Conceptual Gas Turbine Design: The Role of Turbine Maps

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ABSTRACT

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Compressor and turbine maps are both required for modelling off-design behaviour of gas turbine systems accurately. Their efficiency at part-load affects the thermal efficiency (and thus specific fuel consumption) of the gas turbine directly, the variation of the corrected flow with pressure ratio affects the operating lines in the core stream compressor maps and - at low power - the exhaust gas temperature significantly.

True maps are seldom available outside industry and therefore it is common practice to scale maps from similar machines. Alternatively, one can calculate maps, provided the component geometry is known at least approximately. Turbine power requirement, mass flow, a rough idea about the dimensions of the turbine flow annulus as well as spool speed can all be found from conceptional engine design studies.

A non-CFD turbine map calculation program, based on NASA publications, is presented and its results are compared with measured data.

The contribution of the LPT to the differences in off-design behaviour is demonstrated by comparing calculated turbine maps from conventional and geared turbofans with bypass ratio 12 and a common core. These differences are nearly invisible if scaled versions of the same LPT map for both engine concepts are used.

Keywords: Gas Turbine Performance Simulation; Conceptual Design; Preliminary Design; Turbine Map; Turbine Characteristics; Conventional Turbofan; Geared Turbofan; Off-Design Behaviour; GasTurb;

NOMENCLATURE

D	Diameter [m]
H	Specific work [m^2/s^2]
ISA	International Standard Atmosphere
SLS	Sea level static
U	Circumferential speed [m/s]
V	Velocity [m/s]
δ	P/P_{std} with P_{std}= 101.325kPa
Θ	T/T_{std} with T_{std}=288.15K
Ψ	Turbine stage loading H/U^2

1.0 INTRODUCTION

Any aircraft gas turbine design study begins with the computation of the thermodynamic cycle at a given flight condition. Conceptual design studies add spool speeds and flow path geometry to the results of the computation. With this additional knowledge, component efficiency estimates at the design point can be improved quite substantially.

The next step in the evaluation of the concept is the investigation of the performance at important off-design operating points. Compressor and turbine maps are needed for that purpose, but where do they come from? Usually, scaled component maps from similar turbomachines from literature are employed for off-design performance evaluation, but this is hazardous because scaled versions of the *same* component map in a study which compares quite different engine concepts will very likely yield imprecise or misleading results. This is especially true if component stage numbers, aerodynamic loading or the Mach numbers differ significantly. Scaling *different* maps – taken from literature - introduces uncertainty if the differences between the un-scaled maps are inconsistent with the differences in the engine concept.

Calculating new maps is the only way out of this dilemma. But it should be acknowledged that for such a calculation only the limited amount of geometric data generated as part of the conceptual engine design is available.

Predicting a compressor map is generally more challenging than predicting a turbine map; but this paper is limited to the latter and illustrates the consequences of using various low pressure turbine maps to compare off-design performance of conventional and geared turbofans.

2.0 CONCEPTUAL ENGINE DESIGN

As mentioned above, the conceptual design of a turbofan begins with the calculation of the thermodynamic cycle design point to obtain mass flows, total temperatures, and total pressures at the component interfaces. Except for the exhaust area, the size of the engine is not directly apparent in these numbers.

Conceptual design as described in Ref. 1 deals with the geometry of the flow path, the compressor and turbine disks. Ref. 2 and 3 describe the application of GasTurb to the conceptual design of a series of turbofans with a common core. For the conventional turbofans considered, the bypass ratio varies between 6 and 12, while for geared turbofans the bypass ratio ranges from 12 to 18.

Two engine models have been selected from these studies, both with bypass ratio 12, and both models are complemented with an off-design simulation capability. Table 1 shows engine design data which are the same or very similar while Table 2 lists the main differences between the two concepts.

Table 1
Common Cycle Design Point Data (Cruise @ 35000ft/Mach 0.8)

Thrust [kN]	~32.4
Bypass Ratio	12
Corrected Fan Mass Flow [kg/s]	~700
Corrected HPC Mass Flow [kg/s]	25
Fan Pressure Ratio	~1.545
Booster Pressure Ratio	~1.78
HPC Pressure Ratio	18
Overall Pressure Ratio	45
Burner Exit Temperature	1700
HP Turbine Pressure Ratio	~4.3
LP Turbine Pressure Ratio	~8.95

