	Bleed air flow (kg/s)
BTS	Bureau of Transportation Statistics
CAEP	Committee on Aviation Environmental Protection
EGT	Exhaust Gas Temperature (K)
EPR	Engine pressure ratio
FHV	Fuel heating value (MJ/kg)
FN	Net thrust (kN)
GAG	Ground-Air-Ground
HPC	High Pressure Compressor
HPT	High Pressure Turbine
ICAO	International Civil Aviation Organization
IGV	Inlet Guide Vane(s)
LPC	Low Pressure Compressor
LPT	Low Pressure Turbine
MFP	Mass Flow Parameter
PWX	Power off-take (kW)
RNI	Reynolds number index
TSFC	Thrust Specific Fuel Consumption (mg/Ns)
USDOT	US Department of Transportation

ROMAN SYMBOLS

Symbol	Description/Definitions
B	Booster
c_p	Constant pressure specific heat (kJ/kg K)
F	Fan
f	Fuel flow rate (kg/s)
M_i	Mach number (at station 'i')
m	Mass flow (kg/s)
$\tilde{m}$	Corrected mass flow (kg/s)
N1	Low pressure spool speed (rpm)
P	Pressure (Pa)
P_t	Stagnation pressure (Pa)
R	Gas constant (J/kg K)
T	Temperature (K)
T_t	Stagnation temperature (K)

GREEK SYMBOLS

Symbol	Description/Definitions
α	Bypass ratio
γ	Specific heat ratio (cp/cv)
δ	Ambient humidity (%)
Δ	Change
$\eta_{isen,poly,th}$	Efficiency (isentropic, polytropic, thermal)
μ	Mean value
π	Pressure ratio
ϖ	Flow capacity
σ	Standard deviation value

τ	Temperature ratio
τ_M	Mixer temperature ratio

GASTURB STATION DEFINITION

The station definition used in GASTURB follows the international standard for performance computer programs. This standard has been published by the Society of Automotive Engineers, SAE, as ARP 755A.

Station	Definition
0	Ambient
2	First compressor (fan & booster) inlet
12	Fan core flow exit
13	Fan bypass flow exit
16	Bypass-duct exit into mixer
21	Booster exit
25	High pressure compressor inlet
3	High pressure compressor exit
31	Combustor inlet
4	Combustor exit
41	High pressure turbine IGV exit = rotor inlet
43	High pressure turbine exit before addition of cooling air
44	High pressure turbine exit after addition of cooling air
45	Low pressure turbine inlet
49	Low pressure turbine exit before addition of cooling air
5	low pressure turbine exit after addition of cooling air
6	Core flow (LPT) exit into mixer
64	Mixed flow (mixer)
8	Exhaust nozzle

Chapter 1

Introduction

1.1 Background

Aerothermal performance variation of newly manufactured aircraft engines results from a combination of factors including, but not limited to, manufacturing inconsistencies and deviations in elementary parts, stringency of tolerances, missed targets, human factors and assembling irregularities. Variability in engine performance is generated not only at the lowest level of the engine building process (such as parts manufacture), but also at other stages of the construction hierarchy. The geometric variation in elementary parts, which dictates that 'no two parts are exactly the same', propagates to the component level and finally to the completely assembled product. Thus, engine performance variation as evaluated by the dependent parameters, for example, specific thrust or thrust specific fuel consumption (TSFC), is a direct result of the variation in component performance as measured by the independent parameters, for example, efficiencies, pressure ratios or corrected mass flow. Performance variability at other times is a result of this initial variability and the variability in the operating conditions across a fleet of engines.

Frequently, a large percentage of newly manufactured engines fail to meet the original design targeted performance and this could serve as a significant cost for manufacturers and operators alike. A contributing factor to the failure to meet targeted performance is the typically deterministic design process that neglects anticipating variations in manufactured parts and subsequently the assembled product. For jet engines, with highly coupled subsystems and relations of high order non-linearity, the result is often a difference between the design targeted nominal and the actual mean performance.

The theoretical significance of component performance variability may be demonstrated by simple second moment probability analysis. Let us assume a system performance, f, determined by two independent parameters, X_1 and X_2, through the relation

$$f(X_1, X_2) = c_1X_1 + c_2X_2^2 + c_3X_1^2X_2 + c_4X_1^2X_2^2, \tag{1.1}$$

where $c_1, c_2, ...$ are constants.
The assumed deterministic values for the independent parameters are in general what the designers expect to be the *most probable* values for the respective parameters and thus are essentially the parameter's mean values. As a result, the nominal performance of the system is evaluated by the performance of the mean of the independent parameters given by,

$$f(\mu_{x_1}, \mu_{x_2}) = c_1\mu_{x_1} + c_2\mu_{x_2}^2 + c_3\mu_{x_1}^2\mu_{x_2} + c_4\mu_{x_1}^2\mu_{x_2}^2. \tag{1.2}$$

A probabilistic analysis which acknowledges the variability of the independent parameters, leads to a mean performance given by,

$$\mu_f = c_1\mu_{x_1} + c_2(\sigma_{x_2}^2 + \mu_{x_2}^2) + c_3\mu_{x_2}(\sigma_{x_1}^2 + \mu_{x_1}^2) + c_4(\sigma_{x_1}^2 + \mu_{x_1}^2)(\sigma_{x_2}^2 + \mu_{x_2}^2). \tag{1.3}$$

Thus, the *mean performance* is shifted away from the *performance of the mean* (the nominal targeted value) by the amount equal to the difference between Equations 1.3 and 1.2 given as

$$shift = c_2(\sigma_{x_2}^2) + c_3(\sigma_{x_1}^2\mu_{x_2}) + c_4(\sigma_{x_1}^2\sigma_{x_2}^2 + \sigma_{x_1}^2\mu_{x_2}^2 + \sigma_{x_2}^2\mu_{x_1}^2). \tag{1.4}$$

Note that some terms in the *shift* contain the mean squared of some parameters.

More importantly however, is that each term in the expression *always* contains the variance of at least one independent parameter, emphasizing the control of mean-shift which may be exercised through comprehension and acknowledgement of independent parameter variability. This indicates that improvements in the attainment of engine performance design objectives, requires that manufacturers either place greater emphasis on the reduction of independent parameter performance variability or alternatively incorporate anticipated parameter performance variation in the design phase of engine construction. However, before either action is justified, the astute engine manufacturer must evaluate the economic investment of driving down performance variability against its impact on the economics of in-service engine operation. This evaluation of the potential economic impact of component performance variation of aircraft engines is the topic of this thesis.

1.2 Goals and Objectives

The principal goal of this work is to evaluate and quantify the potential impact of component performance variability on direct engine operating cost, namely, fuel burn and maintenance, for a particular family of engines. The first objective towards achieving this goal requires the selection of a particular engine model and establishing its representative aerothermodynamic engine performance cycle. Analytic models representing the performance of a mean engine generated from open literature data will then be necessary in performing a mean engine analysis. We also intend on evaluating the validity of constant thrust design-point performance of the mean engine compared to off-design matching operation. To facilitate a probabilistic analysis, we next formulate models for the variability of component performance parameters, the independent parameters. To assert the impact on fleet maintenance cost, fuel cost and maintenance reliability due to component parametric aerothermal variability, we then conduct a comparative probabilistic aerothermodynamic performance cycle and cost analysis.

1.3 Thesis Overview and Methodology

The thesis is organized into five (5) chapters and four (4) appendices.

In **Chapter 2**, a mean engine off-design matching performance analysis is conducted after the generation of mean engine data models and the establishment of a representative parametric cycle model. Multiple public literature sources and typical data values are utilized in constructing the time-zero mean engine thermodynamic parametric cycle-deck for the Pratt & Whitney JT8D-9 engine model. Open literature degradation data from a Pratt & Whitney study [1] is then used to formulate models representative of the performance of the mean engine prior to the first overhaul. These models are then used to perform a matching analysis of this engine with increasing degradation (flight cycles). In addition, a constant thrust design-point performance analysis of the mean engine is conducted for comparison against the off-design matching process.

Chapter 3 is concerned with a probabilistic engine performance analysis based on derived component variability. A time-line scatterplot of various models of the JT8D engine series from the literature source is employed in creating a time dependent model for the variability of thrust specific fuel consumption (TSFC). Based on this model, models for the variability of subcomponent performance parameters are also derived. These variability models along with the previously determined mean engine models, are used to probabilistically analyze the fleet's performance.

In **Chapter 4**, the impact of subcomponent parametric aerothermal variability on fleet maintenance reliability and operation economics (fuel and maintenance cost) is explored based on pre-set overhaul criteria. Marginal increase in mean thrust specific fuel consumption and exhaust gas temperature (EGT) from their respective time-zero values are utilized as criteria for engine removal for servicing. These criteria allow for a comparative probabilistic maintenance reliability and operation economics analysis. These analyses provide the means by which we may finally quantify the impact of parametric aerothermal variability.

Chapter 5 presents a brief summary of this thesis work and the conclusions that may be inferred from the results obtained. A proposal of future work to complement and expand on this study is also disclosed here.

In **Appendix A**, appropriate supporting information from the International Civil Aviation Organization's (ICAO) engine exhaust emissions data bank is disclosed. **Appendix B** presents fuel prices as published by the Bureau of Transportation Statistics for scheduled domestic airline services.

Chapter 2

Mean Engine Performance

2.1 Introduction

The objective of this chapter is to develop a model of the mean engine performance for a typical engine. Additionally, we will assess the performance of a selected mean engine at constant thrust using off-design and on-design analyses. We begin the process by selecting a specific engine exemplar, the Pratt & Whitney JT8D-9, based on availability of pertinent information and then proceed to establish its production run thermodynamic performance cycle-deck. Degradation data germane to the selected engine model is then employed to generate mean engine performance models as functions of engine cycles. These models employed in the gas turbine cycle analysis software, GASTURB, depict the mean engine performance, which may then be compared to public source performance data.

2.2 JT8D-9 Cycle-Deck

In 1981 Pratt & Whitney Aircraft Engines Group studied the impact of wear on the performance of the JT8D engine series as part of a NASA Aircraft Engine Diagnostic Program [1]. The JT8D is a first generation axial, mixed flow, dual spool turbofan, with a low bypass ratio and is one of the most widely used engines in commercial service. The long service life of this engine and its slow degradation profile have facilitated numerous developmental changes resulting in increased thrust, reliability, and service life. Extensive studies have also been conducted on the performance retention characteristics of the engine in demonstrating the derivable benefits of refurbishment, resulting in a relative preponderance of public data on the series. Thus, the JT8D was selected as an exemplary engine series for investigating the significance of parametric performance variability on engine operating cost. Furthermore, as performance degra-

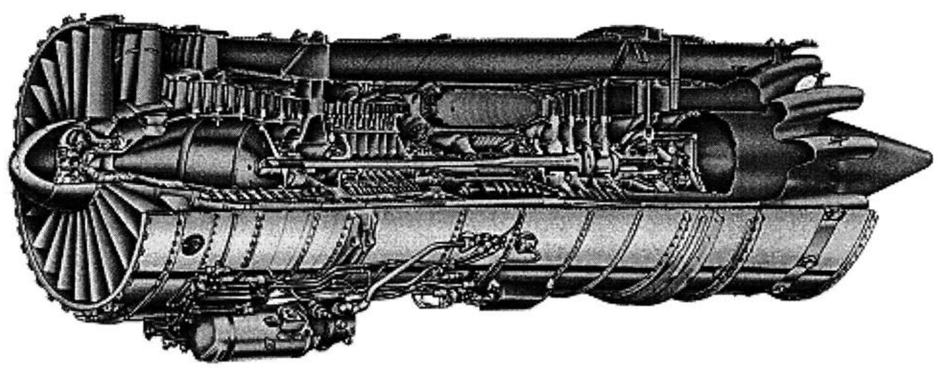

Figure 2-1: JT8D gas turbine engine [2]

dation data was available for the JT8D-9 [1], the thermodynamic cycle model was based on this specific engine. Various open literature sources [1,3–6] were consulted in constructing the JT8D-9 cycle-deck from its time-zero performance parameters. However, appreciable variability exists on the value of component parameters and other information contained in these sources. Thus, in developing the cycle model, information and data acquired from the original engine manufacturer were given priority where conflict existed between the different literature sources. To perform the aerothermodynamic aspects of the study, GASTURB, a PC based software program to calculate design and off-design performance of gas turbines was utilized [7,8].

