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Design Study of Propulsion and Drive Systems for the Large Civil TiltRotor (LCTR2) Rotorcraft

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ABSTRACT

Boeing, Rolls Royce, and NASA have worked together to complete a parametric sizing study for NASA's Large Civil Tilt Rotor (LCTR2) concept 2nd iteration. Vehicle gross weight and fuel usage were evaluated as propulsion and drive system characteristics were varied to maximize the benefit of reduced rotor tip speed during cruise conditions. The study examined different combinations of engine and gearbox variability to achieve rotor cruise tip speed reductions down to 54% of the hover tip speed. Previous NASA studies identified that a 54% rotor speed reduction in cruise minimizes vehicle gross weight and fuel burn. The LCTR2 was the study baseline for initial sizing. This study included rotor tip speed ratios (cruise to hover) of 100%, 77% and 54% at different combinations of engine RPM and gearbox speed reductions, which were analyzed to achieve the lightest overall vehicle gross weight (GW) at the chosen rotor tip speed ratio.

Different engine and gearbox technology levels are applied ranging from commercial off-the-shelf (COTS) engines and gearbox technology to entry-in-service (EIS) dates of 2025 and 2035 to assess the benefits of advanced technology on vehicle gross weight and fuel burn. Interim results were previously reported[1]. This technical paper extends that work and summarizes the final study results including additional engine and drive system study accomplishments. New vehicle sizing data is presented for engine performance at a single operating speed with a multispeed drive system. Modeling details for LCTR2 vehicle sizing and subject engine and drive sub-systems are presented as well. This study was conducted in support of NASA's Fundamental Aeronautics Program, Subsonic Rotary Wing Project.

INTRODUCTION

Rotorcraft propulsion systems generally operate within a narrow range of rotor tip speeds. However, tiltrotor aircraft are able to utilize a wider range of rotor cruise tip speed (Vtip). For example, the V22 operates at a higher RPM (103.8%) for hover operations and at a lower RPM (84%) for airplane cruise conditions. This study was conducted to identify and evaluate propulsion system concepts to achieve a rotor cruise Vtip of approximately 54% of the hover Vtip for a large civil tiltrotor air vehicle. It also investigates the most advantageous speed variation strategies and technologies for the integrated engine and drive system. The evaluation was performed for the NASA Large Civil Tiltrotor (LCTR2) configuration, shown in Figure 1, resizing the aircraft according to the impact of component weights, engine and rotor performance, and mission fuel. .

The NASA LCTR2 payload is 90 passengers, weighing 19,800 pounds with baggage. Vehicle characteristics include a takeoff gross weight of 107,700 pounds, with 65 foot diameter rotors near the wing tips. The LCTR2 design rotor tip speed is 650 fps during takeoff / hover to maintain high rotor efficiency and to manage noise levels during takeoff and hover. The vehicle then decreases to a 350 fps rotor Vtip for cruise, or 54% of the hover RPM. The four engine arrangement was selected for hover OEI conditions, with transmission technology comparable to Advanced Rotorcraft Transmission Program (ART I & II, AATD Program[2]).

This paper summarizes many of the efforts and accomplishments by Boeing and Rolls-Royce engineers under NASA NNA06BC41C Task Order 10 entitled, “Engine/Gearbox Assessment for 50% Variable Rotor Tip Speed”. The study analyzed operation at full rotor tip speed and at partial tip speeds of 77% and 54% for climb and cruise segments of the mission profile, which dominate fuel usage. The cruise condition is 310 knots, at 25,000 ft altitude for a range of 1000 nm.

While an overview of the project and results were presented in Reference 1, the current paper provides additional details of the analysis methodology, notional propulsion and drive system configurations, and additional vehicle sizing data for an EIS 2035 engine configuration focused on optimized engine performance near 100% (engine) speed with a fixed-geometry variable-speed power turbine (VSPT).

The primary goal of this study is to identify the best engine and drive system concepts and technology to achieve a 54% rotor cruise Vtip variation, and desired operating economics, for the LCTR2 rotor disk loading, fuselage size, and mission profile. Project tasks include an evaluation of LCTR2 vehicle sizing and performance characteristics, development of sizing methodology, generation of engine data for COTS and advanced technology engines (EIS 2025 and 2035), development of the drive system configurations and performance, analysis of prop-rotor performance, assessment of advanced technologies and operational scenarios conducted at 54% rotor cruise Vtip, and identification of technology challenges and needs for the overall system.

Figure 1: Conceptual view of LCTR2.

TECHNICAL APPROACH

Three engine and drive system technology levels were studied in this effort: commercial off the shelf (2015 / COTS), and technology levels expected for 2025 entry into service (EIS), and 2035 EIS. These configurations were evaluated to find the propulsion and drive system configuration that results in minimum vehicle weight and fuel burn for the three technology levels evaluated. Operational variables affecting that balance include engine speed reduction fraction, drive system speed reduction fraction, technology factors, efficiencies, and configuration variables (fuel quantity, vehicle size). Mission characteristics of range, cruise speed, and altitude were constrained to the original NASA design. Climb and cruise segments drove the fuel consumption in this study, which had a major effect on rotorcraft sized for long-range such as the LCTR2. Results of the sizing studies, engine and drive system configuration data, and study methodologies are all presented in this report.

