Towards a full two dimensional gas turbine performance simulator

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ABSTRACT

In commercially available gas turbine performance simulation tools, individual engine components are typically represented with non-dimensional maps of experimental or default data. In those cases where actual component characteristics are not available and default characteristics are used instead, conventional tools can deviate substantially at off-design and transient conditions. Similarly, when real component characteristics are available, conventional engine cycle simulation tools can not predict the performance of the engine at other than nominal conditions satisfactorily, or account for the impact of changes in component geometry.

This study looked into the full integration of two-dimensional streamline curvature component models with a low fidelity cycle program. Firstly, the obtained engine performance was compared against the one calculated based on default component characteristics. As a second case study, a range of flight Mach numbers and angles of attack were examined together with the effect of three different intake lip geometries on the performance of a notional, two-spool, low-bypass ratio, military engine. Two-dimensional models were used in the engine cycle analysis to provide a more accurate, physics- and geometry-based estimate of intake and fan performances.

The analysis carried out by this study demonstrated relative changes in the predicted engine performance larger than 1%. For briefness, representative results are presented and discussed in this paper for one flight Mach number and angle of attack setting. More importantly, this research effort established the necessary methodology and technology required towards a full, two-dimensional engine cycle analysis at an affordable computational resource in the very short term.

NOMENCLATURE

Abbreviations

AoA	angle-of-attack
BPR	bypass ratio
CFD	computational fluid dynamics
CMF	corrected mass flow
DLL	dynamic link library
ETA	isentropic efficiency
GT	gross thrust
LES	large-eddy simulation
LBR	low by-pass ratio
OPR	overall pressure ratio

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PCN	relative to DP rotational speed
PR	pressure ratio
RANS	Reynolds-averaged Navier-Stokes
SLC	streamline curvature
SFC	specific fuel consumption
TET	turbine entry temperature
0D	zero-, non-dimensional
1D	one-dimensional
2D	two-dimensional
3D	three-dimensional

Greek symbols

Δ	delta
η	efficiency
λ	ratio
φ	diffuser semi-angle

Subscripts

contr	contraction
csd	constant section duct
diff	diffuser
dwstr	downstream
isentr	isentropic
lip	intake lip
mag	magnification
upstr	upstream
∞	free stream conditions

Latin symbols

A	area
L	length
M	Mach number
N	magnification factor
W	engine mass flow

1.0 INTRODUCTION

This section of the manuscript attempts to discuss the reasons for carrying out this particular study. By integrating a higher fidelity component simulation within a low-fidelity system simulation, it is possible to account for geometry effects and also capture relevant flow physics taking place in any given component in the context of the overall engine performance. The work reported here is part of a wider research effort that focuses on the investigation of 'zooming' strategies. These essentially allow the performance characteristics of a gas turbine engine component, resolved from a detailed, high-fidelity analysis, to be integrated into an engine system analysis performed at a lower level of detail, at an affordable computational cost and time.

Over the years, several 'zooming' research efforts have been reported utilizing mainly 2D and 3D CFD component models, integrated with low-fidelity engine simulation software. These same authors in Pachidis, *et al*[1,2,3,4] discussed the de-coupled, partial and full integration of 3D CFD component models with PYTHIA, the low-fidelity cycle analysis software developed at Cranfield University in the UK. Turner, *et al*[5] demonstrated a multi-fidelity simulation by NASA and GE of a turbofan engine with CFD component characteristics zoomed into 'partial' performance maps for a 0D cycle simulation. Reed and Afjeh[6,7,8] have also published on CFD numerical zooming techniques, in the context of the Numerical Propulsion System Simulation (NPSS) program. In July 1997, Reed and Afjeh[9] published a paper on a comparative study of high and low fidelity fan models for turbofan engine system simulation. Smith[10] reported a collaborative research effort between NASA and GE on fan and compressor high-fidelity zooming. More recently Schluter, *et al*[11] demonstrated the full 3D CFD simulation of the high-spool of a Pratt & Whitney gas turbine by linking together several RANS and LES solvers and by using a cluster of 502 processors running for 48 hours.

Despite all these achievements, from the literature mentioned above it becomes obvious that CFD tools can 'perhaps' nowadays predict the performance of individual engine components satisfactorily, under various operating conditions, but can not offer whole engine performance prediction. It is these authors' view that several issues would prevent this from being a practical solution, at least in the near future. Firstly, for a complete 3D system simulation, the amount and level of detailed information needed as boundary and initial conditions would be extremely difficult to obtain. Secondly, the computational time and cost would be extremely high for effective and practical use in an industrial or academic research environment. Despite the greater computational power that every generation seems to have available, this usually tends to be consumed internally, by upgrading the internal workings of CFD tools (e.g. better numerical methods, better turbulence models etc.), without really contributing to faster computations.

Finally, commercially available CFD tools do not allow in-house empiricism and expertise to be incorporated in the flow-field solution in the form of deviation and loss models, and in those cases where CFD results differ from experiments there is really little one can do in order to identify the source of the inaccuracy.

Nevertheless, in the simulation of a complete gas turbine system, the presence of upstream and downstream engine components (intake, compressor, bypass duct, etc.) does affect the flow through a given component, therefore, the 'presence' of the remaining engine components must be brought in the simulation to account for inter-component effects.

This particular study looked into the integration of high-fidelity SLC component models with a 0D cycle analysis. Streamline curvature methods have continued to receive refinements over the years and are still considered by industry as 'state of the art software', capable of providing an accurate, quick and inexpensive solution compared to the full, three-dimensional CFD methods. Although Wu provided the basis for a hub-to-shroud flow field calculation, the term 'streamline curvature' became generally associated with through-flow analysis in 1967 following the work of Novak[12], and Jansen and Moffatt[13]. Since the early 50s a substantial number of computer codes for axial-flow turbomachine flow field analysis have been developed using SLC methods such as Denton[14], Jennions and Stow[15,16], Barbosa[17], Templalexis, *et al*[18], Pachidis, *et al*[19]. Although SLC methods have been around since the early 50s, they have been mainly focused on simulating the flow field inside isolated components. There is actually little evidence in literature on the integration of SLC component models with zero-dimensional cycle analysis, for high-fidelity studies in the context of the whole engine performance.