Given combustor fuel flow and station temperatures and pressures, we may determine fan and compressor pressure ratios and efficiencies, combustor exit temperature and turbine temperatures and efficiencies. The majority of the former station properties were readily available from the open literature sources. In accordance with the originally manufactured 8D-9s, compressor air bleeding for hot-section cooling purposes were not simulated. The Mach number of the mixing chamber for the hot and cold exhaust streams, M_{64}, was computed from the flow properties of the bypass exit and the core exit by [4, 9],

$$M_{64} = \sqrt{\frac{2\Phi_{64}}{1 - 2\gamma_{64}\Phi_{64} + \sqrt{1 - 2(\gamma_{64}+1)\Phi_{64}}}}, \tag{2.1}$$

where

$$\Phi_{64} = \left[\frac{1 + \dfrac{\alpha}{1+f}}{\dfrac{1}{\sqrt{\Phi_6}} + \dfrac{\alpha}{1+f}\sqrt{\dfrac{R_{16}\gamma_6}{R_6\gamma_{16}}\dfrac{T_{t16}/T_{t6}}{\Phi_{16}}}} \right]^2 \frac{R_{64}\gamma_6}{R_6\gamma_{64}}\tau_M.$$

The mixer temperature ratio, τ_M, is obtained from an energy balance of the mixer as follows

$$\tau_M = \frac{c_{p6}}{c_{p64}}\frac{1+f}{1+f+\alpha} + \frac{\alpha}{1+f+\alpha}\frac{c_{p16}T_{t16}}{c_{p64}T_{t6}},$$

and Φ_6 and Φ_{16} are computed from,

$$\Phi_x = \frac{M_x^2(1 + [(\gamma_x - 1)/2]M_x^2)}{(1 + \gamma_x M_x^2)^2}.$$

The secondary stream (bypass) exit Mach number, M_{16}, is determined from the known core exit Mach number, M_6, the total pressure ratio, P_{t6}/P_{t16} and the Kutta condition ($P_6 = P_{16}$) at the end of the splitter between the streams. Thus,

$$M_{16} = \sqrt{\frac{2}{\gamma_{16}-1}\left(\left[\frac{P_{t16}}{P_{t6}} \left(1 + \frac{\gamma_6 - 1}{2}M_6^2\right)^{\gamma_6/(\gamma_6-1)} \right]^{(\gamma_{16}-1)/\gamma_{16}} - 1 \right)}.$$

Please see the **Nomenclature** section for station identification and definition of symbols.

The remaining unknown parameters were either inferred from those known or were iterated until sufficient closure to the known outputs, TSFC and net thrust (FN), was obtained. Some parameters of less significance were set to typical values, such as the burner partload constant and the fuel heating value. The thermodynamic cycle was also corrected for ambient effects by including a value of 60% relative humidity, which is equivalent to a water-to-air ratio of 0.0064, this being consistent with the conditions at testing of newly manufactured JT8D-9 engines by the International Civil Aviation Organization (ICAO) [6].

A common practice in the aircraft engine industry is to define the performance of the fan as a single stream. However, GASTURB treats the flow as two separate streams, the core and the bypass stream, and accordingly facilitates the assignment of two separate sets of performance parameters for the bypass fan [7, 8]. For the purposes of this study and to accommodate the proper utilization of the software, the term 'fan' where used refers to the bypass section of the fan only (the secondary stream), while 'booster' defines the combined pressure rise of the core section of the fan and what is generally the low pressure compressor (LPC).

The time-zero JT8D-9 established cycle-deck resulting from the above exercise is presented in Table 2.1 with data from Pratt & Whitney Aircraft Engine Group [5], the ICAO Database [6] (**Appendix A**) and other sources for comparison.

Station Parameters				
Station	m **[kg/s]**	**T [k]**	**P [kPa]**	$\tilde{m}$ **[kg/s]**
Amb		**288.15***	**101.352***	
2	**144.240***	288.15	101.325	144.520
13	**72.570***	**364.26***	**199.258***	
16	72.570	364.29	197.313	
21	**71.670***	**459.26***	**430.922***	21.316
25	71.674	459.26	428.781	21.423
3	71.674	701.47	1689.824	6.718
31	71.674	**701.48***	**1689.910***	
4	72.732	**1214.82*** (**1210.93**$^{\oplus\ddagger}$)	**1545.800***	9.808
41	72.732	1214.93	1545.682	9.808
43	72.732	**1002.59***	**619.149***	
44	72.732	1002.70	619.509	
45	72.732	1002.70	619.509	22.232
49	72.732	786.48	202.887	
5	72.732	786.48*	202.887 (205.463*)	60.115
6	72.732	786.33	200.858	
64	145.302	582.17	196.540 (199.95$^{\oplus\ddagger}$)	
8	1450.302	582.17	194.575	107.752

Sub/Component Parameters				
Sub/Component	η_{isen}	η_{poly}	π	**RNI**
Fan (bypass)	0.8033	0.8210	1.967	1.000
Booster	0.8540	0.8799	4.253	1.000
HPC	0.8664	0.8883	3.941	1.923
Burner	**0.9710**$^{\infty}$		0.915	
HPT	**0.8800***	0.8709	2.495	1.376
LPT	**0.8800***	0.8685	3.053	0.756
Mixer	**0.5000**$^{\infty}$			
HP Spool	**0.9900**$^{\infty}$			
LP Spool	**0.9990**$^{\infty}$			

Engine Parameters					
FN [kN]	**TSFC [mg/Ns]**	**f [kg/s]**	**f-type**	**FHV [MJ/KG]**	α
64.50*$^{\dagger\oplus}$	16.40* (16.124†,16.85$^{\oplus}$)	**1.0578*** (**1.04**†)	Jet A†	**43.124**†	**1.0125*** (**1.04**$^{\dagger\oplus}$)
EPR	η_{th}	M_{64}	δ[%]	**BLD [kg/s]**	**PWX [kW]**
1.9203	0.369	**0.37***	**60**†	**0.00***$^{\dagger\oplus}$	**0.00**†

Table 2.1: JT8D-9 time-zero cycle-deck. **Bold face** values represent inputs to the cycle model while all normal size font values are outputs. Sources for the data are as follows:
* – Pratt & Whitney Aircraft Engine Company [5],
† – ICAO Database [6],
$^{\oplus}$ – Jane's Aero-engines [3],
‡ – Mattingly [4],
$^{\infty}$ – Values manually computed or iterated to convergence of known outputs.

2.3 Mean Engine Degradation Data

The Pratt & Whitney performance retention study of the JT8D provides estimates for mean thrust specific fuel consumption (TSFC) and exhaust gas temperature (EGT) as a function of flight cycles for first installation only (no previous overhauls) [1]. Additionally, subcomponent mean changes in flow capacities (percentages) and efficiencies (points) at time points of 4,000 and 8,000 flight cycles were estimated and are reproduced in Table 2.2. Two separate data sources were utilized in the reference to

	Efficiencies (points)				
	$\Delta\eta_F$	$\Delta\eta_{LPC}$	$\Delta\eta_{HPC}$	$\Delta\eta_{HPT}$	$\Delta\eta_{LPT}$
4000	−1.000	-0.400	-0.600	-0.047	-0.047
8000	−1.467	-0.467	-1.267	-0.800	-0.233
	Flow Capacities (percent)				
	$\Delta\varpi_F$	$\Delta\varpi_{LPC}$	$\Delta\varpi_{HPC}$	$\Delta\varpi_{HPT}$	$\Delta\varpi_{LPT}$
4000	−0.600	-0.200	-0.800	3.230	0.120
8000	−1.000	-0.600	-1.400	5.240	0.130

Table 2.2: Model losses derived from teardown data [1]

construct the JT8D engine performance degradation model and losses were identified both by module (fan, low pressure compressor, etc.) and cause (vane bow, erosion of airfoil, etc.). Limited first run pre-repair data from airline test cell runs provided estimates of important parameters. Efficiency and flow capacity changes for each module were then computed by an appropriate engine thermodynamic cycle analysis software through the comparison of the pre-repair data for a particular engine to its production run data. In addition, the Pratt & Whitney study used data from teardown inspections, where used parts with known service times were collected and analyzed in determining performance changes from new part configuration. From this source, both knowledge of causes as well as magnitude of module performance losses were inferred. The results from both sources were then compared and iterated until reasonable closure was obtained. The analysis concluded that whereas the primary damage mechanisms in the compression components were erosion and increased airfoil roughness, those of the turbine section were vane bow, vane leakage and increased clearances.

The flow capacity at station 'i', $\varpi_i = (m_i\sqrt{T_i})/P_i$, is a measure of the station's restriction to airflow. While the typical aging trend of efficiencies for both the compression and expansion components is a diminution, flow capacity changes with age differ from compressor to turbine as a consequence of differing damage mechanisms. Fouling of airfoil, airfoil leading edge erosion and increased aerodynamic blockage due to blade tip clearance increases and other effects result in a typical decrease in compression flow capacity. Vane bow and other thermal distortions conversely increase expansion (hot-section) blade passages and thus the flow capacity often increases.

As discussed in Section 2.2, the low pressure flow capacity and efficiency are represented as two streams within GASTURB. Fan and LPC mean changes in efficiencies and flow capacities presented in the literature [1] had to be appropriately converted to correctly describe mean changes in the corresponding GASTURB components, fan (bypass only) and booster. During this conversion exercise, we assumed that the literature mean changes for the fan parameters equally describe its core and bypass and thus a literature 1% delta in a fan parameter was implemented as 1% core change and 1% bypass change. Delta flow capacities for the GASTURB components (fan(bypass only), booster) were therefore equivalent to those presented in the literature for the fan, since this change is measured at the inlet to the component and these components all share a common inlet. To determine the booster efficiencies away from time-zero, the following procedure was employed:

- Determine the time-zero fan core and LPC efficiency.

  To perform this task, we assumed that at the initial time-point the LPC and fan core had equivalent mean efficiency values. Other possible assumptions produced values unrealistically high for the engine technology and compared to other component parameters. With the time-zero cycle-deck already established, flow properties (temperature, pressure and specific heat) at the inlet, fan bypass exit and LPC exit (same as booster exit) are thus available. By implementing,

$$\eta = \frac{(P_{tb}/P_{ta})^{(\gamma-1)\gamma} - 1}{(T_{tb}/T_{ta}) - 1}, \tag{2.2}$$

first across the fan core and then across the LPC, we generated two simultaneous equations with unknowns T_{t12} (fan core exit, LPC inlet stagnation temperature) and η (fan, LPC mean efficiency). For the first part of the above exercise, we assumed a common pressure at the exit of the fan core and its bypass.

- Determine booster efficiency from literature fan and LPC efficiency deltas.
  At points away from time-zero the literature mean efficiency deltas for the fan and LPC are imposed on the initial values determined above. Equation 2.2 was then individually applied across the fan core then the LPC to determine the exit flow temperature of the latter. To execute this we assumed the fan and LPC pressure ratios remained constant with flight cycles, which is a reasonable assumption during constant thrust (re-matching) operation. From the flow properties at the fan inlet (ambient) and the LPC exit, the booster efficiency may then be determined at any time-point by again invoking Equation 2.2.