Rotor speed variability of 100% to 54% was achieved with two methods that were investigated as a part of this study: changing gear ratios in the output/transmission drive train and/or using highly variable output speed gas turbine engines. An additional engine was added to the study to evaluate the value of the highly variable output speed approach using fixed geometry. This fixed-geometry VSPT was optimized for operation over a large output speed range with 2035 technology. Table 1 contains the combinations of engine and drivetrain options that were evaluated in this study.

TABLE 1: ROTOR CRUISE TIP SPEED

Engine Technology (for all combinations)	Rotor Cruise Tip Speed, (%)	Engine Cruise RPM (%)	Drive System Cruise RPM, %
COTS 2015 Engine	650 fps, (100%)	100%	100%
EIS 2025 Engine 1*	500 fps, (77%)	100%	77% (2-speed)
		77%	100%
EIS 2035 Variable Geometry Engine 1* & EIS 2035 Fixed Geometry Engine 2*	350 fps, (54%)	100%	54% (2-speed)
		77%	70% (2-speed)
		54%	100%

1* refers to variable geometry 'Variable Speed' power turbine technology

2* refers to fixed geometry 'Variable Speed' power turbine technology.

An Excel based aircraft performance and sizing tool was constructed to include many of the performance and sizing procedures from VASCOMP[3]. This format allowed Boeing to perform "Concept Evaluation" analysis for the LCTR2 air vehicle. The sizing tool used basic aircraft parameters from the LCTR2 vehicle design. such as fuselage size and wing characteristics, and incorporated scalable engine performance models, prop-rotor performance models, and drive system characteristics. Fuselage characteristics remained constant while wing parameters and all performance models (engine, drive and rotors) provided scalable input and output for the vehicle sizing model. The sizing tool is described in the Vehicle Sizing section of this paper which is preceded by descriptive sections on engine, prop-rotor and drive system models.

ENGINE MODELS

Team-mate Rolls-Royce provided tabulated engine data for different advanced technology engines at each of the specified engine operating speeds. Four engine technologies at three operating RPMs gave a total of twelve combinations of engine data. Each set of data covered power available, fuel flow and residual thrust over an operating range of Mach number and altitude.

Power available is tabulated at the takeoff max rated power (MRP), intermediate rated power (IRP), and max continuous power (MCP) for each of the twelve combinations of engine data. Referred fuel flow collapsed well versus referred horsepower for all power settings and altitudes, and was modeled in Visual Basic (VB) as part of the Excel sizing program. Figure 2 shows sample data supplied by Rolls-Royce for the 2035 variable-geometry VSPT engine (PD 647).

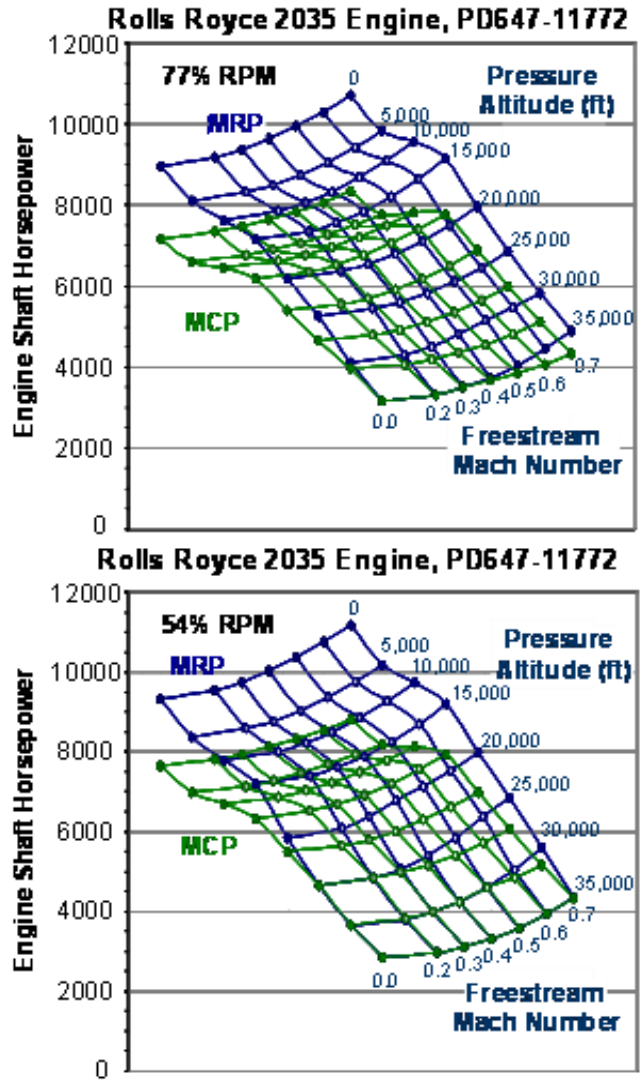

Figure 2: 2035 EIS Variable Geometry Engine Power Available at 54% Speed and 77% (sample data supplied by Rolls-Royce)

The baseline COTS (2015) engine is a current technology core of the appropriate flow size with a free power turbine driving the rotorcraft transmissions. The engine design and cycle performance are representative of commercial production technology generally available in the industry today. Engine component matching is optimized to provide good performance and high levels of efficiency over a broad power and speed regime, see Figure 3.

Figure 3: Representative Image of the EIS 2015 Engine.