2.0 SIMULATION STRATEGY

This work adopts the same overall principles of a 'fully integrated' zooming strategy, as reported in Pachidis, *et al*[3], which has the potential to:

(*i*) investigate relevant physical processes occurring in an engine component in more detail,
(*ii*) take into account component geometry effects,
(*iii*) assess the effects of various isolated flow phenomena on overall engine performance in a timely and affordable manner.

It is a rather automatic and fully integrated approach to high-fidelity analysis with the 2D SLC component model being directly linked to

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the 0D engine model, instead of the 0D component representation. During a design point calculation, the 2D component is called at run-time in order to establish the component performance at the selected operating conditions and power setting. Averaged component performance characteristics are then returned back to the low-fidelity cycle analysis for the determination of the overall engine performance. Upstream component boundary conditions are determined by the user, in two dimensions, according to the needs of the particular study (e.g. particular type and extent of compressor inlet pressure distortion), or are determined from the outlet conditions of an upstream 2D component. During off-design calculations, the 2D component is called at run-time several times, in an iterative manner, until continuity of mass flow and power balance is satisfied throughout the engine.

The same process can be repeated for all engine operating conditions, power settings and engine components. Generation of a component characteristic map is not required. The high-fidelity 2D SLC component model can fully define the characteristics of the actual engine component at several operating conditions and can be used to provide a more accurate, physics-based estimate of the component's performance and hence, engine performance, replacing the default maps within the 0D cycle model.

3.0 SIMULATION TOOLS

As mentioned before, this study looked into the full integration of 2D SLC component models with a low fidelity cycle program. This section refers briefly to the in-house simulation software that was utilised for the purposes of this analysis, namely: (*i*) the 2D SLC intake software, (*ii*) the 2D SLC compressor software, and (*iii*) the 0D gas turbine modelling and performance simulation system.

3.1 Two-dimensional SLC intake software

The development of the 2D SLC intake software is reported in detail in Pachidis[20]. This software was specifically developed for the modelling of the meridional flow field in conical and annular intakes by adopting an inviscid SLC through-flow analysis method, in which viscosity effects are taken into account by means of empirical models and correlations. The basic capability that the 2D SLC intake software was initially developed to handle, is outlined below:

- Facilitate 2D meridional flow analysis in conical and annular intakes
- Handle both subsonic and transonic regimes
- Identify choking conditions
- Handle any intake geometry
- Calculate overall performance map
- Handle non uniform inlet flow conditions
- Handle standard and user defined models for rounded or sharp lip losses, diffuser losses, entry-diffuser interaction losses, Reynolds effects, incidence angle effects, boundary-layer blockage etc.
- Provide a converged solution at any given operating point within minutes

For the calculation of the meridional flow field this work adopted the same philosophy as presented by Barger[21]. As far as losses is concerned, the 1D calculation procedure outlined in ESDU Item No 80037[22] for axi-symmetric intakes was adopted, converted however into a 2D calculation. This assumes that the total pressure loss of the intake is the result of the interaction of two different loss components, which are considered to act through independent mechanisms. The loss associated with flow separations, which can occur at the lip for some combinations of intake mass flow, lip geometry and incidence angle, and the loss associated with the diffuser, which results mainly from the boundary-layer growth on the diffuser walls and the effect of the pressure gradient imposed on it by the flow diffusion. The diffuser loss is significantly influenced by the state of the boundary layer at the entry to the diffuser. Therefore, the interaction effect between the entry flow and the diffuser was also taken into account together with the pressure loss in any constant section duct which may be present in the intake. Generally, the intake pressure recovery was calculated by the following relationship:

$$\eta_{intake} = 1 - \Delta\eta_{lip} - \Delta\eta_{diff} N_{mag} - \Delta\eta_{csd_upstr} - \Delta\eta_{csd_dwstr} \quad \ldots (1)$$

Where η_{lip} is the loss in pressure due to intake lip flow separation. $\Delta\eta_{diff}$ is the diffuser loss assuming no interaction between the entry flow and the diffuser and N_{mag} is a magnification or scaling factor that accounts for the interaction between the entry flow and the diffuser loss. $\Delta\eta_{csd_upstr}$ and $\Delta\eta_{csd_dwstr}$ are factors that account for the loss due to any lengths of constant-section duct which may be present upstream and downstream of the diffuser respectively. The current version of the 2D SLC intake software does not account for the effect of swirling inlet flow. The effects of swirl on intake flow angle, pressure recovery and boundary layer stability could potentially be incorporated by means of a separate model, as in the case of intake pressure losses.

3.2 Two-dimensional SLC compressor software

Similarly to the 2D SLC intake software, this software was specifically developed for the modelling of the flow field in multi-stage, axial-flow compressors by adopting an inviscid SLC through-flow analysis method, in which viscosity effects are taken into account by means of empirical models and correlations. The internal workings of the 2D SLC compressor software have been reported in detail by Templalexis, *et al*[18], Pachidis, *et al*[19] and also in Pachidis[20]. It is therefore inappropriate to repeat here the description of the various loss and deviation models used in the code. The interested reader should refer to the above publications. The basic capability however that the 2D SLC compressor software was initially developed to handle is outlined below:

- Facilitate steady-state, multi-stage compressor performance analysis in 2D, at both subsonic and transonic regimes
- Handle any type of standard or user-defined blade profile and compressor geometry
- Handle standard and user-defined models for secondary losses, shock losses, Reynolds, deviation, incidence, boundary layer blockage, tip clearance losses etc.
- Identify conditions for surge and choking and handle non-uniform inlet flow conditions
- Calculate the overall compressor map and provide a converged solution at any given operating point within minutes

Generally speaking, the 2D SLC software was developed to provide great flexibility, in the sense that it can be used as a performance prediction tool for engine components of a known design or as a development tool to assess the changes in performance of a known engine component after implementing small geometry changes. Moreover, it can be used as a design tool to verify and refine the outcome of a preliminary design analysis. Finally, the software can be used to create 2D engine component models that can be integrated into a conventional 0D engine cycle code for high-fidelity studies in the context of the whole engine performance.