To provide information on the mean performance of the subcomponents at other time points besides 4,000 and 8,000 cycles, best fitting exponential functions constrained by a monotonic property were generated through the known data points and extrapolated across the life of the fleet. The resultant plots, depicting mean percent changes, that is, change as a percent of the production run value, in efficiencies and flow capacities are displayed in Figures 2-2 and 2-3 respectively with their corresponding functions given below. The mean percent change in efficiency functions respectively for the fan (bypass only), booster, HPC, HPT and the LPT are as follows:

$$\Delta\eta_F = -1.4467 + 1.4467e^{-t} - 2.8642te^{-t} \tag{2.3}$$

$$\Delta\eta_B = -1.1971 - e^{-3.5t} \tag{2.4}$$

$$\Delta\eta_{HPC} = -4.9095 + 4.9095e^{-t} + 3.4538te^{-t} \tag{2.5}$$

$$\Delta\eta_{HPT} = -227.05 + 227.05e^{-t} + 227.04te^{-t} + 111.81t^2e^{-t} + 45.03t^3e^{-t} \quad (2.6)$$

$$\Delta\eta_{LPT} = 0.0181 - e^{3.45t} \quad (2.7)$$

The corresponding percent change in flow capacity functions are:

$$\Delta\varpi_F = \Delta\varpi_B = -1.825 + 1.825e^{-t} + 0.024798te^{-t} \quad (2.8)$$

$$\Delta\varpi_{HPC} = -3.09311 - e^{-0.7511t} \quad (2.9)$$

$$\Delta\varpi_{HPT} = 8.57011 - e^{-1.18t} \quad (2.10)$$

$$\Delta\varpi_{LPT} = -0.068732 + 0.068732e^{-t} + 0.49476te^{-t} \quad (2.11)$$

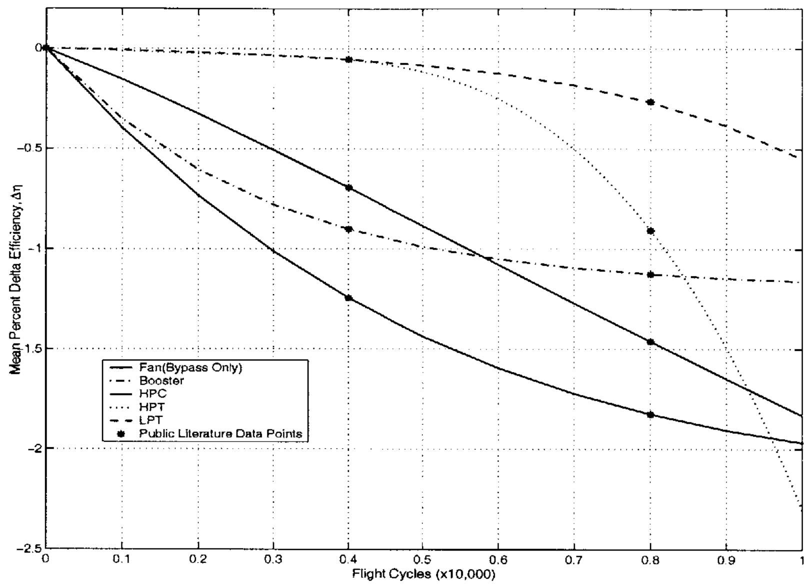

Figure 2-2: Mean percent change in subcomponent efficiency

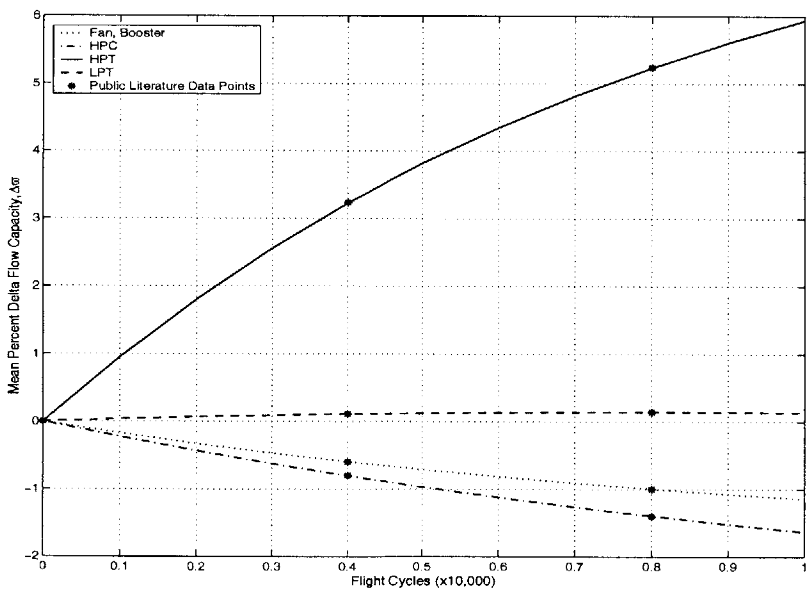

Figure 2-3: Mean percent change in subcomponent flow capacity

2.4 Mean Engine Performance Analysis

Engine performance cycle analysis studies the thermodynamic transitions of the working fluid, namely atmospheric air and the products of combustion, as it flows through a *specific* engine, to estimate the performance of the engine at varied flight conditions and throttle settings. A re-matching or *off-design* cycle analysis is used where the performance of the engine components are provided through respective component maps. For example, a compressor performance map relates total pressure ratio and temperature ratio for a given rotational shaft speed and mass flow. Whereas in an *on-design* or *design-point* analysis all parameters, such as total pressure ratio, are independent and consequently free to be modified; in the case of off-design, flight conditions (ambient pressure, temperature and Mach number), throttle settings, and nozzle settings (for variable nozzle geometry) are the only independents.

Off-design analysis of the mean engine

The GASTURB deterministic thermodynamic cycle analysis was conducted for the family of JT8Ds under the constraint of constant static sea level take-off thrust and with the mean functions for the independent performance parameters from Section 2.3. The net thrust was constrained to the production value of 14,500lbs (64.5kN), however in practice an indicator is actually used to set the thrust in real life circumstances. Typically, the low pressure shaft spool speed, N1, or the engine pressure ratio, EPR, are used as indicators since it becomes unfeasible to measure thrust in everyday situations. Both approaches produced comparable results, though only the constant thrust analysis is documented here.

The TSFC determined from the off-design analysis of the mean engine is presented in Figure 2-4 with the literature degradation model for the JT8D-9. The latter is extrapolated across the remaining life of the fleet to enhance comparison. Despite not exactly matching the literature model, the plots possess similar curvatures implying the mean cycle model was able to replicate fairly well the characteristics of this engine. The corresponding EGT matching results however were far less satisfactory

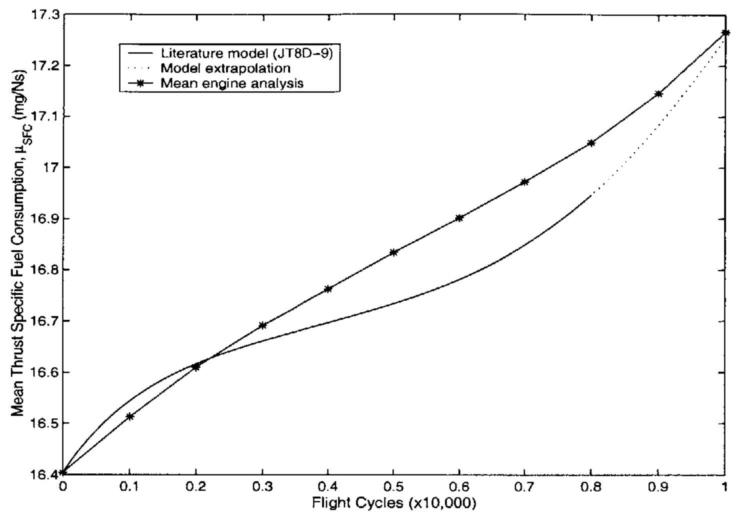

Figure 2-4: TSFC mean engine analysis results

as is depicted by Figure 2-5.

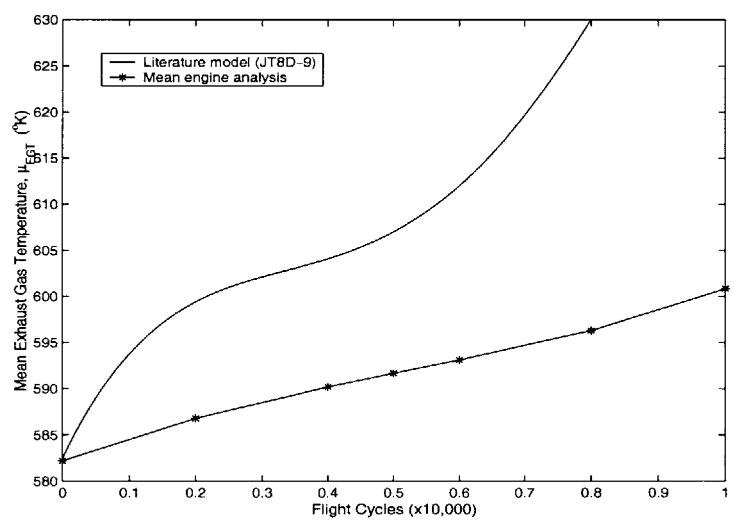

Figure 2-5: EGT mean engine analysis results

While multiple factors contributed to the errors in TSFC and EGT, the unavailability of component performance maps, typically proprietary items, was thought to be the lead determinant [10]. The component maps used in this thesis are the generic maps provided with GASTURB. GASTURB ensures that each component's design point is accurately defined in their respective maps by imposing scaling factors on the parameters that define this point in the generic maps. This correlates the component's design point with the reference design point in the map. Due to the map geometry, however, the components may not be reliably represented by their respective maps away from this nominal point. The GASTURB maps representing the undeteriorated components are reproduced on the following pages in Figures 2-6 to 2-10. The square in the maps on speed line 1 identifies the production run (time-zero) design-point performance of the component.