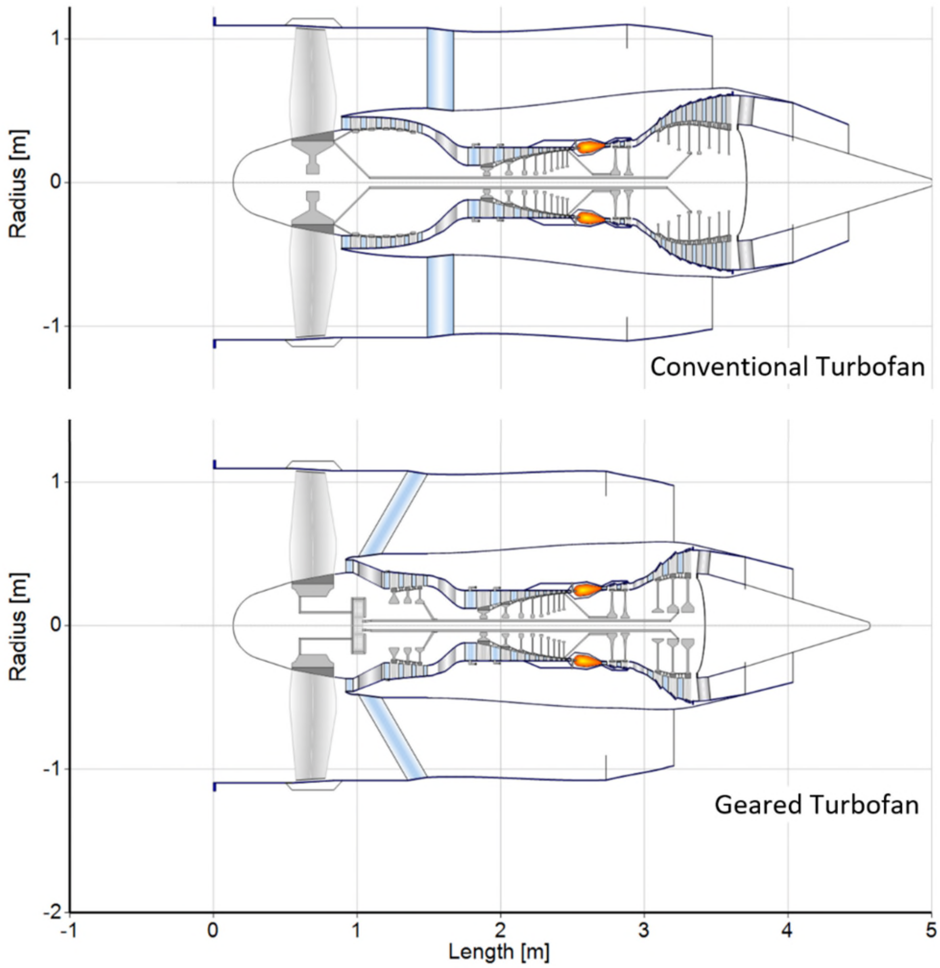

Figure 1 Conceptual design results for a conventional and a geared turbofan with common core and bypass ratio 12

Table 2
Important Differences

	Conventional Turbofan	**Geared Turbofan**
Fan speed [RPM]	4112	3776
Fan Relative Tip Mach No.	1.66	1.54
Booster Speed [RPM]	4112	9439
Booster Stage Count	5	3

LPT Speed [RPM]	4112	9439
LPT Stage Count	8	3
LPT Stage Loading H/U²	2.71	1.69

The off-design behaviour is examined by comparing the sea level static operating lines and for that purpose maps are needed. Since the differences in the relative blade tip Mach number of the fan are modest, the same map is used and scaled appropriately.

The two boosters are quite different: in the conventional turbofan the flow field is subsonic while in the geared turbofan it is transonic because there the booster runs at a much higher speed. For simulating the off-design performance of the conventional turbofan, a map from a subsonic compressor with shallow speed lines is employed. For simulating the booster performance of the geared turbofan, a map with steep speed lines is used.

This paper mainly addresses performance changes due to differences in the low pressure turbine (LPT) design. The top row of Figure 2 shows the geometry of the two conceptual designs of interest while the lower row contains their velocity diagrams.

The velocity diagrams are calculated from a simplified version of the program published by Glassman (1972), which considers the design of un-cooled axial turbines. The method is based upon an analysis of the flow at the turbine mean diameter. The specific heat ratio is assumed constant throughout the turbine.