3.3 Zero-dimensional gas turbine cycle programme

For the purposes of this investigation the 0D gas turbine cycle program known as PYTHIA was also used. The PYTHIA scheme was developed by the Gas Turbine Engineering Group at Cranfield University (Pachidis[23]). Based on Cranfield's previous 'generation'

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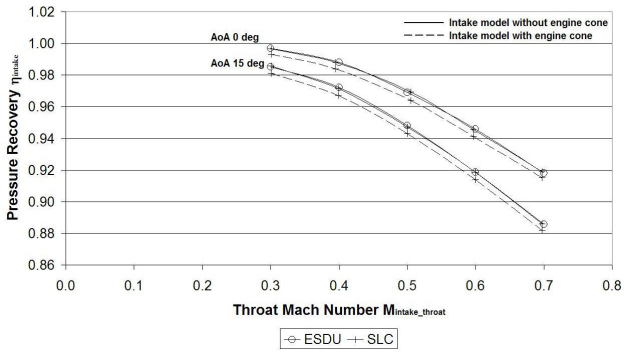


Figure 1. Comparison between 1D ESDU data and averaged 2D SLC results.

engine simulation software, called TURBOMATCH (Palmer[24]), PYTHIA was specifically developed to be a fully modular, object-oriented, engine cycle simulator that can perform steady state design, off-design and degraded performance analysis of civil aero, industrial and military engines. PYTHIA is also a versatile engine diagnostics tool. A PYTHIA engine model is assembled from a collection of interconnected elements ('Bricks'), and controlled by an appropriate numerical solver. By means of engine component icons and via an engine component toolbar, various pre-programmed routines ('Bricks') can be called up to simulate the action of the different components of the engine, resulting finally in output of engine thrust or power, fuel consumption, s.f.c., etc, together with details of individual component performance and of the gas properties at various stations within the engine.

4.0 TWO-DIMENSIONAL SLC SOFTWARE VALIDATION

This particular section describes briefly the validation of both 2D SLC Software used in this study. An analytical description of the validation of this software can be found in Pachidis, *et al*[19] and Pachidis[20].

4.1 Two-dimensional SLC intake software validation

As mentioned before, this work adopted a similar approach to intake pressure recovery calculation as the one-dimensional analysis described in ESDU Item No 80037[22] which is based on the experimental findings of several researchers. The software's capability to calculate the pressure loss in conical and annular intake configurations was tested against worked examples provided in the ESDU report. In the absence of other experimental data, the objective of this exercise was to validate the inner workings of the various loss models programmed in the 2D SLC Intake Software and their successful conversion from 1D to 2D, rather than to assess the agreement of the loss models published in the ESDU report with other experimental results.

For the purposes of this validation, two notional 2D intake geometries were built in order to investigate the performance of two similar intake models, with and without an engine cone. Other geometric properties, such as intake lip geometry, entry contraction ratio and diffuser area ratio were kept the same for both models. More analytically, an elliptical lip configuration was assumed in both cases with a contraction ratio λ_{contr} of 1·1. The diffuser area ratio λ_{diff} was set to 1·75 and a constant section duct, between the lip and diffuser, of length Lcsd equal to half the throat diameter was used in both cases. Attached flow was also assumed throughout both intake models at all conditions.

The performance of both models was established at a constant free-stream Mach number of 0·2, at 0 and 15 degrees of incidence and a range of throat Mach numbers from 0·3 to 0·7. The area-averaged, 2D SLC results are shown plotted against the 1D ESDU data in Fig. 1.

Since the 1D ESDU analysis does not take into account the presence of the engine cone, the averaged 2D SLC flow solutions seem to be in an excellent agreement with the ESDU data in the case of the intake model without an engine cone, as expected. Minor differences in the results mainly arise from the different thermodynamic models used, the averaging of the 2D profiles back to 1D values and rounding arithmetic errors. A very good agreement can be observed at both incidences examined, proving that the loss models in ESDU Item No 80037 were successfully converted and transferred to the 2D SLC intake software.

Although ESDU data for intake configurations with an engine cone were not available, one would expect in this case a slightly less pressure recovery to be achieved at all flow conditions. The presence of an engine cone increases the total skin friction and flow blockage in the intake and introduces the growth of an extra boundary layer. But perhaps even more importantly, the slight reduction in pressure recovery in the case of an intake with a cone can be attributed to the fact that the diffuser semi-angle φ had to increase from 5·0 deg to 7·4 deg approximately, in order to maintain the same diffuser area ratio. The intake model with an engine cone demonstrated an almost constant reduction in pressure recovery of 0·4%, with respect to the intake model without a cone, throughout the range of incidence angles and throat Mach numbers tested.

4.2 Two-dimensional SLC compressor software validation

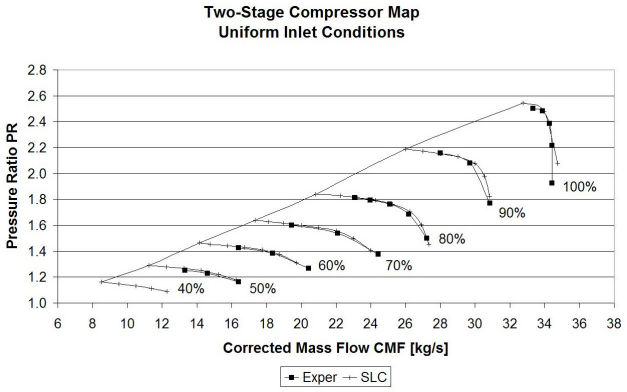
The validation of the 2D SLC Compressor Software against experimental data for both clean and distorted inlet conditions has been reported in Pachidis, *et al*[19] and is briefly repeated here for consistency. A 2D model of a two-stage fan was constructed according to the detailed geometric data published in NASA Technical Paper 1493 by Urasek, *et al*[25]. The performance of the SLC two-stage compressor model under uniform inlet conditions was compared against the measured performance data provided in the aforementioned report. The overall design performance of the two-stage compressor is given in Table 1.

The analysis showed that there was a very good qualitative and quantitative agreement between the simulated and experimental data, especially in the case of the pressure ratio versus corrected mass flow speed lines. Isentropic efficiency versus corrected mass flow speed lines were in a good qualitative agreement as well, although the overall shape of the lines did not exactly match the experimental readings (Fig. 2). It must be stated that no particular effort was made to achieve a better agreement between simulated and experimental data by trying different combinations of the various loss models provided in the SLC compressor software. It was decided that the initial agreement was more than sufficient in order to allow the subsequent qualitative, trend analysis to take place.