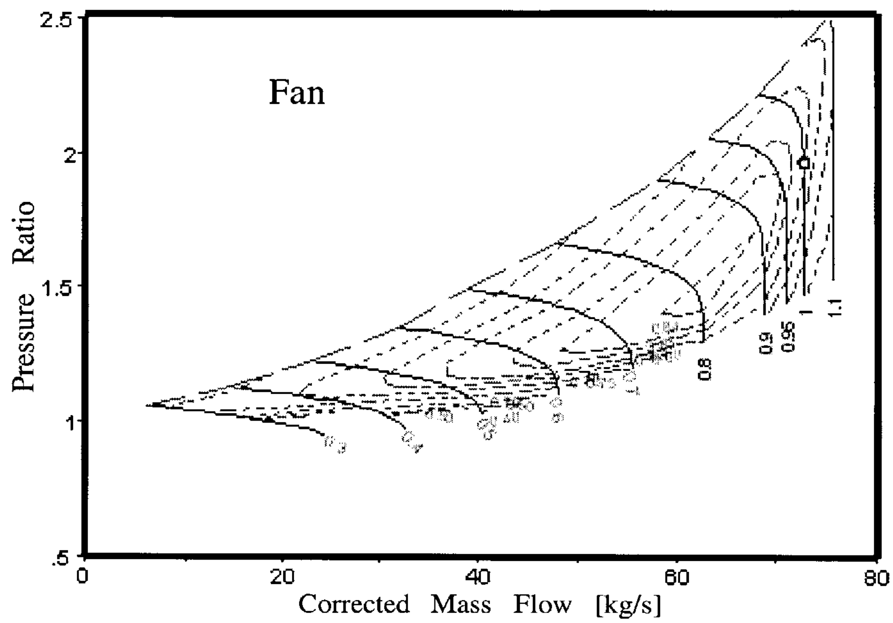

Figure 2-6: Fan performance map

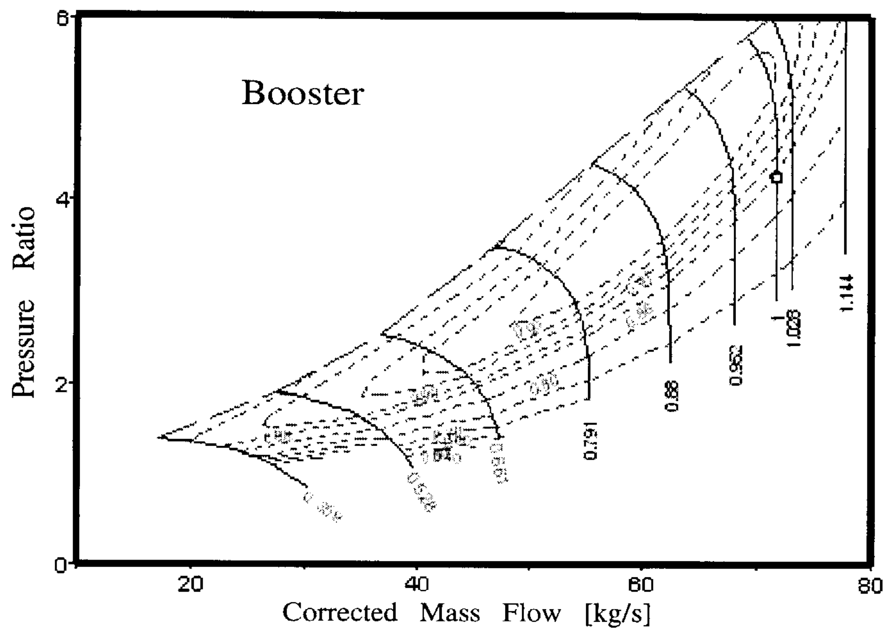

Figure 2-7: Booster performance map

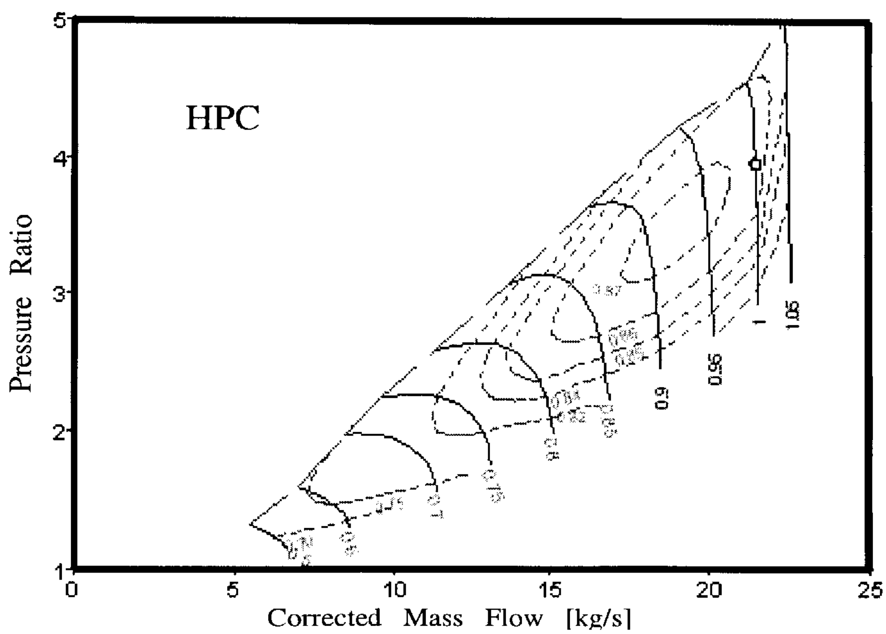

Figure 2-8: HPC performance map

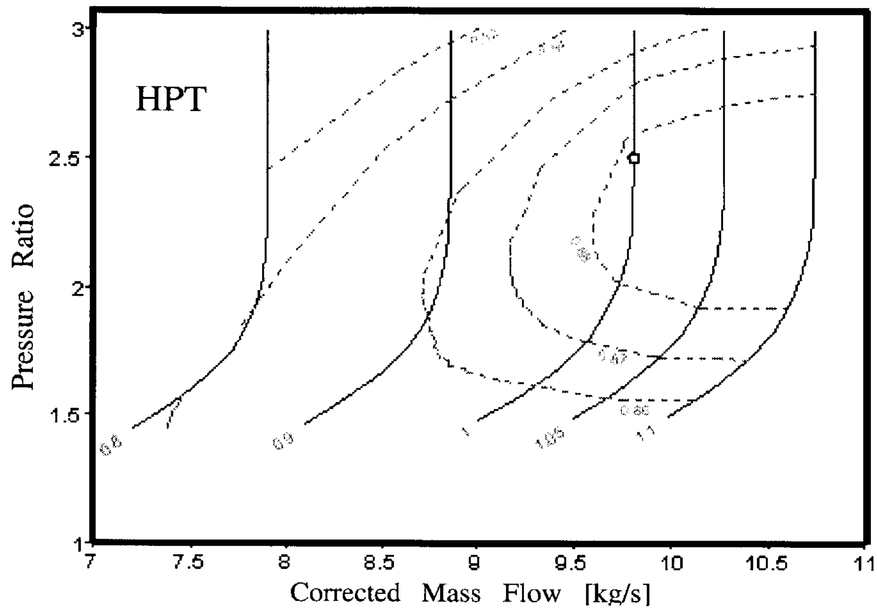

Figure 2-9: HPT performance map

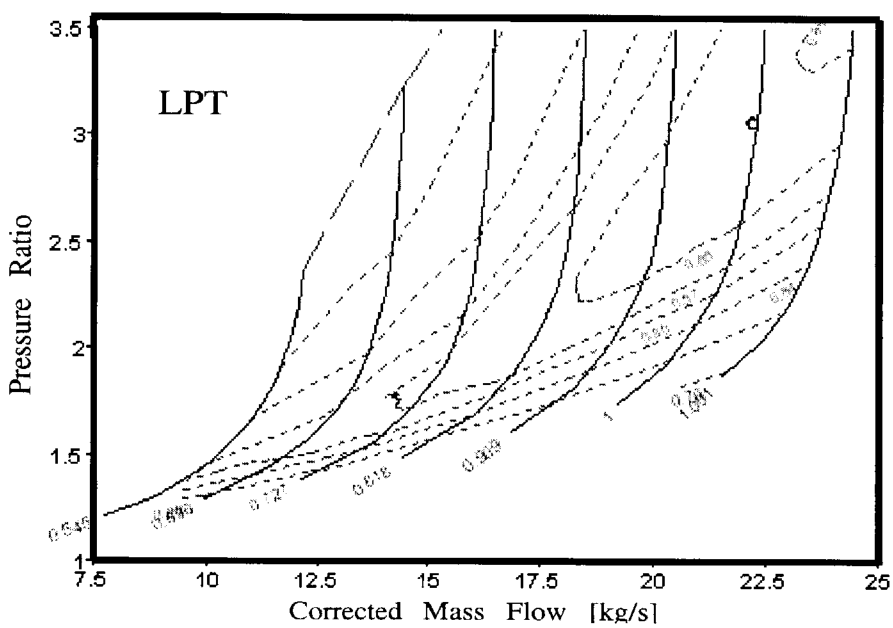

Figure 2-10: LPT performance map

Maps are essential in assessing the performance of components away from their design points and without them one can merely speculate as to the true performance of the respective component under off-design conditions. Various attempts were made at improving the simulated results including using different combinations of the various maps available with the software, performing sensitivity analyses of the dependent variables based on differing control knobs in GASTURB and even perturbing the map shape around the performance point by rotating the speed lines and shifting the efficiency contours [11]. The latter had an appreciable impact on the results, but the magnitude and type of shape perturbation proved difficult to control.

On-Design Comparison

An on-design analysis of the mean engine was conducted for comparison to the results of the off-design study. During this process the mean engine inlet mass flow was held constant with flight cycles while the subcomponent mean efficiencies were progressively decreased in accordance with their respective functions derived in Section 2.3. Constant production run mean thrust was maintained with increasing degradation by iteratively increasing the combustor exit temperature at the selected time-points.

The trends of mean TSFC and EGT obtained in both the off-design and on-design scenarios are compared to the literature mean model in Figures 2-11 and 2-12 respectively. The plots demonstrate that the results from the off-design matching process are more satisfactory when compared to the public literature data.

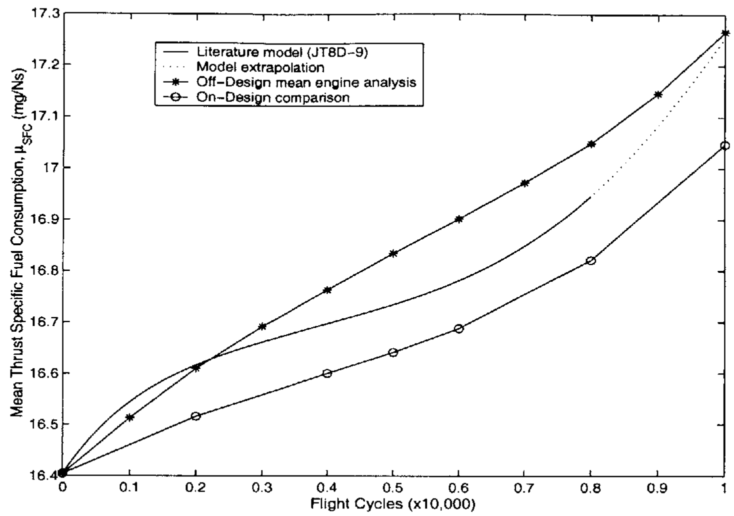

Figure 2-11: TSFC Off-design and On-Design comparison

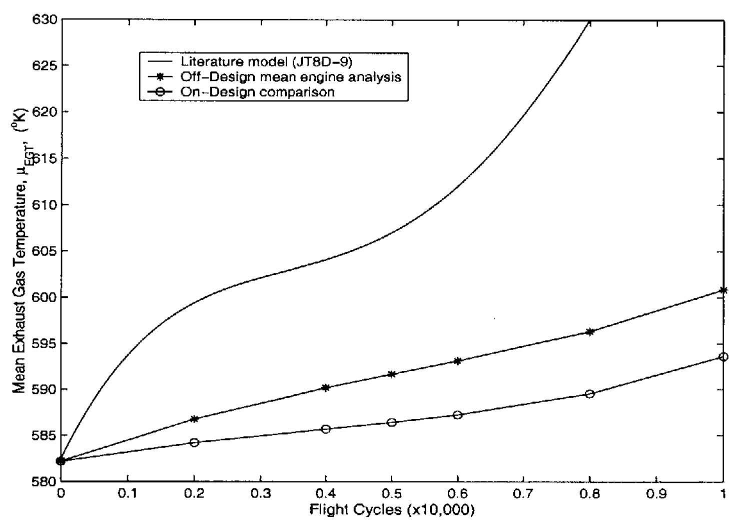

Figure 2-12: EGT Off-design and On-Design comparison

2.5 Chapter Summary and Conclusions

The JT8D-9 aircraft engine was introduced in this chapter as the exemplary engine model to be utilized throughout this study. Appropriately, its aerothermodynamic performance cycle was established with information from several public literature sources with the use of GASTURB. Mean models defining the performance of the selected engine type were then constructed from public data and used to assess the engine's performance. These models will also serve the purpose of conducting a probabilistic analysis of the engine in **Chapter 3**. The relatively poor simulated mean performance results as compared to the literature data was attributed to the unavailability of component performance maps and the consequent need to use the generic software maps. Given the use of these maps however, it was evident that the off-design approach was a more appropriate assessment of the engine's performance than was the on-design analysis.

Chapter 3

Probabilistic Analysis of Engine Performance

3.1 Introduction

The goals of this chapter are the derivation of component performance variability models and a probabilistic assessment of fleet engine performance. Public literature scatter-plot data is utilized in deriving a variability model for the dependent parameter, TSFC. Variability models for the component performance parameters, the independent parameters, are formulated by assuming that their variabilities are correlated with their respective mean rates of degradation. The probabilistic results are then compared to the previous mean results and the public literature data.

3.2 Quantification of Performance Variability

3.2.1 Variability of Thrust Specific Fuel Consumption

In this section, we derive a model for the standard deviation of thrust specific fuel consumption versus time using a regression analysis [13]. A time-line scatter plot of several models of the JT8D (-1, -7, -9, -15 & -17) series provide a recourse to establishing this function. The use of this scattered data is solely in establishing a standard by which variability may be introduced into the study as no other information on parameter variability is presented in the literature.