The 2015 engine configuration is an axial core with a conventional compressor and cooled turbine, along with a free power turbine. The turbine in this turboshaft application is only driving a power output shaft and will therefore be referred to it as a power turbine (PT), consistent with the helicopter world. The compressor has variable geometry stators to allow satisfactory operation at off-design speeds. The power turbine matching was optimized to provide good efficiency between 80% and 100% RPM. As such, the engine is well suited for a variable speed transmission/rotor system with operation down to a 77% shift point. When coupled with a fixed transmission gear ratio, there is an appreciable drop in performance at PT speeds below 77%, resulting in non-optimal performance at 54% PT speed due to the wide variation in power turbine inlet incidence angle, which occurs at significantly reduced power turbine speeds.

The 2025 engine utilizes COTS engine architecture with future technology insertion to improve performance and provide greater efficiency at reduced output speeds. It incorporates cooling and materials improvements to allow an increase in cycle temperatures based on projected technology maturation over the next 10 years. This engine also features the addition of variable geometry in the power turbine. With the fixed geometry COTS engine, incidence angle changes in the power turbine due to the speed difference between 100% takeoff and the 54% cruise operating rotor speed leads to efficiency losses. For the 2025 engine, turbine geometry is varied to accommodate wide variations in incidence resulting in appreciable improvement in specific fuel consumption (SFC) at the cruise condition, which is a major driver in mission fuel consumption.

The 2025 engine variable turbine control system and mechanism does result in an increase in power plant system weight, which is accounted for in the aircraft studies. The 2025 engine data were supplied to Boeing in tabular form, with scaling factors to allow performance, weight, and envelopes established across a broad power range.

Two versions of the advanced technology 2035 VSPT engines were constructed for this study, one with a variable geometry turbine shown in Figure 4, the other with a fixed geometry turbine. These engines are based on a new, higher technology core with a high cycle pressure ratio, improved engine component efficiencies, and increases in turbine inlet temperature representative of technologies expected for the 2035 timeframe. The aggressive overall pressure ratio (OPR) target of the 2035 engine resulted in a departure from the architecture employed in the 2015 and 2025 engines.

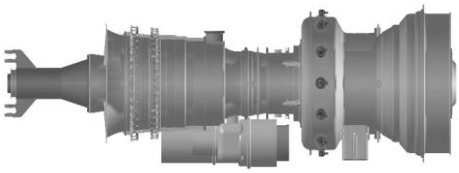

Figure 4: Representative Image of the EIS 2035 Engine.

To provide good operability and part power efficiency, the Rolls-Royce PD647 2035 variable geometry engine is a three-shaft design with Intermediate Pressure (IP) and High Pressure (HP) spools. The IP compressor is an all-axial configuration, while the HP compressor is an axial-centrifugal unit that has an appreciable efficiency benefit over an all-axial design given the low exit corrected flow rates produced by the high OPR cycle. Both the HP and IP turbines make full use of the advanced materials and cooling technologies based on projected technology maturation for this time period. The advanced power turbine was an uncooled variable geometry that provided substantially improved power available and reduced fuel flow at reduced operating RPM along with significantly reduced envelope and weight. The engine also embodies advanced controls and diagnostic technologies.

The Versatile Affordable Advanced Turbine Engine (VAATE) technologies reflected in the PD647 provided a significant weight reduction relative to the 2015 and the 2025 engines, as shown in Table 2. But the variable geometry power turbine feature that provided the excellent performance also carried a weight penalty.

TABLE 2: ENGINE DRY WEIGHTS

Engine	Installed SHP (MRP/SLS)	Engine Dry Weight	HP/Weight Ratio
2015 (COTS)	8100 HP	1356 lb	5.97
2025 (PD646)	8088 HP	1556 lb	5.20
2035 Variable Geom. VSPT (PD647)	8088 HP	1020 lb	7.93
2035 Fixed Geom. VSPT (PD628)	8086 HP	807 lb	10.0

NASA Glenn Research Center wanted to include in this assessment the application of 2035 VAATE technologies for a fixed geometry variable speed power turbine (VSPT). The core would be the same as the previous advanced and high performance EIS 2035 engine. For a typical aircraft mission, such an engine design would have a 3 stage power turbine, optimized for operation around 90 to 100% rpm and limited capability outside this range (much like the COTS engine). But due to recent VSPT research efforts[4], Rolls-Royce generated performance data for this engine assuming VSPT technology, optimized around 90% rpm.

The fixed geometry VSPT design includes an extra power turbine stage which was used in the overall design to improve performance and operability over the variable speed range with only minimal additional weight and complexity. This PD628 engine was rated at essentially the same max power at 100% RPM and sea level standard (SLS) conditions as the previous three engines. As shown in Table 2, the PD628 engine with its fixed geometry VSPT weighs 213 lb less than the 2035 engine with a variable geometry VSPT – a substantial 20% weight reduction. And it was 40% lighter than the 2015 COTS engine.

Engine power and fuel flow at reduced engine RPM was a primary focus of the study. Figure 2 showed an example of MRP and MCP shaft horsepower (SHP) for the 2035 PD647 engine at 77% and 54% RPM. In this case, available SHP actually increased at reduced RPM, relative to 100% RPM, for this advanced engine with a variable geometry power turbine, an opposite trend from normal engine performance at reduced RPMs.

Engine data from each case was reformatted for use with the aircraft sizing tool. Representative fuel flow and residual thrust curves were derived. Fuel flow at the power required was obtained from polynomial curve fits to referred fuel flow versus referred power.