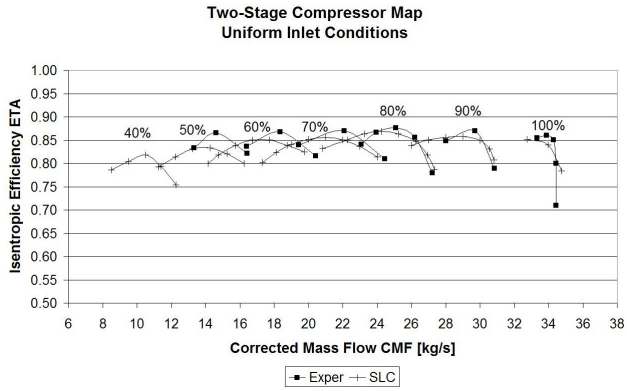
Table 1
Two-stage compressor design overall parameters

Pressure ratio	2·4
Temperature ratio	1·3
Isentropic efficiency	0·85
Corrected mass flow (kg/s)	33·2
Speed (rpm)	16,042·8
Inlet hub to tip ratio	0·38
First rotor tip speed (ms^{-1})	428·9
Second rotor tip speed (ms^{-1})	405·3

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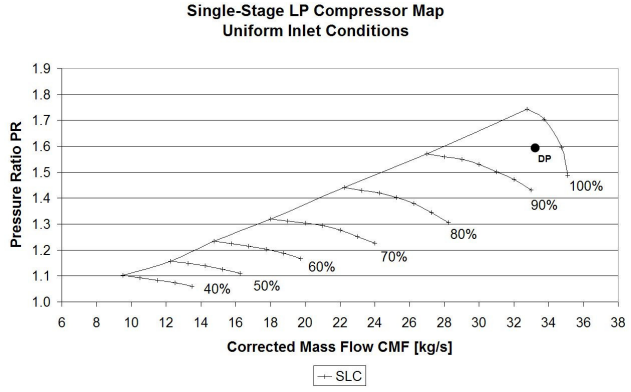


(a)

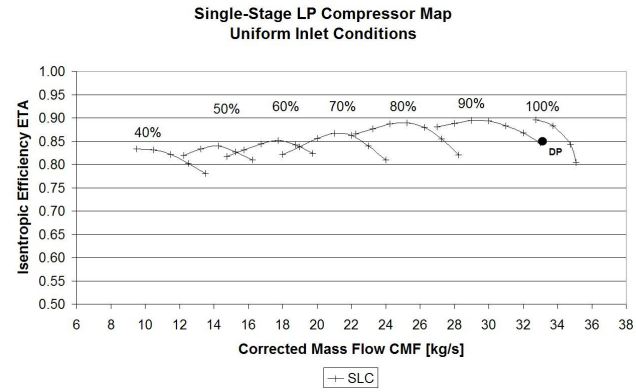


(b)

Figure 2. Uniform inlet conditions comparison with experimental results.



(a)



(b)

Figure 3. Single-stage LP compressor design point and overall performance.

For the software validation under distorted conditions, NASA Technical Paper 1294 by Schmidt and Ruggeri[26] was used as a reference. This paper discusses in detail the performance of a single-stage fan with and without inlet radial distortion. The design overall parameters of the single-stage fan discussed in NASA TP 1294 are very similar to the first stage of the NASA TP 1493 two-stage compressor. The performance of the SLC compressor model, and especially the performance of the first stage, was qualitatively compared against the measured data in NASA TP 1294 for hub and tip radial pressure distortions. The analysis showed similar qualitative trends for the same kind of radial pressure distortion and extend.

5.0 TWO-DIMENSIONAL COMPONENT MODELS

In this high-resolution analysis a 2D SLC compressor model was used to represent the low-pressure fan of a notional, two-spool, LBR, military engine model. As discussed before, the validation of the 2D compressor SLC software was carried out based on the geometric and performance data of a two-stage compressor, published in NASA Technical Paper 1493 (Urasek, *et al*[25]). For this reason, the first stage of the same two-stage compressor was used as the 2D SLC fan model that was integrated with the 0D engine cycle analysis. Only the first stage of the validated two-stage compressor was used in the simulations in order to reduce the amount of convergence time required, particularly when calculating the off-design performance of the engine. The design performance of the first stage, according to the experimental data is given in Table 2 and is also illustrated in Fig. 3, together with the calculated overall performance of the first stage under clean inlet conditions.

Table 2
First stage design compressor performance

Pressure ratio	1·6
Temperature ratio	1·2
Isentropic efficiency	0·85
Corrected mass flow (kg/s)	33·2
Speed (rpm)	16,042·8
PCN	0·96
Inlet hub-tip ratio	0·38
Rotor tip speed (ms^{-1})	428·9

With the 2D SLC compressor being the most critical part of the entire analysis, due to the complexity involved in modelling the compressor geometry and simulating its performance, the 0D engine model and 2D SLC intake model had to be 'tailored' around the available compressor geometry and performance.

For the purposes of this investigation a simple, notional 2D SLC intake model with an engine cone was created (Fig. 4). The intake's outlet lip inner radius and cone's outer radius matched the compressor's casing and hub radii respectively. The 2D intake model was designed to match the mass flow requirements of the 2D compressor, throughout its operating range without choking, and featured an entry contraction ratio λ_{contr} of 1·38 and a diffuser area ratio λ_{diff} of 1·32. A constant section duct was also included between the lip and diffuser entry and between the diffuser outlet and compressor inlet as Fig. 4 illustrates.

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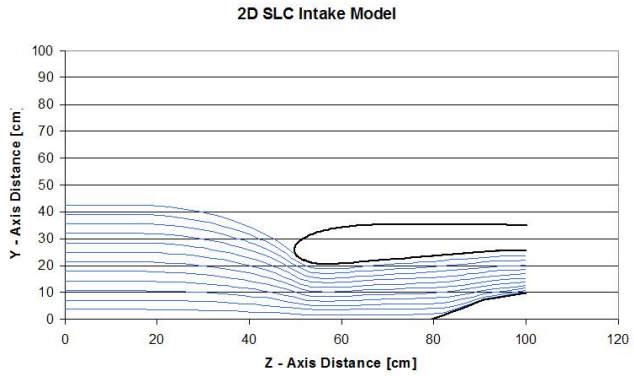


Figure 4. 2D SLC intake model and pre-entry stream tube.