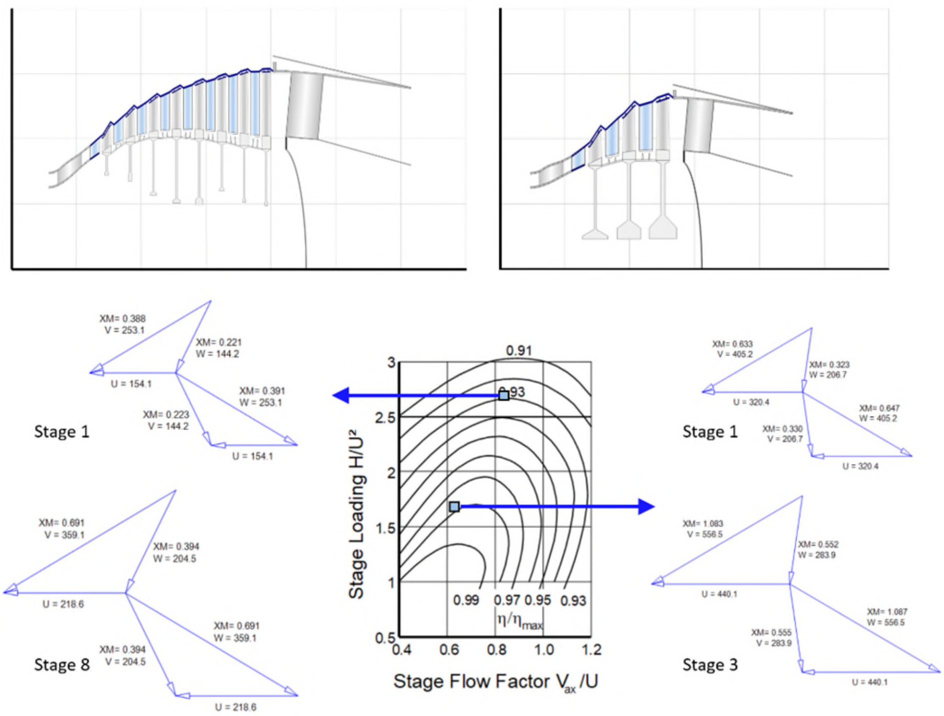

Figure 2: Flow-paths and velocity diagrams of the LP Turbines

For any given turbine, all stages except the first, are specified to have the same shape velocity diagram. The first stage differs only because the inlet flow is axial. The velocity diagram shape depends upon the speed-work parameter $\Lambda = U^2/H$ (the inverse of the turbine loading parameter Ψ) and the specified type of velocity diagram, namely: symmetrical, zero exit swirl, and impulse. Glassman's design of axial turbines with symmetrical velocity diagrams is implemented in the performance program GasTurb.

The turbine design computations are based on mean-diameter flow properties and do not consider any radial gradients. Input to the turbine design subroutine consists of either power or pressure ratio, mass flow rate, inlet total temperature and pressure, rotative speed, inlet and exit diameters, exit radius ratio or stator exit angle, a turbine loss coefficient which allows adjusting the calculated efficiency and gas properties.

The output includes inlet and exit annulus dimensions, exit temperature and pressure, total and static efficiency, blading angles, and last stage critical velocity ratios. Annulus dimensions of intermediate stages are not included.

3.0 TURBINE MAP CALCULATION

A new program with the name TurPer (Turbine Performance) has been developed by the author to calculate turbine maps and this uses the output of the GasTurb conceptual turbine design as input. It is a derivative of the FORTRAN program published by Flagg (1967), converted to a modern Windows program written in Delphi. The original Flagg code has been developed over time and carries the name AXOD which stands for Axial-Flow Turbine Off-Design. Glassman (1994) describes the improvements in some detail and compares the output with measurements. The suggestions of Glassman have been accounted for in the development of TurPer.

The number of input data required for TurPer is significantly less than that needed for the original Flagg program or its derivative AXOD. Many of the recommended default values and settings of AXOD are hard-coded in TurPer.

As mentioned above, the turbine design procedure is based on meanline properties and radial gradients are neglected. The off-design calculation procedure, however, does take radial variation into account. While the stator vane and rotor blade angles are single mean-line values in the design calculation, the off-design procedure needs input at five radii. The vane and blade angles for the mid annulus diameter are set to the corresponding values of the turbine design velocity diagrams. The vane and blade angles at other annulus diameters are calculated from the following general equation for the circumferential velocity component V_U :

$$V_U = const \times D^n \qquad (1)$$

The axial velocity component V_{ax} is assumed to be constant with radius. A value of n = -1 describes a free vortex, a flow phenomenon that is seen in water going down a circular drain, for example. In a turbine, the simple free vortex condition results from the assumption that both specific work and axial velocity are constant with radius.

While a free vortex condition provides a simple basis for a design that ensures radial equilibrium, major problems can occur subsequently due to radial variations. Alternative approaches to the combination of constant work and constant axial velocity with radius are useful. A fixed radial variation of reaction might be one; a fixed radial variation of work is another. Using n=0 in the above equation yields V×U=constant and n=1 creates a solid body.

A comparison with measurements from turbine rigs shows - regardless of the simplifications - that turbine maps calculated with TurPer are as accurate as those calculated with AXOD. This is illustrated in Figure 3, which compares the TurPer results with measured data from the three-stage turbine published by Wolfmeyer (1974) and the five-stage turbine as reported by Davies (1985).

TurPer generates input files for the program Smooth T (Ref.9, Kurzke 2021) which in turn produces tables suitable for input to gas turbine performance programs.