Figure 5 summarizes the relative fuel flow versus SHP of the 2015, 2025 and the 2035 variable geometry VSPT engine, compared to each other at the three cruise RPMs considered in this study.

Fuel flow characteristics are seen to change significantly with engine RPM, and with engine technology. The 2015 engine fuel flow increased some at 77% RPM, but dramatically increased at 54% RPM. While the 2025 engine was previously shown to be heavier, its fuel flow characteristics actually improved at reduced RPM. Lastly, the 2035 engine with its variable speed power turbine (VSPT) has substantially lower fuel flow than either of the other two engines at all RPMs and decreases some at lower RPM. And it had a higher HP/lb, shown in Table 2.

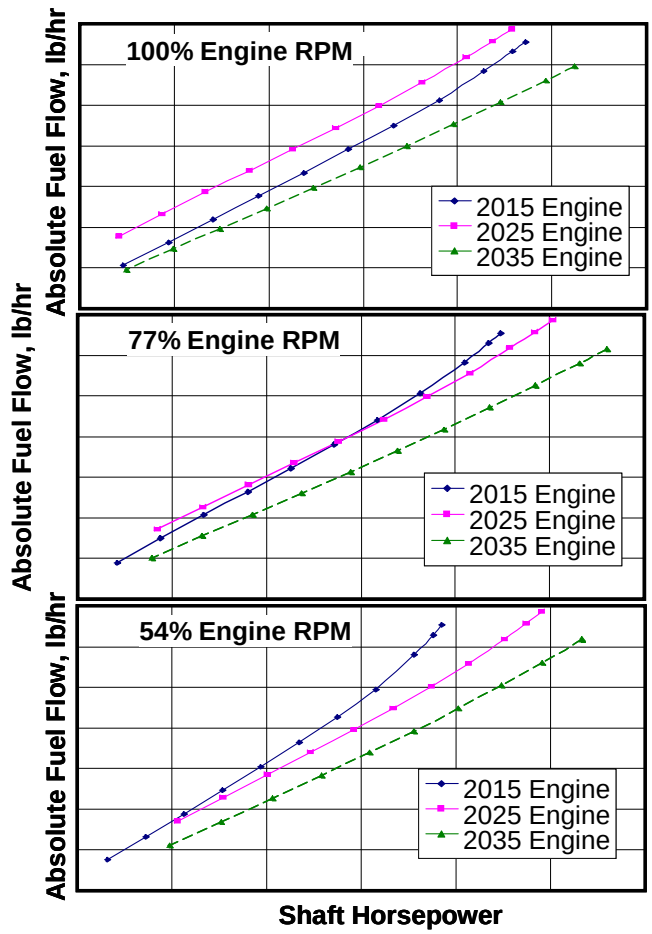

Figure 5: Comparison of Three Engines' Fuel Flow versus Horsepower.

PROP-ROTOR PERFORMANCE MODELS

NASA performed extensive studies to refine the design of the LCTR2 rotor system, including aeroelastic, performance and dynamic analyses. The reference LCTR2 rotor is a four-bladed, 65 ft diameter rotor, with an overall taper ratio of 0.70, a bi-linear blade twist of -38°/-30°, and a thrust-weighted solidity of 0.133.

Using the NASA defined LCTR2 rotor blades, the current study re-evaluated rotor performance with standard Boeing tools within the scope of the project. The geometric twist distribution of the LCTR2 blade was maintained for the 350 fps cruise Vtip rotor and Boeing's predicted rotor performance was very close to that from NASA.

Boeing continued to use NASA airfoil data, the LCTR2 radial distribution of airfoils, blade planform and rotor solidity to define rotor designs for the two additional rotors with cruise Vtip of 500 fps and 650 fps. They were given modified twist distributions to align the local blade chordline with the oncoming flow at the nominal design cruise condition of 310 ktas at their respective cruise tip speeds. In accordance with the statement of work, no blade

optimization was performed to further refine the resulting twist distributions for the cruise condition or to balance the design for hover performance.

NASA supplied 'C81' format airfoil data for the LCTR2 rotor design, which Boeing converted to a format required for the Boeing B08 rotor performance analysis. The airfoil tables were installed as library files available to the B08 program. Boeing applied the NASA blade airfoil performance characteristics and definition of relative chord throughout this study, and the LCTR2 rotor solidity was also preserved. Absolute chord lengths changed with the rotor radius as a result of resizing the aircraft.

A comparison of the twist distributions for the three rotor designs are shown in Figure 6, and are compared to the helical inflow angles for each rotor, operating at 310 ktas. The NASA bi-linear twist for the LCTR2 rotor with the 350 fps cruise Vtip closely agrees with the helical inflow angle ($t_{wist} \cong$ atan (μ/x)) with a bi-linear twist (-38°/-30°).

The blade design for the rotor with 500 fps cruise Vtip rotor had a bi-linear twist (-50°/-34°) to closely match the helical inflow distribution at 310 ktas. It retained the LCTR2 solidity, reference blade planform and airfoil distribution.

A bi-linear twist distribution proved to be inadequate to properly align the blade for the 650 fps cruise Vtip and a tri-linear twist was used instead. Blade twist for the 650 fps rotor cruise Vtip was (-63°/-42°/-33°) for good cruise efficiency.