Table 3
Notional engine design performance parameters

W (kg/sec)	33·2
OPR	3·6
TET (K)	1,000·0
BPR	0·71
GT (N)	10,103·3
SFC (mg/N sec)	26·0

The notional engine model was built based on the overall configuration of an existing two-shaft, LBR, mixed-exhaust, military turbofan. The engine model had to be scaled down in terms of OPR, mass flow and TET in order to match the geometry and performance of the available 2D SLC models described previously. As mentioned above, the first stage of the validated two-stage SLC compressor model was coupled to the software to represent the LP fan of the engine, and similarly, the 2D SLC intake model with the engine cone was also integrated into PYTHIA. The overall design performance of the notional engine is illustrated in Table 3.

The engine model was constructed in PYTHIA with the 0D intake and fan representations replaced by the fully integrated 2D SLC component models. By modelling the intake and the fan in 2D it was possible to investigate the effects of various intake lip geometries and flow conditions on intake, fan and overall engine performance, at several angles-of-attack (AoAs) and flight Mach numbers.

6.0 SOFTWARE INTERFACE

The fully integrated approach requires an explicit interface between the high-fidelity component and the low-fidelity cycle simulation. For this reason, the two 2D SLC engine component models (intake and fan) were integrated with PYTHIA and called at run-time as Dynamic Link Library (.dll) components, instead of the default 0D component representations.

A DLL is a library of functions that uses dynamic linking. A dynamic-link library is a source code library that contains one or more subprogram procedures (functions or subroutines) that are compiled, linked, and stored separately from the application using them. A DLL contains only subprograms and not main programs and shares its code and data address space with the calling application.

The use of DLLs, as separate executable files in this case, offered the organisational advantages of a static library, but with the advantage of a smaller executable file at the expense of a slightly more complex interface. Unlike a static library where routines are included in the base executable image during linking, the routines in a DLL are loaded when an application that references that DLL is loaded during run time. In other words, object code from the DLLs was not included in the program's executable file, but was associated as needed in a dynamic manner while the 0D cycle was executing.

When routines in a DLL are called, the routines are loaded into memory at run-time, as they are needed. This is most useful when several applications use a common group of routines as it could be the case of an engine model utilising several 2D components. By storing these common routines in a DLL, the size of each application that calls the DLL can be considerably reduced, hence making overall execution faster. In addition, the routines in the DLL can be updated without having to rebuild any of the applications that call the DLL. More specifically the DLL advantages are:

- Because the functions or subroutines in a DLL are separate from the application using them, they can be shared or replaced easily
- Individual functions in a DLL may change without recompiling or re-linking the applications that use them, as long as the functions arguments and return types do not change
- Applications can be easily upgraded without affecting DLLs
- When general functions are placed in DLLs, the applications that share the DLLs can have very small executables
- Multiple applications can access the same DLL. This reduces the overall amount of memory needed in the system, which results in fewer memory swaps to disk and improves performance
- Common blocks or module data placed in a DLL can be shared across multiple processes

In PYTHIA the performance of compressors and intakes is handled by FORTRAN 0D component 'Bricks' COMPRE and INTAKE respectively. For the purposes of this investigation, both 2D SLC Compressor Software and 2D SLC Intake Software were separately compiled as dynamic link library files (COMPRE2D.dll and INTAKE2D.dll respectively). They were then integrated into the 0D code by using the generated COMPRE2D.dll and INTAKE2D.dll files, which contain the library's executable code, and the import library files COMPRE2D.lib and INTAKE2D.lib, which the linker requires to associate the main program (PYTHIA in this case) with the DLL files.

Moreover, two new bricks were added in PYTHIA, namely COMP2D and INTA2D. These new bricks were programmed in order to allow the user to call the 2D bricks via the traditional input engine data file, as needed, and in order to provide the explicit interface required between the low-fidelity cycle and the high-fidelity components. The 2D bricks were also used to manipulate the data passed from one software to the other. Obviously, keeping the original 0D component representations in the code provided the extra flexibility to carry out engine performance simulation with any intake or compressor component in the engine being simulated in 0D or 2D.

During the design point calculation, the 2D SLC intake model was called at 'run-time' in order to establish the component performance at the selected operating conditions and power setting. Intake boundary layer blockage factors, together with 2D profiles of the intake's outlet total pressure, temperature, static entropy and absolute angle were then passed as input parameters to the downstream 2D SLC compressor model. Intake inlet boundary conditions were determined from the 1D values supplied by the 0D analysis for uniform inlet conditions. During off-design calculations, both 2D SLC intake and compressor models were called by the 0D cycle program at run-time several times, in an iterative manner, until continuity of mass flow and power balance was satisfied throughout the engine.

The analysis showed that when boundary conditions were exchanged through 'write-read' files the overall simulation time increased, especially at off-design conditions when several iterations are normally carried out. The DLLs offered in this case the advantages of a subroutine in that boundary conditions could be directly exchanged between components as function or subroutine arguments, hence speeding up execution.

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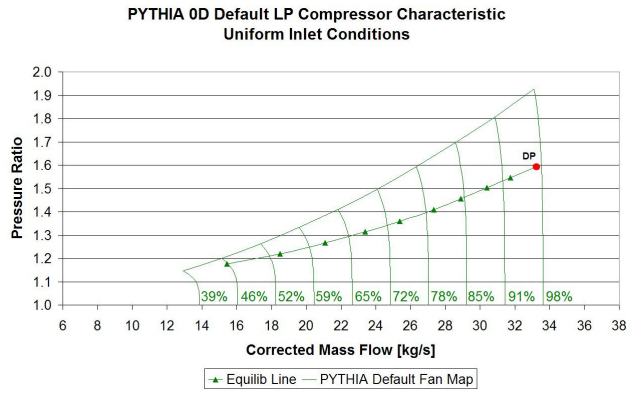


Figure 5. PYTHIA's scaled default map for LP compressor and equilibrium running line.