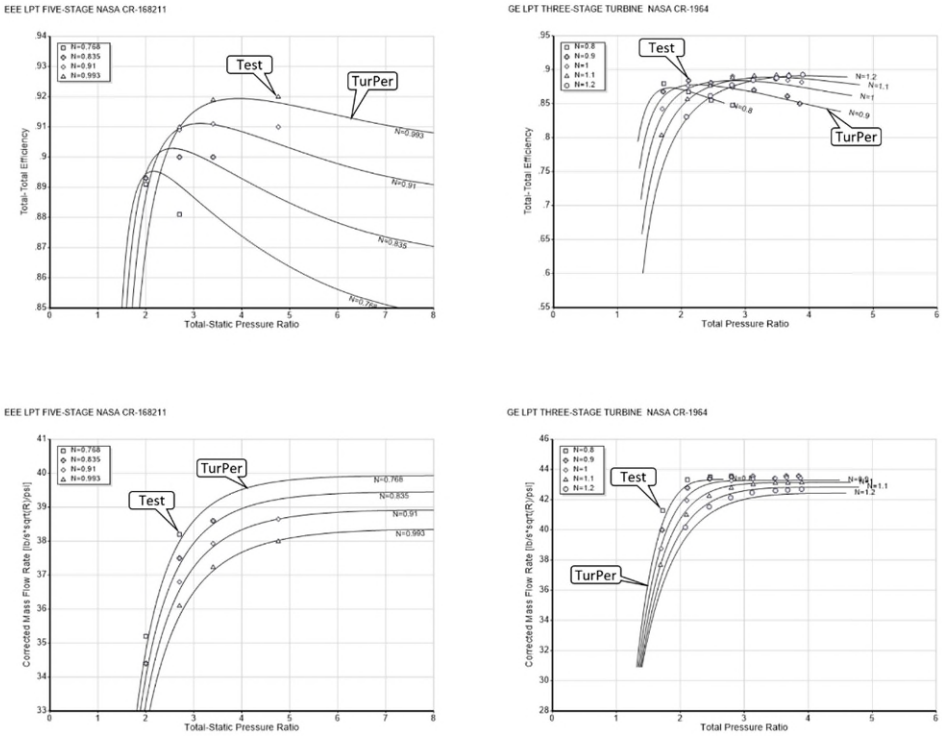

Figure 3: Calculated and measured turbine maps

4.0 TURBOFAN OFF-DESIGN PERFORMANCE

Designing an engine never ends with the cycle calculation at a single operating point. After determining the engine geometry through a cycle design calculation, eventually followed by the conceptual design, more operating points need to be considered. All the additional points are off-design cases, and maps for all the turbomachines are required in their calculation; selection of the fan and booster maps has been already discussed. The core of both turbofans is assumed to be identical, therefore the same the high pressure compressor (HPC) and high pressure turbine (HPT) maps must be used for both engines.

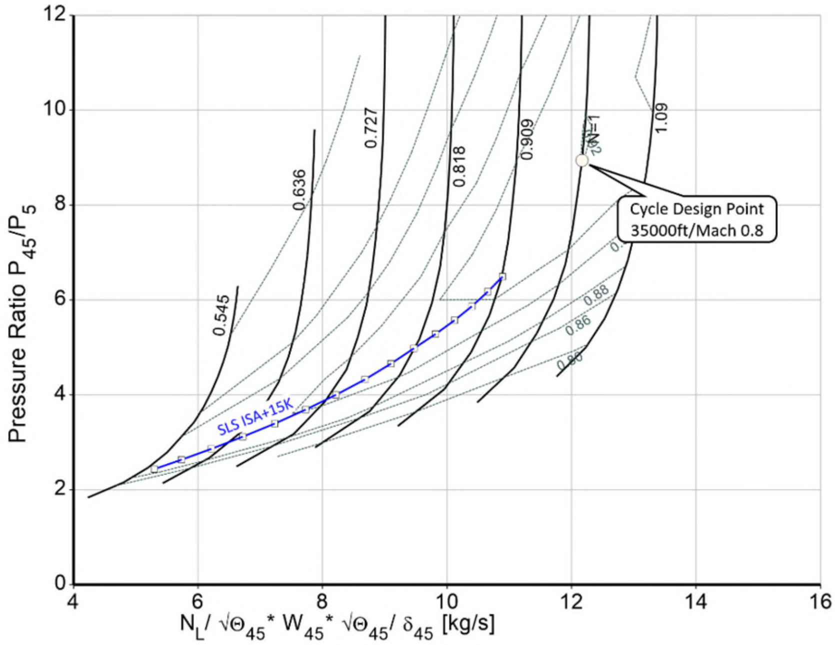

Figure 4: LPT Operating line in the scaled GasTurb Standard map

The topic of this paper is the role of turbine maps during conceptual design which means in this case the role of the LPT map. There are two options: (1) using the same map for both the conventional and the geared turbofan, for example the scaled GasTurb Standard map, or (2) using special maps which reflect the differences between the dissimilar LPT's of conventional and geared turbofans. Next, we examine how much the turbine map selection affects the results of the simulation for the SLS ISA+15K performance of both engine concepts.

Figure 4 is essentially valid for both the conventional and the geared turbofans; the location of the LPT operating line in the map is hardly affected by the differences between the engine architectures. Both efficiency and the corrected flow $W_{45}\sqrt{\Theta_{45}}/\delta_{45}$ decrease with the LPT pressure ratio P_{45}/P_5.