In quantifying variability from the scatter-plot, a moving window approach was employed with a fixed window size of 1000 cycles propagated in increments of 450 cycles. A best fit (exponential) function was then generated for each of the probabilistic moments. The window size of 1000 cycles was selected by minimizing the difference between the resulting mean and a least squares fit to all of the TSFC data. Intervals with less than three occurrences were not considered in the derivation. The fitting process resulted in the following model for standard deviation in TSFC with flight cycles, equivalent to GAG (ground-air-ground) cycles and is depicted in Figure 3-1;

$$\sigma_{TSFC} = 0.0803 - 0.0283e^{-t} + 0.4933te^{-t} \tag{3.1}$$

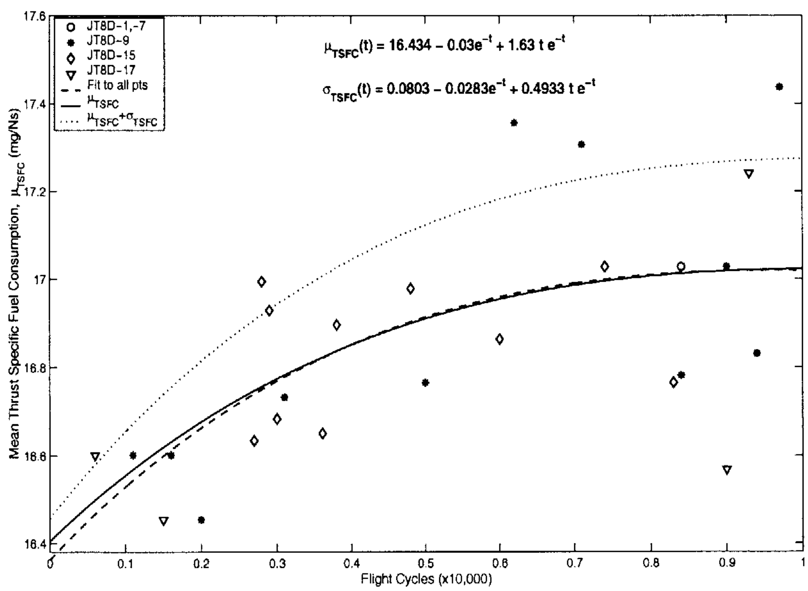

Figure 3-1: Quantification of performance variability

It is noted that the mean function generated from this approach does not conform well with that presented in the Pratt & Whitney study [1]. Appositely, this function is not employed directly in this study, but serves only in the minimization implementation above used to generate the variability model. However, it should also be noted that the model from the Pratt & Whitney study belies the typical trend as can be confirmed elsewhere in the same reference and from [14–17] and that in fact the above generated mean is consistent with the preponderance.

3.2.2 Variability of Subcomponent Performance Parameters

Having established parametric mean functions, we next developed a model for the variability of these parameters. As data on the variability of the components' operating characteristics were also not available, the sensitivity of the dependent variable (TSFC) to the changes in the individual independent parameters was capitalized on in deriving variability models. GASTURB permits imposing variability on the corrected mass flow (as opposed to flow capacity) of turbine components and efficiencies of all components. Appositely, Equation 3.2 was utilized in attributing variability to efficiencies of the fan (bypass only), booster, HPC, HPT and the LPT and corrected mass flow for the HPT and the LPT. The general expression devised to capture the sensitivity of the dependent parameter to the changes in the independents is

$$\sigma_\beta(t) = p\left[\frac{TSFC(\mu_\beta(t))}{TSFC_0} - 1\right]\mu_\beta(0), \tag{3.2}$$

where, β =component's efficiency or corrected mass flow and p = scaling factor.

In implementing Equation 3.2, at a specific time-point, say 2,000 cycles, a deterministic GASTURB matching cycle analysis was conducted for a specific parameter, say booster efficiency, η_B, employing the deteriorated mean value for that parameter as the only source of degradation. The quotient of the resulting TSFC value and the time-zero TSFC value was then noted. The difference between this quotient and unity was multiplied by the time-zero value of the deteriorated parameter, in this case the booster efficiency. All other parameters were likewise treated at this particular time-point and the same approach applied to all parameters at other time-points of interest. This provided relative *magnitudes* of the variabilities of the parameters as opposed to their actual values which are determined in a GASTURB probabilistic analysis.

For the probabilistic analysis, a GASTURB Monte Carlo [18, 19] simulation with a fixed population size of 3000 engines was conducted at selected time-points. Each Monte Carlo process was performed at off-design and constrained by the limiter of constant production run static sea level take-off thrust. The independent parameters were assumed to be normally distributed and their relative magnitudes of variability obtained from Equation 3.2 employed in the probabilistic analysis. At the selected time-points, these magnitudes were iteratively scaled for each Monte Carlo run until the variability of the dependent parameter, TSFC, was consistent with the value obtained from its earlier derived function, Equation 3.1 (Section 3.2.1). The corresponding input variabilities were at this point accepted as the actual independent parameter standard deviations. Figure 3-2 indicates the standard deviations of the independent parameters derived from the foregoing implementation. The standard deviation of the dependent parameter, TSFC, is also plotted for comparison. The

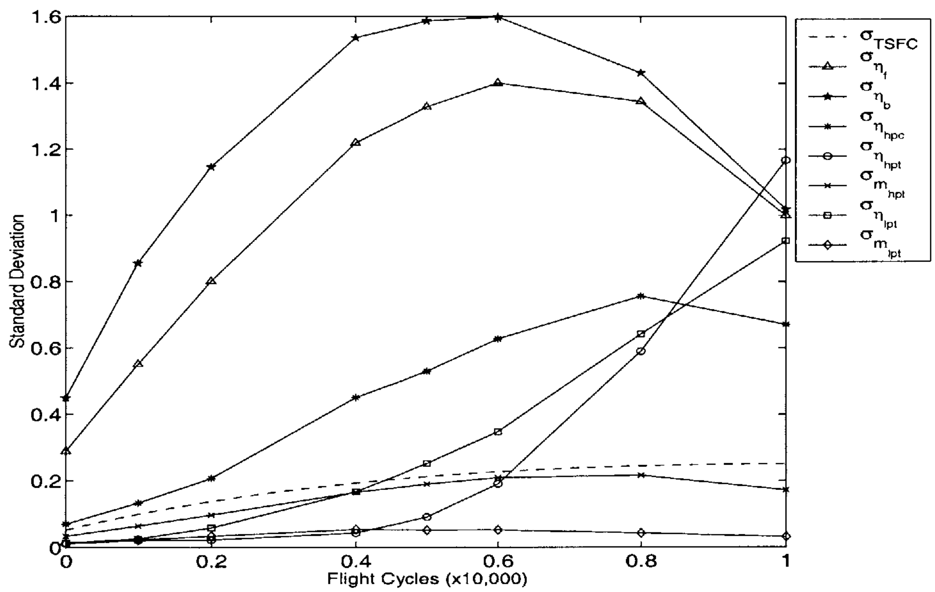

Figure 3-2: Standard deviations of parameters

trends displayed by the plots of subcomponent parameter standard deviations are directly consequential to the employed function, Equation 3.2. Based on this function, the magnitude of a parameter's variability is controlled by the parameters initial value and its impact on TSFC. TSFC is inherently more sensitive to perturbations on the efficiencies of low pressure components (fan, LPC, booster) and in this case more so the booster (than the fan) because of its higher pressure rise. This explains the greater values of variability for the booster and the fan during the initial flight cycles. The standard deviation of TSFC asymptotes while its response due to increased subcomponent degradation increases resulting in a decrease in the magnitude of the scaling parameter, p, with increasing flight cycles. As a result, the rate of change (degradation rate) of a subcomponent's parameter thus becomes the governing factor in the magnitude of its variability as derived from Equation 3.2. Thus parameters with higher rates of change will gradually dominate the overall input variabilities (since 'p' is the same for all parameters) necessitating reduction in the variabilities of those parameters with lower rates of change. This explains the continual increase in the variability of the turbine subcomponents efficiencies and may be confirmed from Figures 2-2 and 2-3; as most of the subcomponents parameters are tapering off, the efficiencies of the turbine subcomponents are increasing. The induced variability in EGT is presented later with the probabilistic results in Figure 3-4.

3.3 Probabilistic Engine Performance Analysis

When the variability of the sampled TSFC in the iterative Monte Carlo process of Section 3.2.2 matched the value as specified by the defining function (Equation 3.1), EGT was also sampled at the particular time point. This provided the opportunity of comparing our probabilistic results to those of the Pratt & Whitney study [1]. The results for TSFC are presented in Figure 3-3 along with the mean engine results from Section 2.4, the literature mean model and bounding plots of the induced variability. Figure 3-4 conveys similar information for EGT.

Both plots show the mean shift from the deterministic output due to the introduction of variability and indicate that a greater portion of the change in either TSFC or EGT is attributable to the actual mean component degradation as opposed to the introduction of variability.

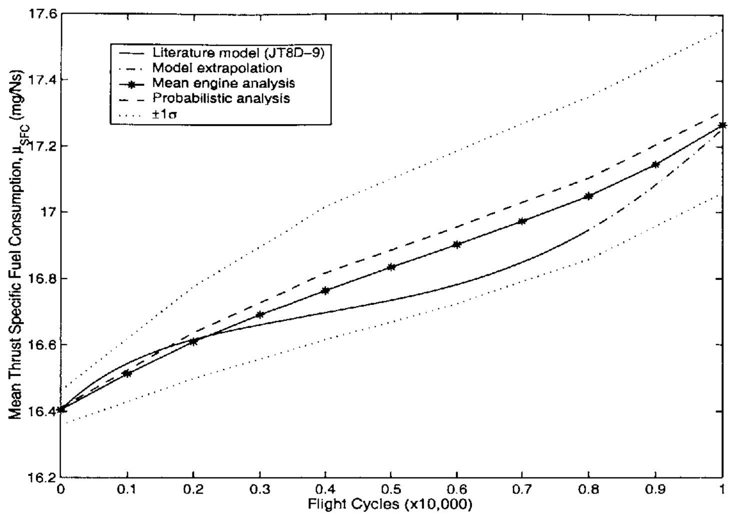

Figure 3-3: TSFC probabilistic matching results

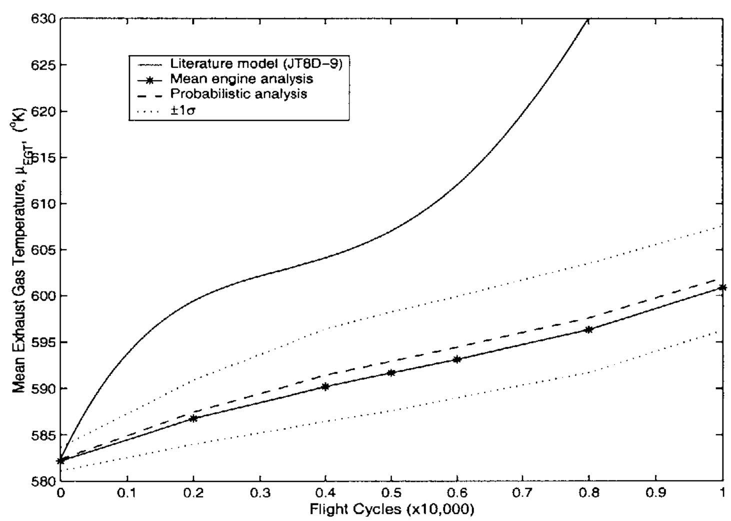

Figure 3-4: EGT probabilistic matching results

3.4 Chapter Summary and Conclusions

In this chapter we studied the probabilistic performance of a nominal fleet of engines. To facilitate this we derived variability models for the response variable, TSFC, and for the component performance variables. For the former we employed public literature scatter-plot data while for the latter me made an assumption of dependence of component variability on degradation rate. Results of the probabilistic engine performance analysis were compared to the mean engine performance and the literature data.

Chapter 4

Impact of Parametric Aerothermal Variability

4.1 Introduction

The matching results to public literature information on the selected engine model obtained with the probabilistic moments for the nominal case, were sufficiently satisfactory to justify the formulation of a study to assert the economic significance of parametric aerothermal variability. The standard deviations of the independent parameters were perturbed by $\pm 30\%$ of their original values at each time point over the life of the fleet and new GASTURB Monte Carlo simulations conducted with these perturbed standard deviations. The distribution type and the population size remained the same as in the previous cases in Sections 3.2.2 and 3.3. The resulting distributions of thrust specific fuel consumption and exhaust gas temperature were then utilized in conducting a reliability study and an economic analysis to assess the economic impact of the perturbations on variability. For the three individual cases (nominal, plus and minus), the mean component performance was left unchanged.

4.2 Overhaul Criteria

Degradation of engine performance (due to individual component deterioration) warrants the rematching of the components [20] at a performance point that restores engine pressure ratio, EPR, to its initial value, thus regaining required thrust. To regain this lost performance involves the addition of thermal energy to the combustor (burner) by increasing fuel flow, this increases turbine inlet temperature (consequently EGT), power generated by the turbine section, and shaft rotational speed of the respective spool [21]. Compressor pressure ratio increases due to the increased shaft speed that generates greater massflow and as a result EPR is increased. As the engine progressively degrades, subsequent turbine (and combustor) section thermal tolerance limits will be realized due to this rematching process. At this point it becomes unsafe to attempt to regain thrust through increased fuel flow to the combustor due to fear of hot-section failure.