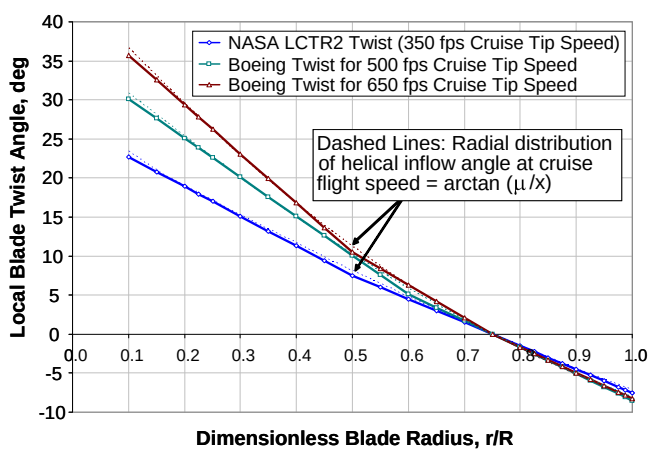

Figure 6: Comparison of Rotor Blade Twist Distributions

Rotor performance in hover and cruise for the objective rotor cruise Vtip was evaluated with Boeing's B08 blade element/momentum theory program for static and axial flight proprotor performance. The method incorporates the effect of tip loss associated with a finite number of blades through Prandtl's tip loss correction. Tip compressibility relief associated with three-dimensional flow effects near the tips is treated using the Lenard correction. The B08 program was considered sufficient for this trade study, since prop-rotor cruise efficiency is dominated by blade profile drag with relatively low induced drag, and cruise fuel is the dominant portion of mission fuel.

Rotor hover performance for each rotor design Vtip was modeled as tables of Figure of Merit (FM) versus the hover thrust coefficient (CT) at the LCTR2 hover Vtip of 650 fps and takeoff condition. Calculated installed hover performance for 500 fps and 350 fps designs are shown in Figure 7 at the LCTR2 takeoff condition of 5,000', ISA+20°C, all at 650 fps hover Vtip. The estimates of isolated hover performance were reduced by 4% thrust to account for installation effects.

Rotor cruise performance was modeled as tabulated cruise propulsive efficiency (η) versus advance ratio (μ) and thrust coefficient (C_T), for each rotor design cruise Vtip. The rotor solidity (σ) matches the NASA LCTR2 design – a result of preserving the LCTR2 values of C_T/σ, disc loading, and hover Vtip. An essential element of the sizing model was to capture differences in rotor cruise propulsive efficiency for each rotor's design cruise Vtip. Maps of rotor cruise efficiency from the B08 analysis are presented in Figure 8.