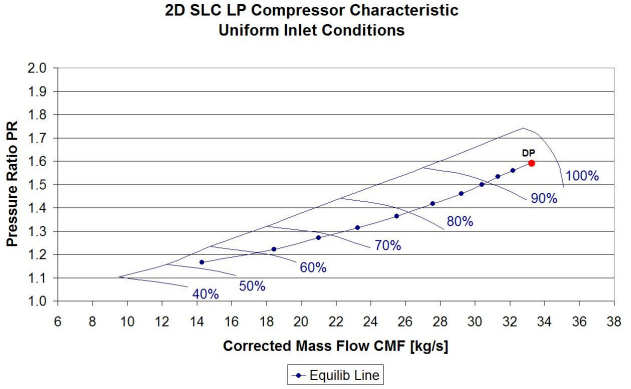


Figure 6. SLC derived map for LP compressor and equilibrium running line.

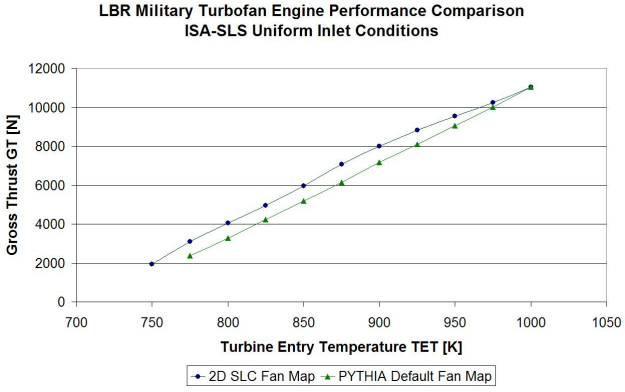


Figure 7. Comparison of engine performance obtained with PYTHIA's default fan map and 2D SLC fan map – gross thrust *vs* turbine entry temperature.

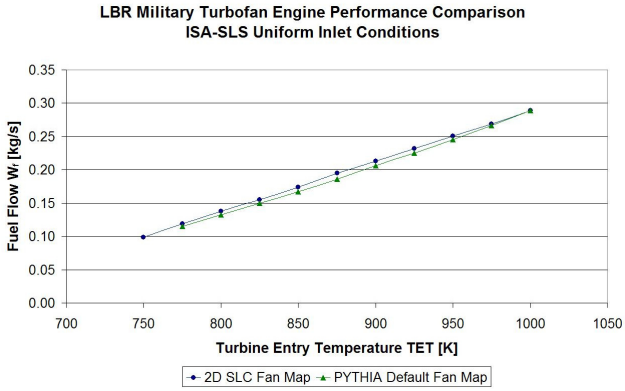


Figure 8. Comparison of engine performance obtained with PYTHIA's default fan map and 2D SLC fan map – fuel flow *vs* turbine entry temperature.

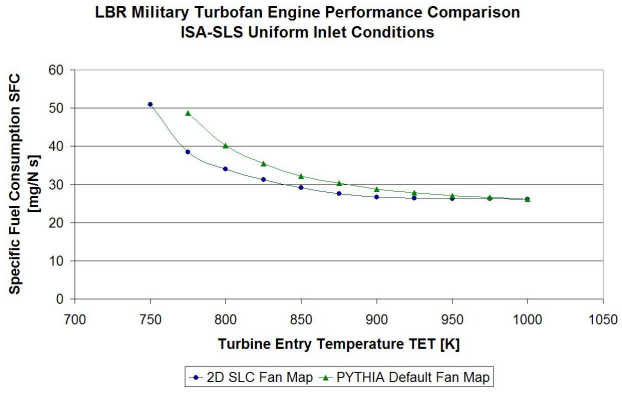


Figure 9. Comparison of engine performance obtained with PYTHIA's default fan map and 2D SLC fan map – specific fuel consumption *vs* turbine entry temperature.

7.0 TWO-DIMENSIONAL ENGINE PERFORMANCE SIMULATIO

This work looked into differences in overall engine performance arising from the full integration of the 2D SLC components with PYTHIA. The first case study carried out examined mainly relative differences between using PYTHIA's default component maps and using the actual 2D component models. For the second case study, a range of flight Mach numbers and angles of attack were examined together with the effect of three different intake lip geometries on the performance of the notional, two-spool, low-bypass ratio, military engine.

7.1 Effect of LP compressor characteristic

The first case study looked into relative differences in the performance of the notional, LBR, military turbofan engine, arising from substituting the 0D intake and LP compressor (single-stage fan) component with the 2D SLC models described above. A typical PYTHIA 0D engine cycle analysis was first carried out at ISA SLS conditions and for a range of power settings, from a TET of 1,000·0K (DP value), down to a TET of 775·0K. Uniform compressor inlet conditions were assumed at all power settings. This initial 0D cycle simulation established the reference engine performance using default component characteristics. Figure 5 illustrates the equilibrium running line established on PYTHIA's default LP compressor characteristic using TET as the handle. The default compressor map was automatically scaled by PYTHIA at design point in order to conform to the design performance of the real LP compressor.

Figure 6 illustrates the LP compressor equilibrium running line established after the full integration of the 2D SLC intake and fan with PYTHIA. The actual fan map was established by running the 2D SLC compressor software alone, during the software validation process, and obviously took no part in the overall engine performance calculation (hence the full integration of the high-fidelity component).