Temperatures of internal hot-section components are not typically measured directly, instead, the exhaust gas temperature, EGT, at the engine nozzle is measured and, if necessary, internal temperatures inferred from analytic relations of the parameters and the known engine architecture. The measured EGT may thus be used, and frequently is, in determining if the engine needs to be removed for refurbishing to facilitate increased hot-section temperature margins. From the open literature [21–23], an overhaul condition is roughly implied by an increase in EGT (for reasons of safety) between 30-50 K (^{0}C) and/or an increase in TSFC (for economic reasons) of between 2-4%. Based on these implications, therefore, we have opted to observe a rise of 3% in TSFC and/or 30 K in EGT as a reasonable degradation limit for investigating the impact of performance variability. Thus, in our study, maintenance is performed on a particular engine when that engine's TSFC (and/or respectively, EGT) meets or exceeds the value equivalent to a 3% (respectively, 30 K) increase in the production run population (fleet) mean (of the respective parameter). This choice of corresponding EGT is consistent with the apparent practice at Pratt & Whitney where a trade factor of 1% TSFC to 10^{0}C(K) is typically employed [14]. We found in our study however, that the 3% increase in TSFC consistently predominated over the 30 K increase in EGT.

4.3 Data-Based Results

To assert the impact of parametric aerothermal variability on paramount issues especially to airline operators, metrics of direct operating cost (fuel consumption and maintenance cost) and fleet maintenance reliability were deemed most appropriate.

4.3.1 Maintenance Reliability Impact

Fleet maintenance reliability analyses were performed for three cases, the nominal, 30% increased variability and 30% reduced variability, employing the populations of engines generated from the respective GASTURB Monte Carlo simulations conducted in Section 4.1. Maintenance reliability here is defined as the probability of achieving a specified life (number of flight cycles) without requiring overhaul [24] and represents the total (as opposed to the instantaneous) probability of success. The numerical value was computed at a particular time-point as the quotient of the present number of engines *not* meeting the overhaul criteria and the total number of engines in the fleet. The results of the analysis of fleet maintenance reliability for varied degrees of variability are presented in Figure 4-1 and displays a particular area of interest where the reliabilities nearly coincide at about 5,500 cycles. This is a direct consequence of maintaining the same mean component performance for each fleet analysis. Figure 4-2, in which engines to the right of the marker, 'C', have met (or exceeded) the overhaul criteria, helps to explain the reason behind the crossing of the plots. At a relatively early point in flight cycles, the fleet with largest variability (greatest spread) will have the most engines meeting the overhaul criteria while the fleet with smallest variability will have the least. This results in greatest reliability for the fleet of smallest variability and conversely least reliability for that fleet with greatest variability. The assumption of constant mean of independent parameters (across fleets) dictates that the mean of the dependent parameters (across fleets) will be similar though not identical because

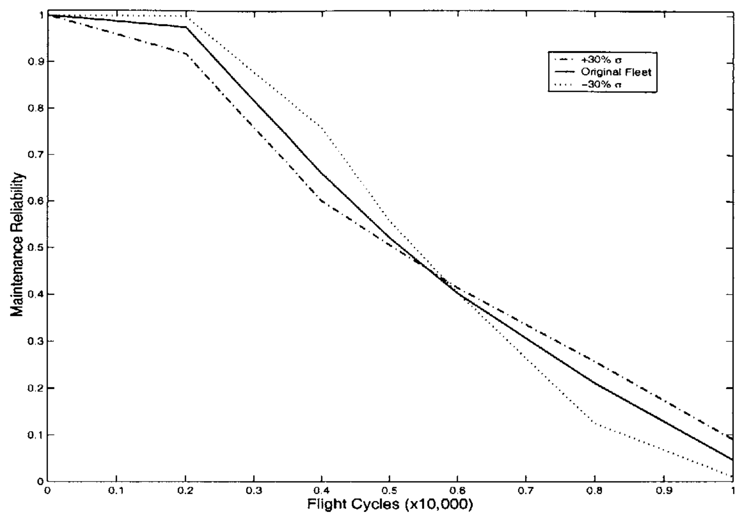

Figure 4-1: Fleet maintenance reliability

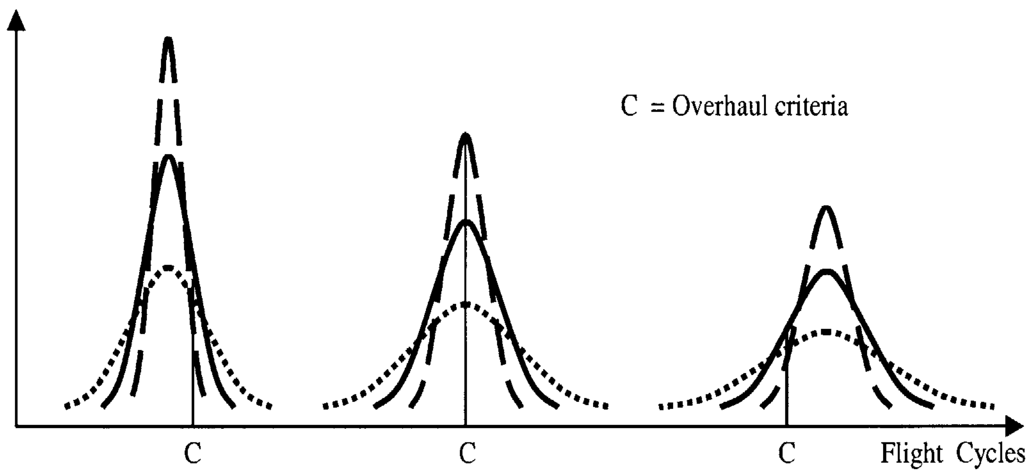

Figure 4-2: Effect of the constant mean assumption

of non-linearity and probabilistic second moment effects in the relation between the dependent parameters, i.e. the overhaul criteria, and the independent parameters. The fleet with largest variability will experience greatest mean-shift and thus its mean engine will meet the overhaul condition earliest. Within some region, the means of the dependent parameters across fleets coincide with the overhaul criteria and the plots cross. Beyond this time, the opposite trend occurs and the fleet with smallest variability possesses the most engines requiring overhaul.

4.3.2 Economic Impact

To assess the economic impact of aerothermal variation, a model aircraft employing these engines, the out-of-production Boeing 737-100, was selected. A typical class-2 configuration was assumed permitting 99 passengers full capacity with a maximum range of 2,160 statute miles (3,440 km) at an average cruise speed of 575 mph [25]. The JT8D engine series is used in the short to medium range of the industry where typical aircraft GAG (ground-air-ground) cycle times vary between 20 minutes and 2 hours with the industry average being just over an hour, considerably shorter than the typical long range aircraft which run anywhere from four to seven hours per cycle [1]. In accordance with this information, and given the range and speed of the 737, an average flight cycle time of 1.5 hours was selected for this study. Based on the selected flight duration, an average ticket cost per passenger per engine per cycle of $100 was assumed in computing generated revenues. The fuel price used ($0.70 per gallon) was a preliminary value published by the Bureau of Transportation Statistics for the month of May 2002 for scheduled domestic airline services [26]. It is worth noting here that static sea level take-off fuel consumption rates were employed in the economic analysis as opposed to cruise values. An overhaul cost of $1.2 mil per engine was used in the computations and assumed from [22, 29] in collaboration with financial data obtained from the Bureau of Transportation Statistics' *Form 41 Schedule P–5.2* financial database [29]. The BTS *Form 41 Schedule P–5.2* financial database provides quarterly reported airline operators' expenses for all categories of operating expenses. A Delta Airlines Inc. domestic route utilizing the 737-100/200 was selected and the total expenses incurred per engine computed from the available information.

On meeting the maintenance criteria, engines were no longer considered in the computations of fuel costs nor generated revenue. This is because engines 'removed' for maintenance servicing were not reintroduced into the study because of a lack of an appropriate re-introduction model. This does not compromise the probabilistic properties of the fleet at any point in the analysis however, since at each time-point of interest the original GASTURB Monte Carlo populations are employed in determining the number of engines to be 'removed'. This measure only impacts the revenue generating capabilities and the cost expenses of operating the fleets causing an equal decrease in revenue generating and expense potential.

Revenues generated from the operation of individual fleets were calculated with a trapezoidal approximation [30] employing the time-line of GASTURB Monte Carlo populations for each individual case of fleet variability. Total direct operating expenses were then computed based on fuel consumption and total maintenance cost. Profits were taken simply as the difference between generated revenues and total direct operating costs. No other cost factors (administrative, executive, cancellations, etc.) or other income sources (interest, etc.) were considered in the study. Also, during the economic analysis, no accommodations were made for inflation or other socio-economic indicators, thus, fuel prices, maintenance/overhaul costs and generated cyclic revenue were considered constant over the life of the fleet. The generated

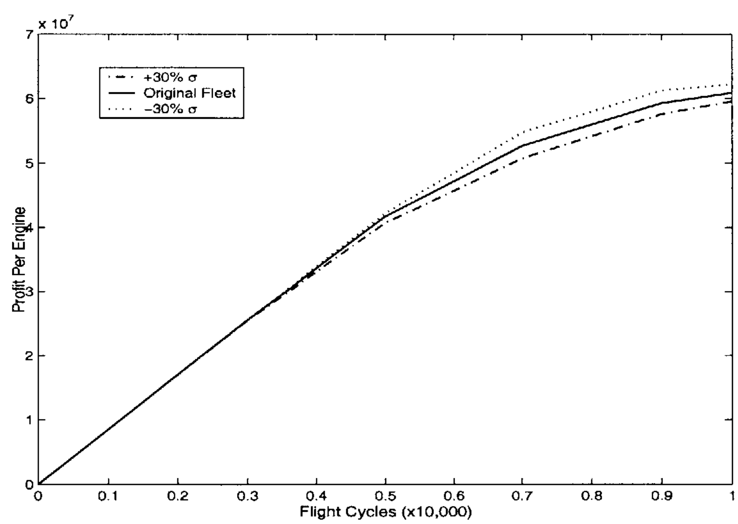

Figure 4-3: Fleet generated profits

profits (respectively, incurred cost) per engine are depicted in Figure 4-3 (respectively, Figure 4-4) and implies that reduced fleet performance variability generates greater profits while incurring greater operating expenses. The incremental profits generated

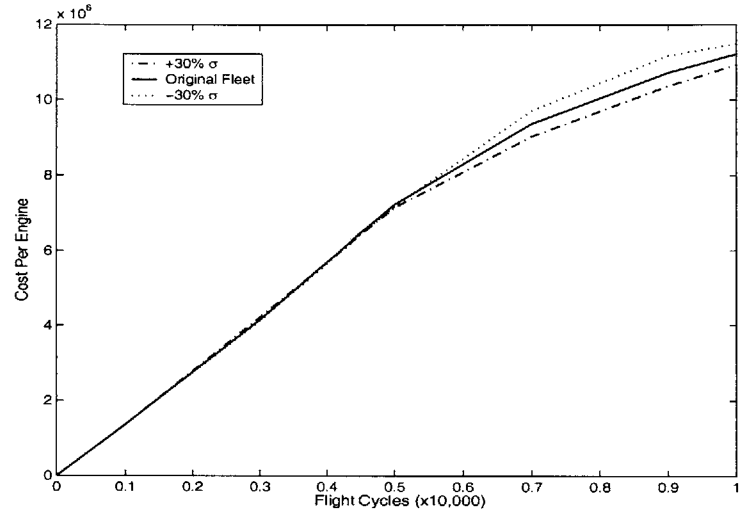

Figure 4-4: Fleet operating cost

per engine for the individual fleets are presented in Figure 4-5.The results presented are normalized per engine of the fleet size as opposed to per operating engine.