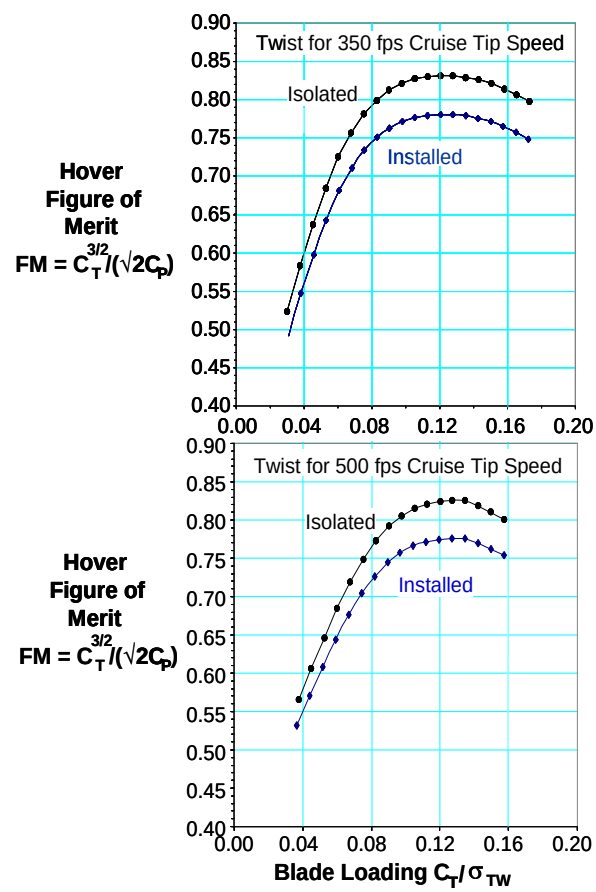

Figure 7: Rotor Hover Figure of Merit; 500 and 350 fps Cruise Tip Speed Design

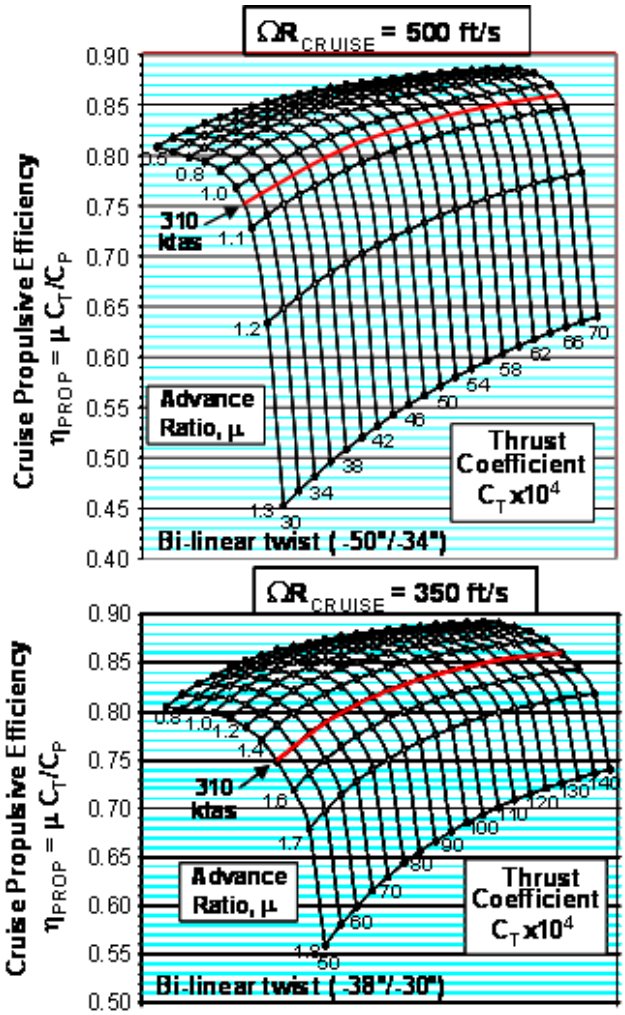

Figure 8: Rotor Propulsive Efficiency for 350 and 500 fps Cruise Tip Speed Designs

DRIVE SYSTEM MODELS

As a tiltrotor vehicle, the LCTR2 drive system general arrangement is similar to the V22 Osprey drive system. The LCTR2 configuration has evolved to a high wing, tilting nacelle aircraft like the V22 in many respects except with four engines, 2 engines at each nacelle. The notional baseline drive system for this study consists of 5 transmissions – A left hand (LH) and right hand (RH) Proprotor Gearbox (PRGB, borrowing V22 nomenclature), LH and RH Tilt Axis Gearboxes (TAGB) and a Mid-Wing Gearbox (MWGB) for cabin accessory power.

The PRGB transmissions are power-combining transmissions which collect power from the 2 engines (per nacelle) and deliver power to the rotor system. The PRGB transmissions are located near the rotor system to minimize the weight of the heavy rotor shaft. The TAGB transmissions are located on the nacelle tilting axis which is assumed to be aft of the wing rear spar similar to the V22.

For operational scenarios where all the rotor speed reduction is accomplished with engine speed variation (like the V-22), a single ratio transmission is required, see Figure 9.

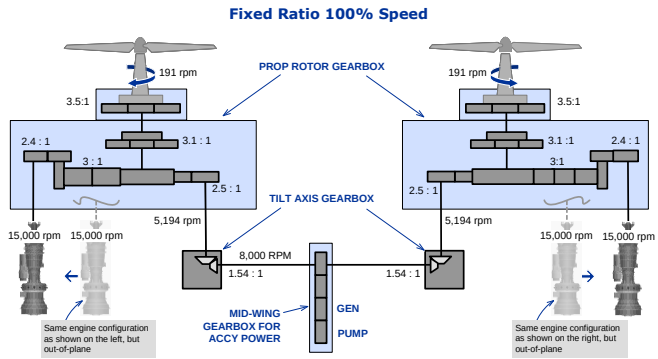

Figure 9: LCTR2 Single Speed (Direct Drive) Drive System Schematic Diagram with Helical Gears

To satisfy the reduced rotor Vtip in cruise segments of the LCTR2 mission, a variable or multi-speed configuration is needed. This configuration is shown in Figure 10. Speed changing modules are located at the input stage of the PRGB transmissions for all configurations in this study. This requires 4 speed changing modules, one at each engine input shaft. This configuration is potentially the lightest weight and most flexible configuration for speed changing events. There are additional benefits with this location in that the modules would be accessible and repairable since they can be configured as a 'line replaceable unit'

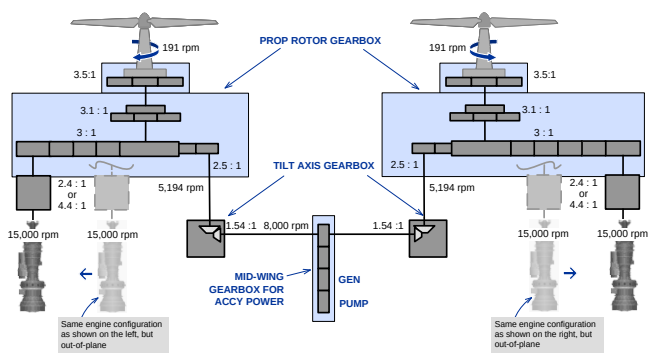

Figure 10: LCTR2 2-Speed Drive System Schematic Diagram with Helical Idler gears

Characteristics of the notional drive systems are:

- Speed changing gearboxes are located in the high speed portion of the drive train to minimize weight impacts for those devices. Engine input speed is based on a maximum of 15,000 RPM for all engines.
- A Helical Idler geartrain is used to transfer power from engines to Bull Gear, Planetary Systems and Rotor Shaft.

- Output Planetary System reduction ratios are moderate to low to allow for a rotor shaft that extends through the gearbox and is supported by a bearing in the base of the Proprotor Gearbox, similar to the V22.
- A Mid Wing gearbox is required to provide auxiliary power for control systems and cabin environmental and electrical requirements.
- Potential location for the over-running clutch is after the speed changing gearbox so that a failure in the engine or speed changing gearbox can be isolated from the remaining functional propulsion system.