The reference engine performance was compared against the engine performance established with the embedded high-fidelity components. Figures 7-9 illustrate the performance comparison carried out in terms of engine gross thrust, specific fuel consumption

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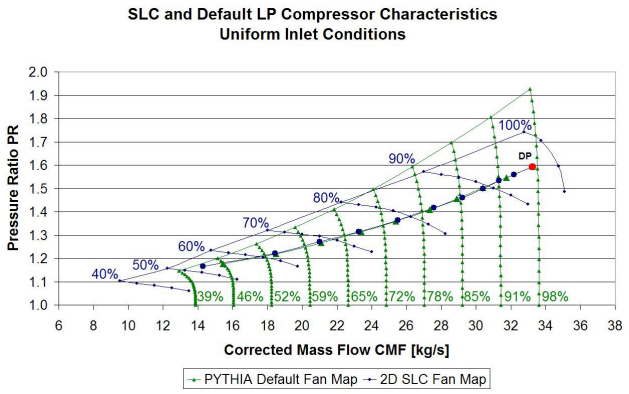
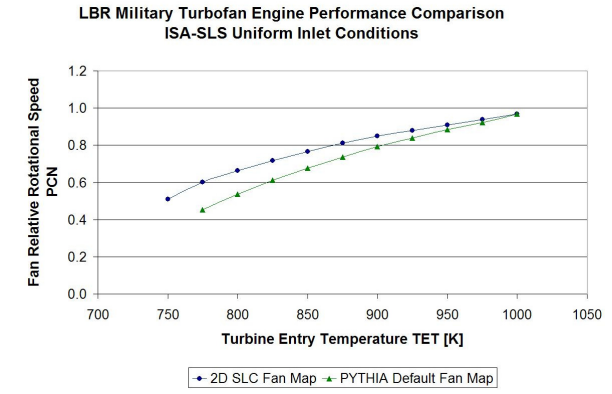
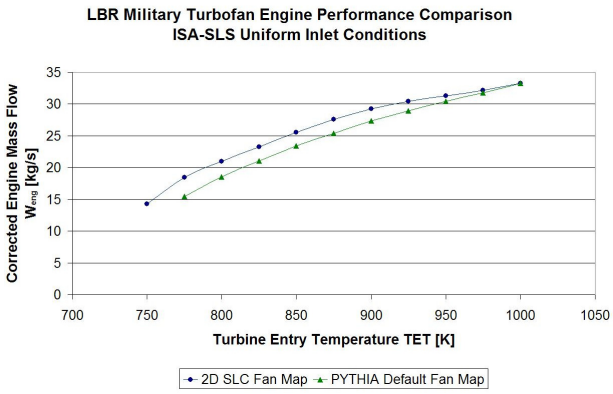


Figure 10. Comparison between the PYTHIA scaled default fan map and the SLC high-fidelity map.



(a)



(b)

Figure 11. Comparison of engine performance obtained with PYTHIA's default fan map and 2D SLC compressor model.

and fuel flow. The two simulations where carried out with PCN as the engine 'handle'.

As expected, although no difference in performance was observed at design point conditions, due to the scaling of the default map in order to match the design point performance of the LP compressor, large changes in engine performance were observed at conditions away from the design point. More analytically, the use of PYTHIA's default maps resulted in the engine's gross thrust being underestimated at almost all power settings, reaching a maximum deviation with respect to the performance obtained with the integrated 2D SLC compressor model, of 23% at a TET of 775·0K. Similarly, the engine's specific fuel consumption was overestimated, throughout

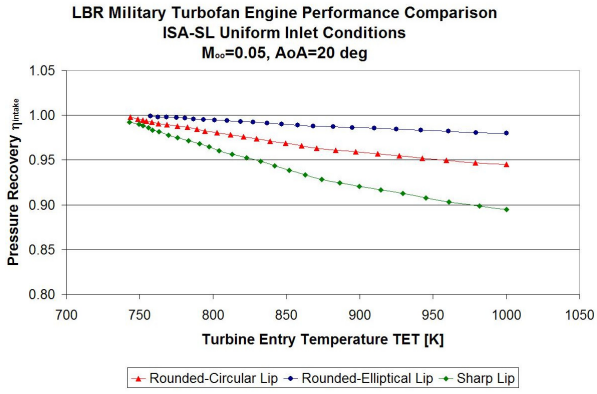


Figure 12. Comparison of engine performance obtained with different lip geometries – intake pressure recovery *vs* turbine entry temperature.

the power range examined, reaching a difference of 26% approximately at a TET setting of 775·0K. Despite the large reduction in gross thrust and the large increase in SFC, fuel flow remained at approximately the same levels and within a 3·5% compared to the performance obtained with the integrated 2D SLC fan.

With the 2D intake component contributing only a small change in the engine's overall pressure ratio (due changes in pressure recovery being very small off-design), the above differences in engine performance mainly arise from the large differences between the default LP compressor characteristic and the one obtained from modelling the actual geometry of the compressor. The two LP compressor maps have been superimposed in Fig. 10.

The equilibrium running lines appear to be in a good agreement since their overall position on the compressor map largely depends on turbine performance, nozzle areas and free stream Mach number, which are the same in both cases. However, operating points along these lines actually correspond to different thermodynamic balances in the engine and hence, different engine power settings, for the same relative rotational speed and corrected mass flow, as Fig. 11 shows.

As power setting reduces, relative rotational speed and isentropic efficiency reduce faster for the default 0D compressor model than do for the high-fidelity component. Moreover, the faster reduction in engine mass flow contributes to the faster reduction in engine's gross thrust compared to the performance obtained with the 2D SLC fan model.

7.2 Effect of intake geometry

As a second case study, the effect on engine performance of three intake lip geometries (namely a rounded-circular, a rounded-elliptical and a sharp lip geometry) was examined throughout a range of engine power settings, AoAs between 0 and 25 degrees, and flight Mach numbers between 0·0 and 0·2. Figures 12 to 15 illustrate the overall engine performance obtained for the three intake lip configurations at a flight Mach number of 0·05 (approx. ISA-SLS), angle of attack of 20 degrees and a range of engine power settings from a TET value of 1,000·0K (DP value) down to a TET value of 750·0K approximately. A direct comparison against a reference engine performance was not possible since PYTHIA does not have the capability to model intake geometries or the effect of angle-of-attack.

The worse intake pressure recovery at the design point power setting was achieved by the sharp lip configuration (0·8945), followed by the rounded-circular lip configuration (0·9452), with the rounded-elliptical lip geometry providing the higher intake pressure

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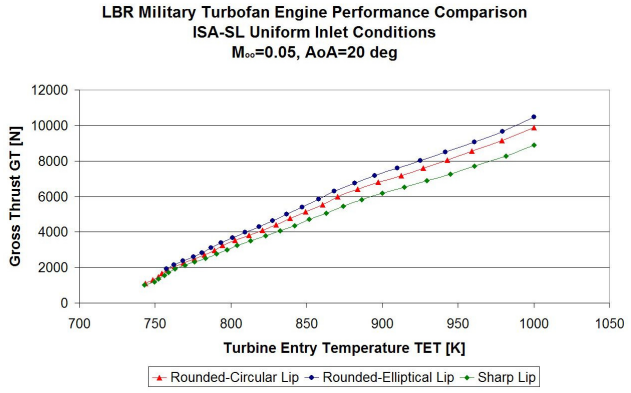


Figure 13. Comparison of engine performance obtained with different lip geometries – gross thrust *vs* turbine entry temperature.