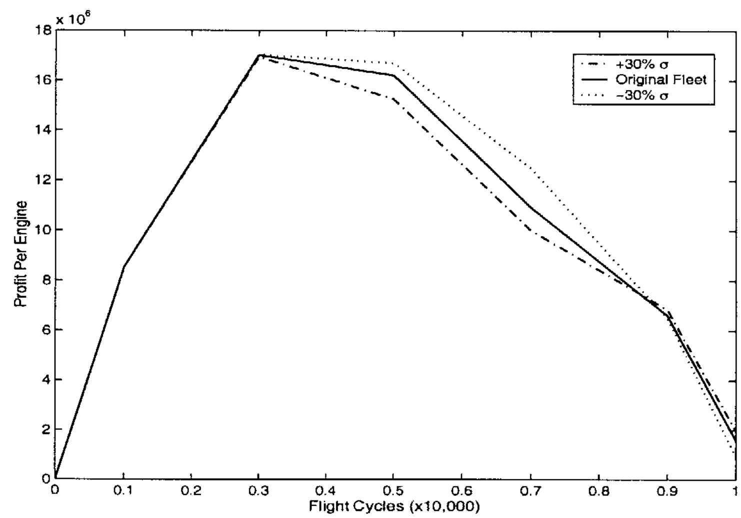

Figure 4-5: Incremental profits per engine

4.4 Chapter Summary and Conclusions

The impact of component parameter aerothermal variability was assessed and determined in this chapter. Overhaul criteria based on dependent parameter performance were established early in the chapter and utilized in determining time for maintenance. A comparative probabilistic analysis quantified the impact on fleet maintenance reliability and the economics of engine operation due to changes in component parameter variability. Decreased component parameter variability demonstrated greater maintenance reliability for the initial 5,500 flight cycles, after which the fleet with increased variability demonstrated greater reliability. As explained above, these reliability trends were consequential to maintaining the same mean component performance. During the economic analysis, reduced component parameter variability displayed greater generated profits with increased operating expenses.

Chapter 5

Conclusion

5.1 Summary and conclusions

5.1.1 Summary

The primary objective of this thesis was to model and assess the impact of aircraft engine component aerothermal variability on direct engine operating cost. The motivation for this work was the desire to comprehend the potential benefits of producing engines with lower performance variability.

To initiate the study, the JT8D-9 model engine was selected and through the use of a gas turbine cycle analysis software, GASTURB, and various open literature sources, a production run thermodynamic parametric cycle-deck was established for the selected engine model. Mean subcomponent performance models were generated from open literature degradation data for this particular engine. These models were then utilized in conducting a mean engine matching performance analysis and the results compared to those available in the literature. To compare to the off-design matching analysis, a constant thrust design-point mean engine performance analysis was also performed employing the mean subcomponent performance models.

Standard deviation models for the dependent parameter, TSFC, and the component performance parameters were then derived. The variability model for TSFC was constructed from a time-line scatterplot of several models of the JT8D engine series also presented in the open literature [1]. Standard deviation models for the subcomponent performance parameters were derived in an iterative probabilistic off-design matching analysis from the variability model of TSFC by assuming a correlation between known component mean performance degradation and its variability. The subcomponent mean and variability models were then employed in a GASTURB probabilistic engine performance analysis and the results compared to the public source model as well as the results from the mean engine performance analysis.

To appraise the impact of parameter aerothermal variation on fleet maintenance reliability and operating economics, specific overhaul criteria were established based on dependent performance parameters, TSFC and EGT. By varying the magnitude of the variability in the independent parameters, a comparative probabilistic analysis was then conducted to quantify the impact on maintenance reliability and economics of operation.

5.1.2 Conclusions

For the mean engine analysis of **Chapter 2**, we concluded that the generic component performance maps provided with the GASTURB software is most likely the leading determinant in the relatively poor results that were obtained when compared to the literature models. Given the use of these maps, however, the study demonstrated that the off-design constant-thrust matching analysis more accurately portrayed the performance of the mean engine in the fleet when compared to the public literature models than does the design-point approach. This result affirmed the use of the off-design approach to investigate the impact of parameter performance variability.

Preliminary studies determined that based on the constraints imposed in the modeling process (overhaul criteria pertinent to TSFC and EGT) and the assumptions employed, in particular the constant mean across fleets and distribution type of independent parameters, total fuel consumption cost is not very sensitive to the magnitude of variability of the independent parameters. Due to the symmetry of the Gaussian distribution, for each engine with high fuel burn, an equal probability exists for an exact opposing engine of low fuel burn, independent of the magnitude of standard deviation of the distribution. Thus, where operators incur higher fuel costs for relatively high fuel burning engines to the far right of the distribution, they receive greater savings from lower fuel burning ones to the far left. As a result, the significance of the distribution spread relative to fuel costs for this distribution type is negated and only the mean becomes important. Because the imposed variability on the independent parameters did not merit large mean-shifts of the dependents, the latter all had comparable mean values across fleets and thus comparable total fuel consumption costs. Under the above assumptions, the variability of the independents would have to be sufficiently large to warrant an appreciable mean-shift in the dependent parameters for it to be considered an important factor in fuel consumption cost. However, the engine-to-engine variation in performance proved to be of economic significance in maintenance. This point was reflected in both the reliability and the economic analysis. Reduced fleet performance variability demonstrated higher degrees of reliability during the first 6,000-7,000 cycles of operation until the mean engine of the fleet required removal for servicing. At that point the opposite trend occurred and the fleet with highest variability displayed greatest reliability for the remaining 3,000-4,000 cycles of operation as a consequence of having more engines remaining in the fleet. This phenomenon is again consequential to the assumptions of distribution type and the constant mean of independent parameters across fleets. The fleet with largest variability demonstrated lowest reliability in the earlier stages of operation because engines at the far right tail of the distribution, with their higher fuel consumption rates, required servicing earliest.

5.2 Future Work

This current work may be considered an initial phase in the process of quantifying the impact of aerothermal performance variability on fleet operating economics. Significant room for improvements and advances in this particular area exists and should be exploited. Opportunities for improvement or advancement of this work reside in the following areas:

- An appropriate refurbished engine degradation profile would facilitate the re-introduction of engines into the economic analysis after overhaul, thus giving the study more applicability to industry practices.

- An advancement in the research would be to perform an analysis of dependent parameter (TSFC) sensitivity to variability of individual subcomponent performance parameters. The results of this study would help to determine which component has the greatest impact on engine performance variability thus directing manufacturers in determining the parameter on which greatest emphasis (financial commitment) should be placed in reducing performance variability.

- Historical data providing more accurate definitions of subcomponent performance variability and distribution type as functions of time, would establish a more solid foundation from which the probabilistic analyses may expand.

- The impact due to perturbations on component performance map geometry as described in Section 2.4, underscored the importance of employing maps that correctly define the performance of their respective components. Anent this, improvements in this study necessitate the acquisition of appropriate component maps to provide a more accurate assessment of engine performance.

- In addition to the maintenance criteria employed in this study, airline operators may have additional criteria that seek to minimize risks and operating costs while maximizing time-on-wing. Factors such as oil usage and/or leakage, part or component failure, surging or other problematic symptoms may need to be modeled to ensure the study is as close to industry practices as is possible.

- A reliability optimization and operating cost minimization relative to subcomponent aerothermal performance variability may be conducted to reduce expenses while increasing generated revenue.

Appendix A

International Civil Aviation Organization (ICAO) Engine Exhaust Emissions Data Bank

The International Civil Aviation Organization (ICAO) aircraft engine exhaust emissions data bank is an electronic resource of performance characteristics and associated exhaust emissions for operating aircraft engines. This database contains information on exhaust emissions of only those engines that have entered production, irrespective of the numbers actually produced. It has been compiled mainly from information supplied, for certification compliance purposes, for newly manufactured engines. However, for some engines, it provides updated data, using information obtained from engines during further production. It also includes data on older engines which did not have to comply with the emissions Standards and some data from a very limited number of in-service engines measured before or after overhaul.

The information contained in this database was obtained from engine manufacturers and was collected in the course of the work carried out by the ICAO Committee on Aviation Environmental Protection (CAEP).

Note : D_p/F_{00} and SN values are NOT the characteristic levels

UNIQUE ID NUMBER	JT8D-9 Series
ENGINE IDENTIFICATION	1PW006
ENGINE TYPE	MTF

BY-PASS RATIO	1.04
PRESSURE RATIO	15.88
RATED OUTPUT(KN)	64.5

DATA TYPE

X PRE-REGULATION
- CERTIFICATION
- REVISED(SEE REMARKS)

DATA SOURCE

X NEWLY MANUFACTURED ENGINES
- IN-SERVICE ENGINES
  - BEFORE OVERHAUL
  - AFTER OVERHAUL
- DEDICATED TEST ENGINS TO PRODUCTION STANDARD

EMISSION DATA

- UNCORRECTED
X CORRECTED FOR AMBIENT EFFECTS

MODE	POWER SETTING (%F00)	THRUST (KN)	TIME (min.)	FUEL FLOW (Kg/s)	TSFC (mg/Ns)	EMISSIONS INDICES (g/Kg fuel)			SMOKE NUMBER
						HC	CO	NOx	
TAKE-OFF	100	64.5	0.7	1.04	16.12403	0.47	1.24	17.92	-
CLIB OUT	85	54.825	2.2	0.846	15.43092	0.47	1.66	14.21	-
APPROACH	30	19.35	4	0.298	15.40052	1.73	9.43	5.64	-
IDLE	7	4.515	26	0.132	29.23588	10	34.5	2.9	-
NUMBER OF TESTS						14	14	14	14
NUMBER OF ENGINES						13	13	14	14
D_p/F_{00} (AVERAGE) (g/KN) OR SN (MAX)						35	124.3	52.3	23
D_p/F_{00} (g/KN) OR SN (SIGMA)						8.4	11.2	5.7	2
D_p/F_{00} (g/KN) OR SN RANGE						-	-	-	-

ACCESSORY LOAD

POWER EXTRACTION 0 (KW) AT POWER SETTINGS(S)
STAGE BLEED 0 % OF CORE FLOW AT POWER SETTING

ATMOSPHERIC CONDITIONS

PRESSURE	Kpa	100~102
TEMPERATURE	^{0}C	-11 to 27
ABS HUMIDITY	Kg/Kg	0.0005~0.0123

FUEL

SPEC	H/C	AROM(%)
Jet A	1.89	-

MANUFACTURER Pratt & Whitney
TESTS ORGANIZATION P&WA
TEST LOCATION E Hartford, CT, USA
TEST DATES FROM Apr 76 TO Mar 77

REMARKS
1. Smoke fix combustor in production prior to 1/1/84
2 . Applicable to JT8D-9, -9A

Table A.1: Performance characteristics of the JT8D

A	B	C	D	E	F	G	H
Page Number	**Engine Identification**	**Combustor**	**UID No**	**Eng Type**	**B/P Ratio**	**Press Ratio**	**Rated Output, kN**
	Pratt & Whitney Aircraft Group						
C071	JT8D-11		1PW008	MTF	1.00	17.17	66.72
C073	JT8D-15	Red. emiss	1PW010	MTF	1.03	16.81	68.94
C072	JT8D-15	Smoke fix	1PW009	MTF	1.03	16.81	68.94
C074	JT8D-15A		1PW011	MTF	1.08	16.45	68.94
C076	JT8D-17	Red. emiss	1PW013	MTF	1.02	17.01	71.17
C075	JT8D-17	Smoke fix	1PW012	MTF	1.01	17.01	71.17
C077	JT8D-17A		1PW014	MTF	1.05	16.87	71.17
C078	JT8D-17AR		1PW015	MTF	0.96	17.28	77.42
C079	JT8D-17R		1PW016	MTF	0.97	18.24	77.42
C080	JT8D-209		1PW017	MTF	1.80	18.30	85.60
	JT8D-217	E-Kit	4PW068	MTF	1.73	19.66	92.74
C081	JT8D-217 series		1PW018	MTF	1.73	19.66	92.74
	JT8D-217A	E-Kit	4PW069	MTF	1.73	19.66	92.74
	JT8D-217C	E-Kit	4PW070	MTF	1.70	19.05	92.74
	JT8D-219	E-Kit	4PW071	MTF	1.70	20.27	96.52
C082	JT8D-219		1PW019	MTF	1.70	20.27	96.52
C068	JT8D-7 series	Red. emiss	1PW005	MTF	1.05	15.82	62.27
C067	JT8D-7 series	Smoke fix	1PW004	MTF	1.05	15.82	62.27
C070	**JT8D-9 series**	**Red. emiss**	**1PW007**	**MTF**	**1.04**	**15.88**	**64.5**
C069	**JT8D-9 series**	**Smoke fix**	**1PW006**	**MTF**	**1.04**	**15.88**	**64.5**