The LCTR2 four-engine configuration may appear to be more complex than a two-engine tiltrotor configuration but the four-engine configuration has some distinct advantages. In the event of an engine failure, the one engine inoperative (OEI) power available from the remaining engines is only marginally less than with 'all engines operating' (AEO) and the power transfer through the wing shafting is assumed to be less in this study. This results in a lighter weight wing shaft system. There are also perceived benefits in the speed changing mechanisms, even though there are more speed changing boxes needed. With this distributed system, it may be easier to implement a (modified) sequential shifting strategy similar to the method described in NASA Report TM 2007-214842[5].

The concepts study for multi-speed systems was not exhaustive, but the scope was sufficient to support the integration and optimization for an LCTR2 scaled aircraft. Criteria used to evaluate potential multi-speed transmissions in this study include the following:

- The desired speed shifting range is 54%, which corresponds to the rotor tip speed reduction from 650 fps to 350 fps. Additional reduction ranges of 70% and 77% were defined to provide a mid-range data point in the study at 500 fps rotor speed. In this report the ratio (factor) between low and high speed reduction ranges will be referred to as the "speed change ratio", which is the 54% or 77% goals noted above.
- Overall reduction ratios for the speed changing unit must be kept low to reduce the weight in the remainder of the drive system components. For example, it is preferable to have a speed changing module that varies between a ratio of 2 and 4 than a module that varies between 4 and 8. This is particularly true with the series of helical idler gears that are located in the Proprotor Gearbox, since a high reduction ratio speed changing module would present a larger torque to this train and each gear weight would increase.

To meet the above criteria, the speed changing mechanisms considered in this study were based on compound planetary systems that can be enabled with one control input. Either a ring gear or carrier is restrained by an active (multiple disk) clutch, causing the gear ratios to change. Figure 11 shows a schematic arrangement 'Configuration B' that proved favorable for weight and operating characteristics. This configuration was practical for a large ratio change while maintaining a lower overall reduction ratio. Planet speeds were considered reasonable and this configuration worked well with the full LCTR2 drive system as shown in previous diagrams.

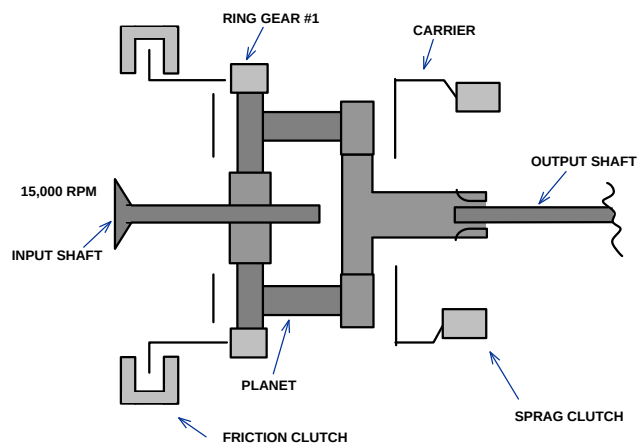

Figure 11: Speed Changing Planetary Schematic.

Similar arrangements were suggested in the NASA sponsored study described in report CR-2002-211564[6]. Relevant concepts were also discussed in CR-2002-211563[7] and in TM-2008-215276[8]. Boeing has recent experience in this area from the A160 program where a 2 speed main rotor transmission is currently in limited production.

Drive System analysis included evaluation of drive system losses for the configurations used in the sizing study as noted above. The drive system power losses were evaluated for the cruise rotor speed condition for each configuration, since cruise segments dominated the defined mission, and differences for hover conditions were considered in the study. Power loss was calculated using methods based on test experience gathered from previous programs. This method assigns a loss factor per mesh based on the type of gearing with an adjustment factor for gear speed. The loss factor includes windage, bearing friction, seals and other losses. Power loss for the high speed (helical idler) portion of the rotor gearbox was studied in greater depth since it is an area of significant power losses for the V22 drive system. Information was extrapolated from a NASA technical memorandum[9]. Table 3 and Table 4 summarize the weight and power losses of various configuration combinations.

Table 3: COTS Drive System Weights and Cruise Power Losses

Configuration	Speed, %	Engine, %	Drive, %	Rotor RPM	Tip Speed, fps	Trend Weight, lbs, Current Production	COTS Weight, lbs, Technology Factor 0.8	COTS Power Loss at Cruise Speed, %
1	100	100	100	191.0	650.0	11,236	8989	4.10
2B	100	100	100	191.0	650.0	11,758	9406	4.70
2B	77	100	77	147.1	500.5	11,758	9406	4.35
1	77	77	100	147.1	500.5	11,236	8989	3.85
2B	77	77	100	147.1	500.5	11,872	9497	4.35
3B	54	100	54	103.1	351.0	12,086	9669	3.90
1	54	54	100	103.1	351.0	11,236	8989	3.40
2B	53.9	77	70	102.9	350.4	11,872	9497	3.80

Table 4: 2025 and 2035 Drive System Weights and Cruise Power Losses

Configuration	Speed, %	Engine, %	Drive, %	Rotor RPM	2025 Weight, lbs, Technology Factor 0.75	2035 Weight, lbs, Technology Factor 0.70	2025 Power Loss, %. Technology Factor 0.95	2035 Power Loss, %. Technology Factor 0.90
1	100	100	100	191.0	8427	7866	3.90	3.69
2B	100	100	100	191.0	8819	8231	4.47	4.23
2B	77	100	77	147.1	8819	8231	4.13	3.92
1	77	77	100	147.1	8427	7866	3.66	3.47
2B	77	77	100	147.1	8904	8310	4.13	3.92
3B	54	100	54	103.1	9065	8460	3.71	3.51
1	54	54	100	103.1	8427	7866	3.23	3.06
2B	53.9	77	70	102.9	8904	8310	3.61	3.42