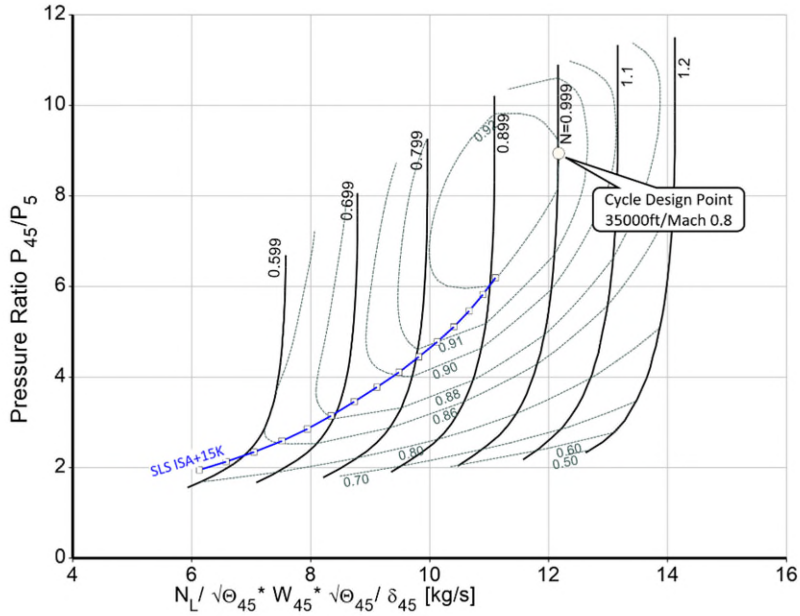

Figure 5: Operating line in the LPT map, conventional turbofan

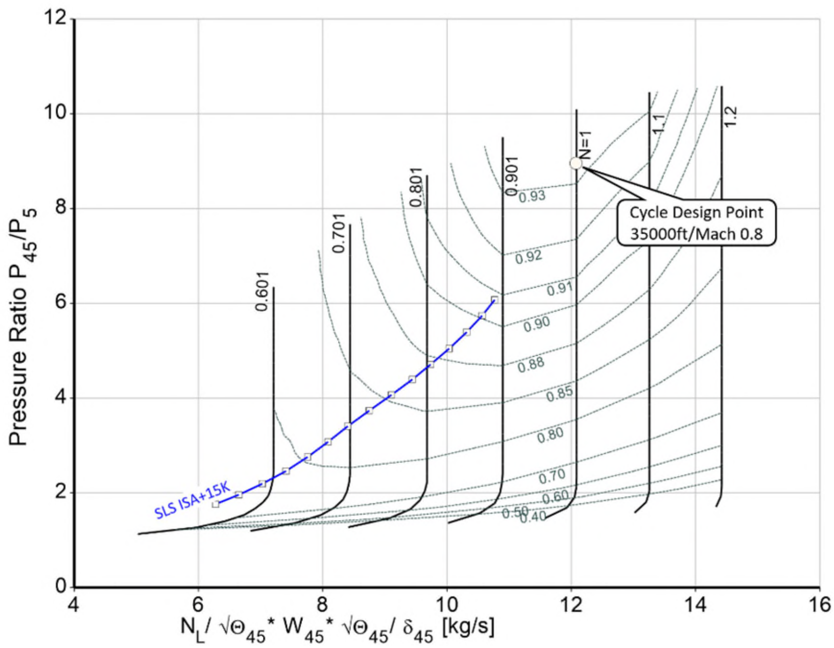

Figure 6: Operating line in the LPT map, geared turbofan

Figures 5 and 6 show the respective operating lines in maps which were calculated with TurPer for the annulus geometry of the conceptual designs displayed in Figure 2. Figures 7 and 8 illustrate what happens to efficiency and corrected flow along the operating line and make it obvious that using scaled versions of the Standard map is not a good idea. The differences between the two engine concepts would nearly vanish, the result in Fig.8 for corrected flow being especially vivid!