I	J	K	L	M	N	O	P	Q	R	S
Engine	**--Data Type--**			**----Data Source------**					**Emiss Data**	
Identification	**PR**	**C**	**R**	**NME**	**ISE**	**BO/H**	**AO/H**	**DTEPS**	**Uncorr**	**Corr**
JT8D-11	x	-	-	x	-	-	-	-	-	x
JT8D-15	-	x	-	-	-	-	-	x	-	x
JT8D-15	x	-	-	x	-	-	-	-	-	x
JT8D-15A	-	x	-	-	-	-	-	x	-	x
JT8D-17	-	x	-	-	-	-	-	x	-	x
JT8D-17	x	-	-	x	-	-	-	-	-	x
JT8D-17A	-	x	-	-	-	-	-	x	-	x
JT8D-17AR	-	x	-	-	-	-	-	x	-	x
JT8D-17R	-	x	-	-	-	-	-	x	-	x
JT8D-209	-	x	-	-	-	-	-	x	-	x
JT8D-217	-	x	-	-	-	-	-	x	-	x
JT8D-217 series	-	x	-	-	-	-	-	x	-	x
JT8D-217A	-	x	-	-	-	-	-	x	-	x
JT8D-217C	-	x	-	-	-	-	-	x	-	x
JT8D-219	-	x	-	-	-	-	-	x	-	x
JT8D-219	-	x	-	-	-	-	-	x	-	x
JT8D-7 series	-	x	-	-	-	-	-	x	-	x
JT8D-7 series	x	-	-	-	x	-	-	-	-	x
JT8D-9 series	**-**	**x**	**-**	**-**	**-**	**-**	**-**	**x**	**-**	**x**
JT8D-9 series	**x**	**-**	**-**	**x**	**-**	**-**	**-**	**-**	**-**	**x**

Table A.2: Type and source of the ICAO testing data for the JT8D

Table A.3: Fuel specifications for the JT8D

BL	BM	BN	BO	BP	BQ	BR	BS
Engine	**-----------Fuel-----------**			**-----------Fuel Flow-----------**			
Identification	**Spec**	**H/C**	**Arom**	**T/O**	**C/O**	**App**	**Idle**
		Ratio	**%**	**-------------kg/sec------------**			
JT8D-11	Jet A	-	-	1.121	0.9136	0.3339	0.1455
JT8D-15	Jet A	-	-	1.178	0.9450	0.3402	0.1477
JT8D-15	Jet A	-	-	1.178	0.9450	0.3403	0.1477
JT8D-15A	Jet A	-	-	1.115	0.8955	0.3120	0.1372
JT8D-17	Jet A	-	-	1.245	0.9970	0.3540	0.1474
JT8D-17	Jet A	1.89	-	1.245	0.997	0.354	0.147
JT8D-17A	Jet A	-	-	1.173	0.9344	0.3304	0.1401
JT8D-17AR	Jet A	-	-	1.365	1.047	0.3574	0.1477
JT8D-17R	Jet A	-	-	1.417	1.103	0.3755	0.1550
JT8D-209	Jet A	-	19.2	1.191	0.9828	0.3592	0.1303
JT8D-217	Jet A	-	18	1.320	1.078	0.3833	0.1372
JT8D-217 series	Jet A	-	-	1.320	1.078	0.3833	0.1372
JT8D-217A	Jet A	-	18	1.320	1.078	0.3833	0.1372
JT8D-217C	Jet A	-	18	1.282	1.045	0.363	0.137
JT8D-219	Jet A	-	18	1.354	1.085	0.3817	0.1344
JT8D-219	Jet A	-	19.2	1.354	1.085	0.3817	0.1344
JT8D-7 series	Jet A	-	-	0.9892	0.8113	0.2861	0.1291
JT8D-7 series	Jet A	-	-	0.9892	0.8113	0.2861	0.1291
JT8D-9 series	**Jet A**	**-**	**-**	**1.040**	**0.8453**	**0.2977**	**0.1323**
JT8D-9 series	**Jet A**	**1.89**	**-**	**1.040**	**0.846**	**0.298**	**0.132**

BT	BU	BV	BW	BX	BY	BZ	CA
Engine	**--------------Loads-------------------------------Ambient--------------------**						
Identification	**Power Extraction**		**-Stage Bleed-**		**Baro**	**Temp**	**Humidity**
	kW	**@ Power**	**% CF**	**@ Power**	**kPa**	**K**	**kg/kg**
JT8D-11	0	-	0	-	-	262 - 300	-
JT8D-15	0	-	0	-	-	266 - 297	-
JT8D-15	0	-	0	-	-	269 - 302	-
JT8D-15A	0	-	0	-	-	266 - 297	-
JT8D-17	0	-	0	-	-	266 - 297	-
JT8D-17	0	-	0	-	-	269 - 303	0.0029-0.0093
JT8D-17A	0	-	0	-	-	266 - 297	-
JT8D-17AR	0	-	0	-	-	266 - 297	-
JT8D-17R	0	-	0	-	-	266 - 297	-
JT8D-209	0	-	0	-	-	275 - 288	-
JT8D-217	0	-	0	-	98.8-103.1	271 - 281	.0009 - .0047
JT8D-217 series	0	-	0	-	-	275 - 288	-
JT8D-217A	0	-	0	-	98.8-103.1	271 - 281	.0009 - .0047
JT8D-217C	0	-	0	-	98.8-103.1	271 - 281	.0009 - .0047
JT8D-219	0	-	0	-	98.8-103.1	271 - 281	.0009 - .0047
JT8D-219	0	-	0	-	-	275 - 288	-
JT8D-7 series	0	-	0	-	-	270 - 311	-
JT8D-7 series	0	-	0	-	100-102	262 - 300	0.0005-0.0123
JT8D-9 series	**0**	**-**	**0**	**-**	**-**	**270 - 311**	**-**
JT8D-9 series	**0**	**-**	**0**	**-**	**100-102**	**262- 300**	**0.0005-0.0123**

Table A.4: Loads (Power extraction and stage bleeding) and ambient conditions at testing for the JT8D

Definitions and Explanations		
Column	**Heading**	**Full Description if different from heading**
A	Page Number	Refers to the page number in the data bank text
B	Engine Identification	
C	Combustor	Type of combustor where more than one type available on an engine
D	UID No	Unique Identification Number
E	Eng Type	Engine type. TF = turbofan, MTF = mixed turbofan
F	B/P ratio	Bypass ratio
G	Press ratio	Engine pressure ratio
H	Rated Output, kN	Engine maximum rated thrust, in kilonewtons
I	Engine Identification	
J	Data type - PR	Data generated prior to regulations being applied
K	Data Type - C	Certification data
L	Data Type - R	Data revised by manufacturer after initial submission.
M	Data source - NME	Data from newly manufactured engines
N	Data Source - ISE	Data from in service engines
O	Data Source - BO/H	Data from in service engines before overhaul
P	Data Source - AO/H	Data from in service engines after overhaul
Q	Data Source - DTEPS	Data from dedicated test engines to production standards
R	Emissions data - uncorr	Emissions data uncorrected for ambient conditions.
S	Emissions data - corr	Emissions data corrected for ambient conditions.
BL	Engine Identification	
BM	Fuel Spec	Fuel specification
BN	Fuel H/C ratio	Ratio of hydrogen atoms to carbon atoms in the fuel
BO	Fuel Arom %	Percentage of aromatic hydrocarbons in the fuel
BP	Fuel flow T/O	Fuel flow (kg/sec) at take off condition
BQ	Fuel flow C/O	Fuel flow (kg/sec) at climb out condition
BR	Fuel flow App	Fuel flow (kg/sec) at approach condition
BS	Fuel Flow Idle	Fuel flow (kg/sec) at idle condition
BT	Engine Identification	
BU	Loads Power extraction kW	Load extracted during tests
BV	Loads Power extraction @ Pwr	Power setting at which load extracted
BW	Loads Stage bleeds - %CF	% core flow taken as stage bleeds
BX	Loads Stage bleeds @ power	Power setting at which stage bleeds taken
BY	Ambient Baro	
BZ	Ambient temp	
CA	Ambient Humidity	Ambient humidity in kg water per kg dry air

Table A.5: Definitions and explanations

Appendix B

Jet Fuel Price

Jet fuel prices reported to the Bureau of Transportation Statistics differ from producer prices. Reports to BTS show the cost per gallon of fuel used by an airline during the month rather than the price charged by a producer on a single day. Fuel costs for scheduled airline services reflect contractual and storage advantages available to large buyers, while fuel costs for nonscheduled airline services reflect economic conditions for smaller buyers. Jet fuel prices also reflect seasonality due to both the seasonality of aviation and because jet fuel has similar refining requirements to heating oil.

Figure B-1: Domestic Unit Prices For Airline Jet Fuel [26].
Prices by type of service (monthly data, not seasonally adjusted).

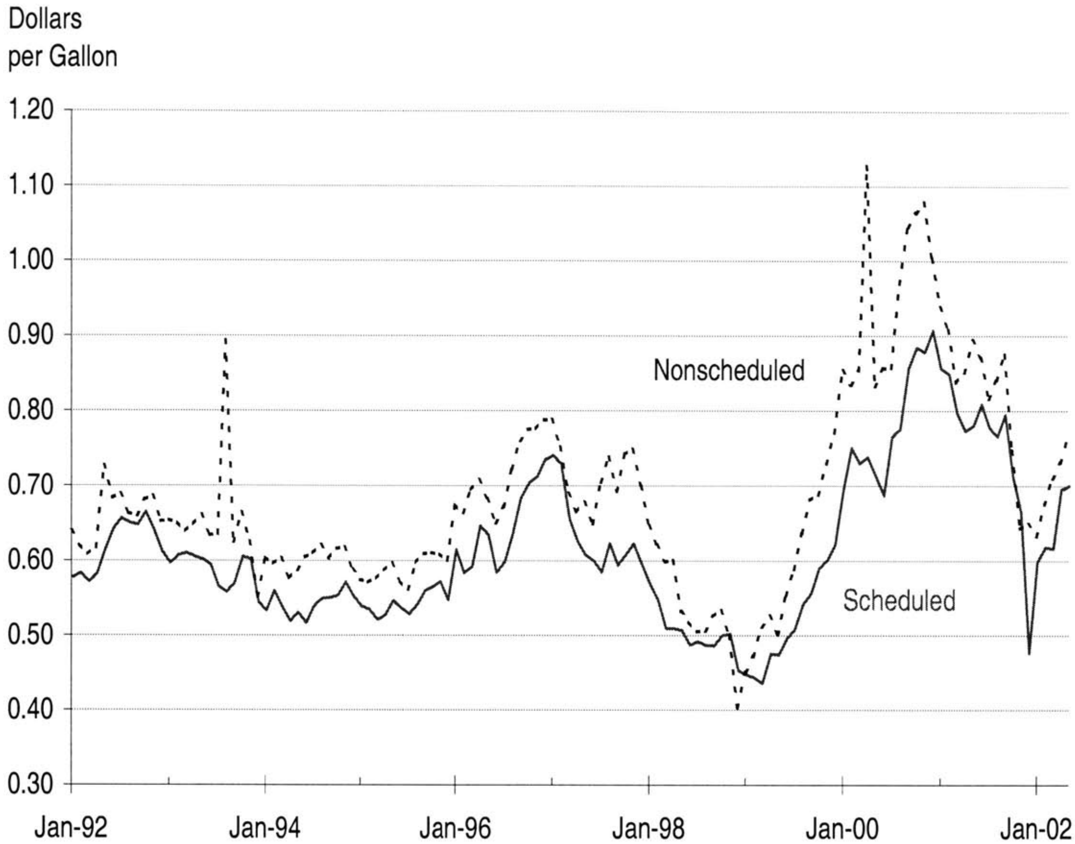

Figure B-2: Comparison of annual fuel prices [26].
Notes: The current value is compared to the value from the same period in the previous year to account for seasonality. Data for February 2002 to May 2002 are preliminary due to late reports by carriers.
Source: Bureau of Transportation Statistics, Office of Airline Information; July, 2002; available at: http://www.bts.gov/oai.

Current Dollars per Gallon	May-01	May-02
For nonscheduled airlines	0.89	0.77
For nonscheduled airlines percent change from same month previous year	7.34	-14.23
For scheduled airlines	0.78	0.70
For scheduled airlines percent change from same month previous year	9.55	-10.36

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