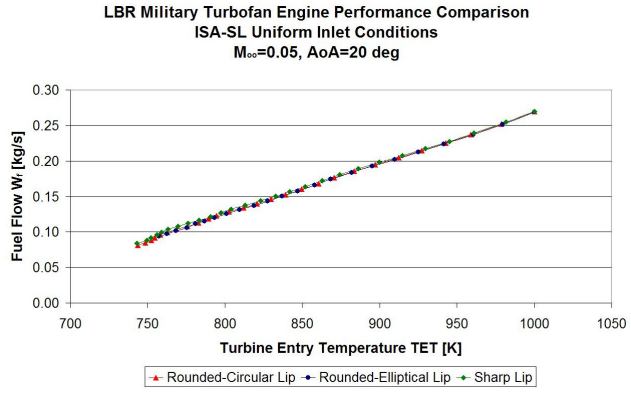


Figure 14. Comparison of engine performance obtained with different lip geometries – fuel flow *vs* turbine entry temperature.

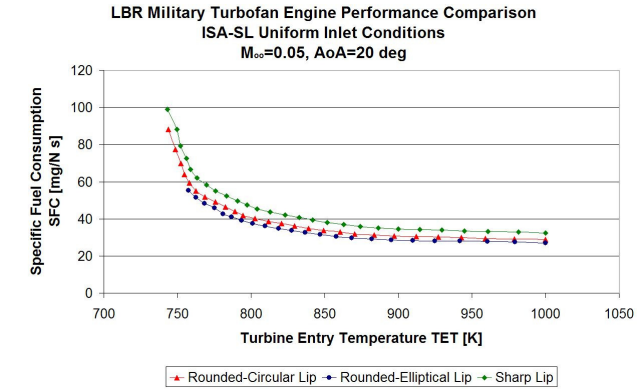


Figure 15. Comparison of engine performance obtained with different lip geometries – specific fuel consumption *vs* turbine entry temperature.

recovery (0.98), and also the best engine performance (Fig. 12). Engine gross thrust was found to reduce by 15·0% with a sharp-lip inlet, compared to the performance calculated with an elliptical lip at the design power setting. Similarly, the circular lip delivered 5·6% less gross thrust than the elliptical lip (Fig. 13). Fuel flow variation remained more or less the same throughout the power range examined, for all three lip designs (Fig. 14). The SFC however, rose by 9·1% and 18·8% for the circular and sharp lips respectively, with respect to the SFC calculated for the elliptical lip (Fig. 15).

Generally, this relative difference in engine performances actually increased at lower power settings due to the reduction in engine thermal efficiency and the shape of the SFC curve. The relative differences in engine gross thrust reduced towards low power settings as pressure recovery rose for all intake geometries to values close to 1·0 due to the reduced engine mass flow.

8.0 DISCUSSION AND CONCLUSIONS

It becomes rather obvious that 0D tools will always be limited by the accuracy of the component characteristics they incorporate and that 1D/2D tools will always be limited by the accuracy of the various loss models they incorporate. It must be pointed out that the proposed method is more advantageous than the traditional 0D approach which is based on default maps, normally established for nominal operating conditions, especially when experimental data are not available. The simulation strategy proposed in this manuscript offers greater flexibility and is much more straightforward, removing the need to manipulate component maps altogether. Having fully integrated 2D models in the cycle analysis, these can be called and executed at run time to produce the component's performance (for given operating conditions) without having to calculate the whole map at all. An improvement in accuracy results from the direct interaction of the 2D components via the 2D flow field and the fact that averaging of flow properties is avoided. A comparison with other methods such as 3D CFD should perhaps not be made in terms of accuracy but speed of execution and computational power. Nevertheless, it is these authors' view that the significance of the proposed simulation strategy is in the flexibility it offers to incorporate in-house experience and expertise in the form of loss and deviation models. This could be developed into a powerful simulation tool within industry (utilising industry's resources and expertise) and is something that CFD tools normally do not offer.

More analytically, this work demonstrated the potentials of a fully integrated approach to high-fidelity analysis utilising 2D SLC component models, directly coupled to a 0D engine performance simulation software. The simulation strategy that was discussed here is a fully automated one, can be applied to all engine components and does not require the generation of component characteristic maps which generally tend to restrict the applicability of low-fidelity cycle programs.

First of all, this paper discussed briefly the development of 2D SLC software for intakes and compressors, its validation against experimental data and its subsequent integration with a low-fidelity cycle analysis program. Subsequently, this manuscript described how two 2D SLC component models were used in the 0D cycle analysis to account for component geometry changes and to provide a more accurate, physics-based estimate of intake, compressor and overall engine performance, under various operating conditions other than nominal.

The above analysis proves the potential of the simulation strategy presented in this paper to investigate relevant physical processes occurring in an engine component in more detail, and to assess the effects of various isolated flow phenomena on overall engine performance in a timely and affordable manner. Moreover, in contrast to commercial CFD tools, it allows in-house empiricism and expertise to be incorporated in the flow-field calculations in the form of deviation and loss models. In this case, the integration of two high-fidelity SLC components into a 0D cycle analysis facilitated engine performance calculations taking into account the full geometry and performance of two engine components within realistic and practical computational resources. What was demonstrated in this case is of great importance since it has the potential to evolve into a full engine 2D analysis with the addition of more 2D components.

At this stage, the reader should be reminded that the objective of this work was the demonstration of a certain capability. Engine performance results presented in this report are to be taken only

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qualitatively, because of the notional nature of the engine model used. Moreover, the geometry of the 2D SLC intake model was artificial and therefore its calculated performance, and resulting engine performance, should not be taken quantitatively. It is the integration of the high-fidelity components into a 0D cycle analysis, and the relative changes in engine performance that are of interest here (larger than 1%), and not the accurate design of engine components.

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