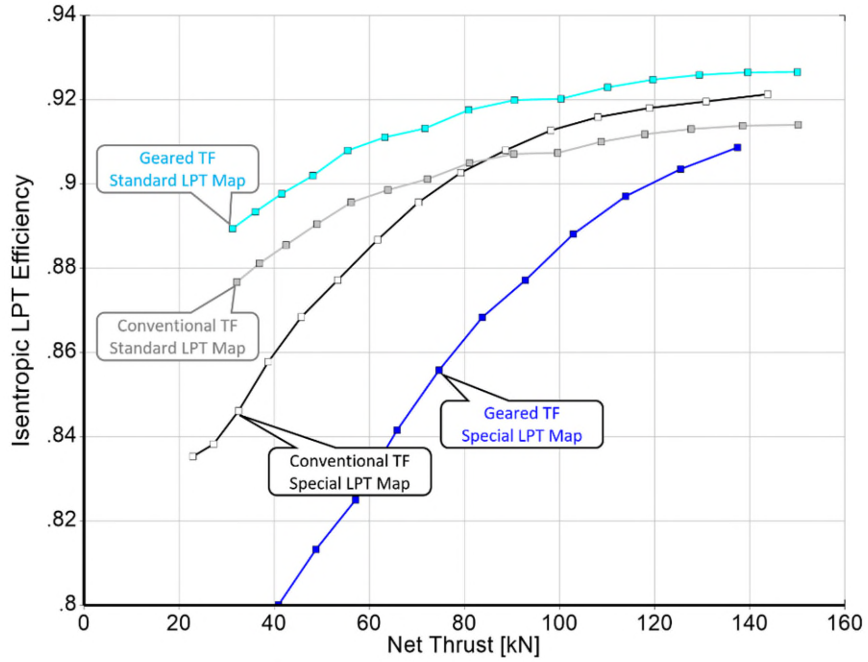

Figure 7: LPT efficiency along the SLS ISA+15K operating line

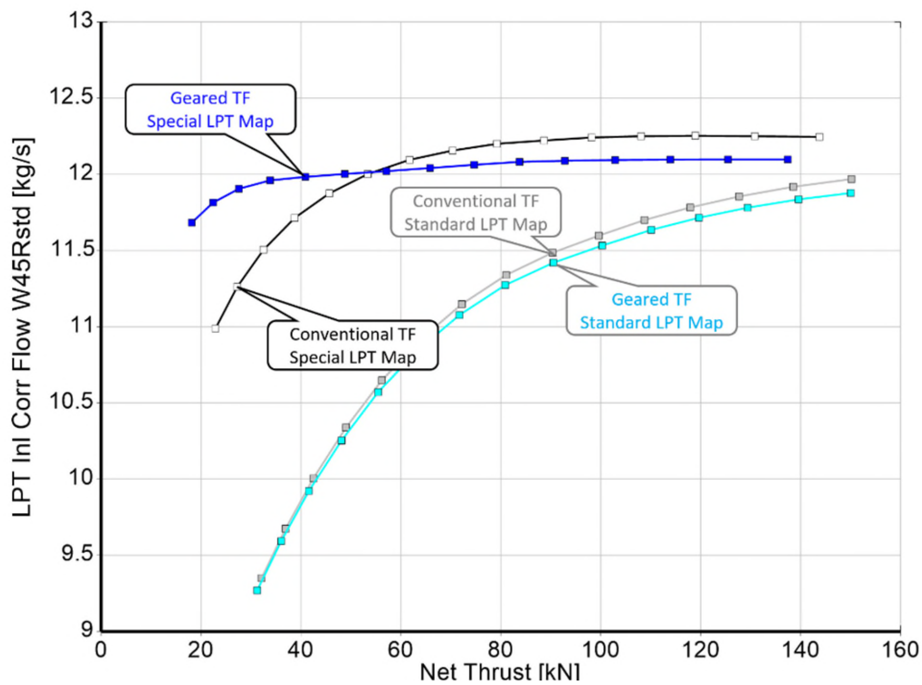

Figure 8: LPT corrected flow along the SLS ISA+15K operating line

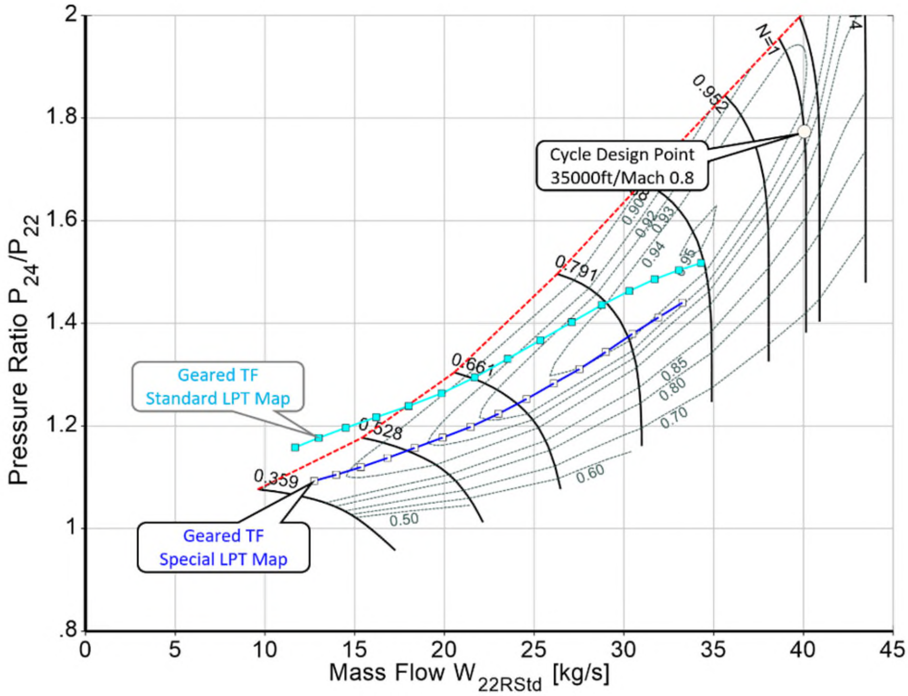

Figure 9: Booster operating lines for the geared turbofan

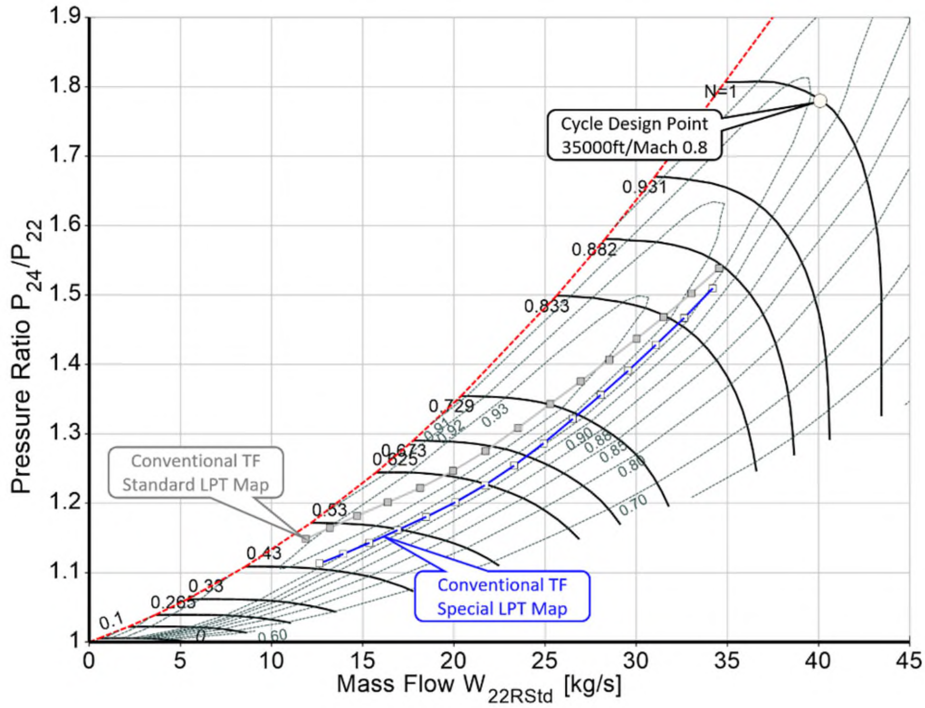

Figure 10: Booster operating lines for the conventional turbofan

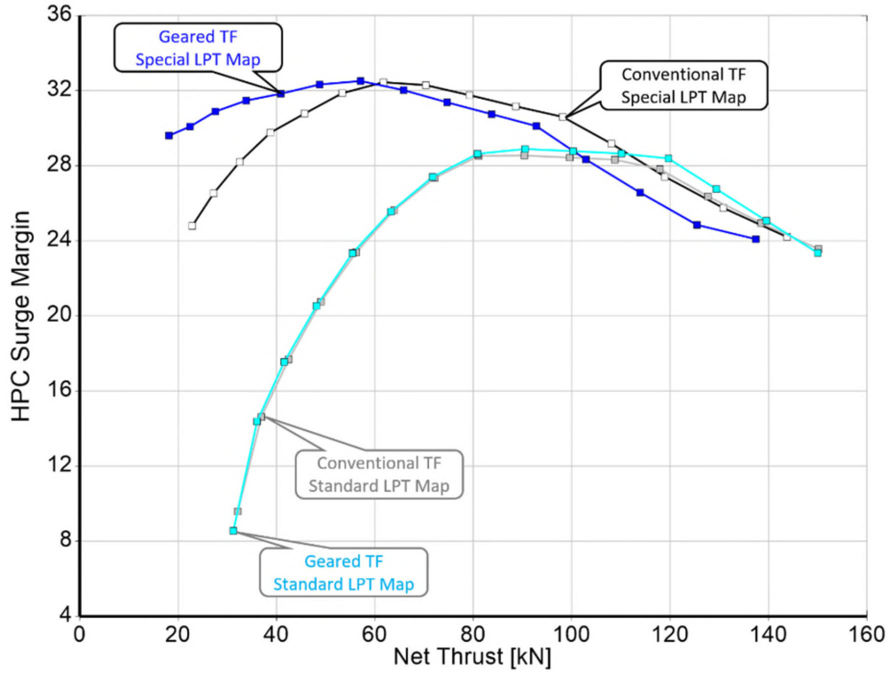

Figure 11: HPC surge margin along the SLS ISA+15K operating line

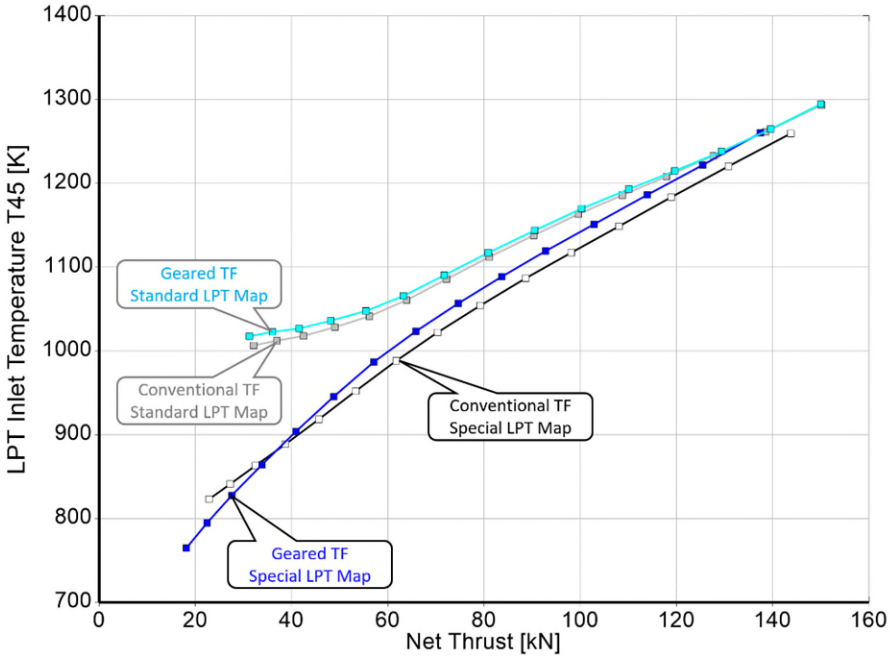

Figure 12: LPT inlet temperature for the SLS ISA+15K operating line

The use of different maps has consequences for the booster operating line as well as for that of the LPT. The simulation result with the LPT Standard map indicates a potential surge problem for both standard and geared engine concepts while with the special LPT maps this does not exist. The danger of surge at low power – which can be eliminated with a handling bleed downstream of the booster – is exaggerated if the Standard LPT map is used.

Besides the booster surge margin, the HP compressor surge margin (Figure 11) and the LPT inlet temperature T_{45} (Figure 12) are also affected significantly by the LPT performance map selection.

All these phenomena are caused mainly by the LPT flow characteristic shown in Figure 8. The LPT efficiency drop with thrust (illustrated with Figure 7) does not affect the booster and HPC compressor operating lines as much as it affects specific fuel consumption (Figure 13). Since reduced surge margin may be mitigated by bleed flow at relatively small cost, increased specific fuel consumption remains a significant factor for a customer.

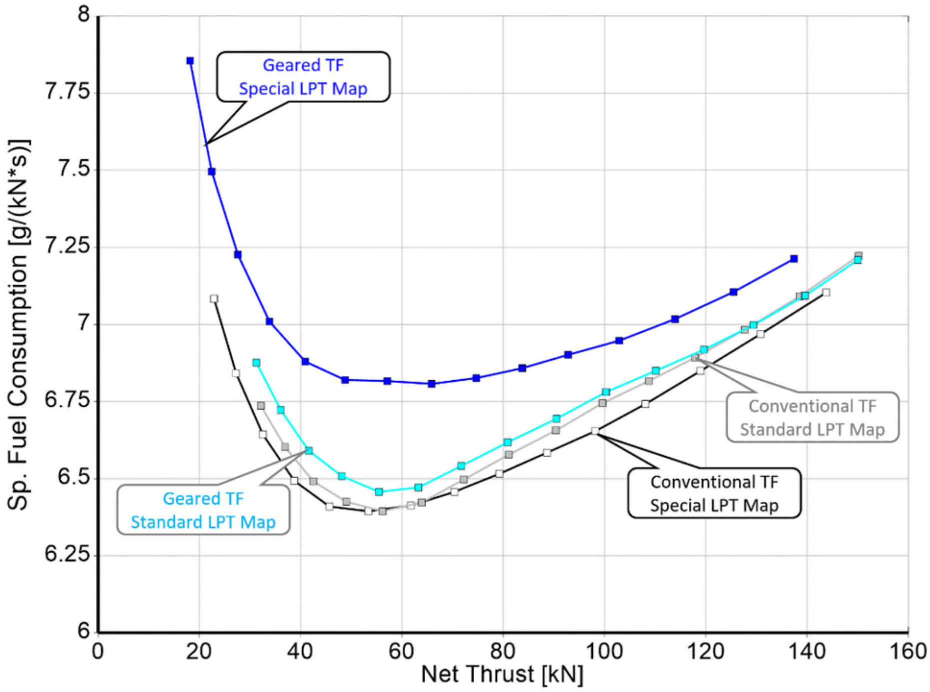

Figure 13: SFC loops for SLS ISA+15K

5.0 CONCLUSIONS

Selection of representative component performance maps is the key to accurate engine performance simulations, and this is true not only for compressors but also for turbines. The map used for high pressure turbines is less important because its operating line between idle and full power is short. The LPT, however, operates over a wide range of pressure ratios unless it is followed by a choked nozzle. Variation of efficiency and corrected flow along the LPT operating line depend on the characteristics of its map. These depend on the turbine design parameters, which in turn are driven by the engine conceptual design.

Turbine maps calculated with the geometric data available during an engine conceptual design study are certainly not as accurate as the results of a modern map calculation program, but there is no choice: The required geometry input for running a CFD program is not yet available in a conceptional engine design study and adequate maps cannot always be found in the literature.

The example presented in this paper shows that using the same LPT map (here the GasTurb Standard LPT map) for very different engine concepts can lead to severe inaccuracies in off-design performance simulations. The generation of new LPT maps using TurPer provides a convenient and acceptable solution.

ACKNOWLEDGMENTS

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