Configuration B consists of a Sun Gear # 1 as the input and a Sun Gear # 2 as the output. Speed changing is accomplished by holding either Ring Gear # 1 or the Carrier stationary with clutches while the other rotates freely. In this case, a (spring apply, hydraulic pressure release) friction clutch is used to stop and hold the ring gear during hover while a sprag clutch is used to hold the carrier stationary for cruise condition. Figure 12 and Figure 13 show recent progress for the speed changer concept sketches.

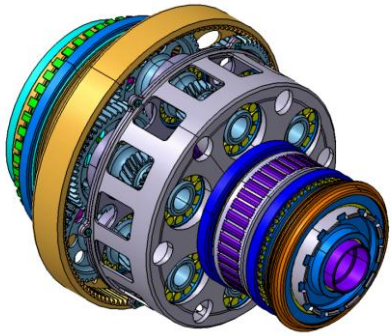

Figure 12: Speed Changer Gearbox: Isometric View

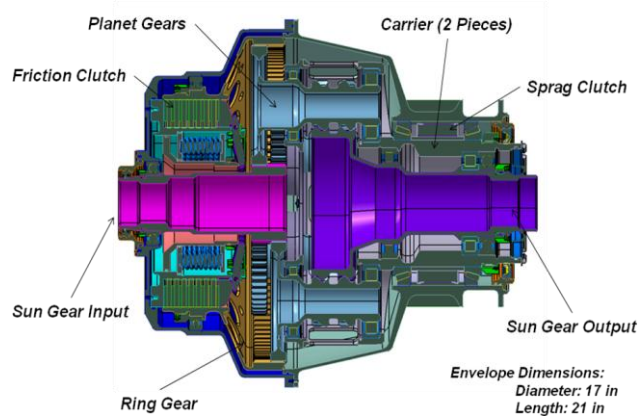

Figure 13: Speed Changer Gearbox: Section View

Models have been generated for most of the major components and supporting analysis done to size gears, bearings and clutch elements. Details regarding this drive systems configuration will be reported in later works.

VEHICLE SIZING APPROACH

NASA provided reference values for the LCTR2 aircraft dimensions, empty weight, mission fuel, and empty weight/gross weight ratios (EW/GW), rotor performance and mission performance. This data provided the basis for all drag and performance calculations.

The NASA LCTR2 fuselage size was used throughout the study. The component weights were scaled up or down with size relative to the Boeing weight estimate for the baseline LCTR2 design, using VASCOMP parametric weight relationships. Structural weights were based on 2025 technology throughout this study to avoid confusing the results by introducing another variable.

Boeing aircraft drag was primarily based on the LCTR2 reference data, scaling the wing profile drag with wing area and using a slightly modified efficiency for induced drag. Rotor diameter, wing span and area, and horizontal tail area changed with GW, maintaining the LCTR2 disk loading and wing loading.

Model assumptions relative to the LCTR2 configuration design are listed below:

- LCTR2 wing loading, sweep, aspect ratio and taper ratio were preserved. Wing area depended on GW.
- LCTR2 wing tip extensions and span were preserved.
- The LCTR2 rotor tip clearance from the fuselage side to inboard rotor tip was preserved.
- LCTR2 fuselage size was preserved, including diameter, length, wetted area, and tail moment arm.

- LCTR2 horizontal tail volume coefficient was preserved. Horizontal tail area depended on wing area and MAC (mean aerodynamic chord).
- LCTR2 rotor hover Ct/σ, disc loading, and number of blades were preserved. Solidity was therefore preserved. Rotor diameter depended on GW.

Model assumptions relative to the LCTR2 performance are listed below:

- Retained NASA hover download/Thrust
- Retained NASA fuel flow conservatism of 5%
- Equivalent flat plate area (fe) was scaled from the NASA fe of 34.18 sq.ft. according to the area of the wing and tail surfaces. Fuselage fe was retained for the NASA LCTR2 fuselage. A VASCOMP value was used for the Oswald induced drag factor.
- Transmission was sized to Hover out of Ground Effects or Cruise torque (cruise for low Vtip).
- Retained NASA mission profile, fixed equipment, and payload weight for 90 passengers with baggage.
- HP available for climb and cruise was limited by transmission rating at cruise RPM.
- The LCTR 4-engine arrangement was preserved. The one-engine-inoperative (OEI) performance was preserved (90% of HOGE SHP is obtained with an assumed 20% contingency power for 4 engines, when engines are sized to HOGE at the design GW).
- The LCTR2 limit load factor of 3.0 was preserved at the design takeoff GW.

Aircraft size and performance was evaluated with an Excel performance and sizing tool, This excel tool modeled most of the VASCOMP performance and sizing procedures in a format that allowed Boeing to perform "Concept Evaluation" analysis for the LCTR2 air vehicle. Boeing generally uses the VASCOMP sizing program[10] to evaluate aircraft size and performance for tiltrotor type aircraft. However, the work to be performed in this study required evaluation at different combinations of engine RPM and drive system RPM, which are not independently modeled in VASCOMP. The alternative spreadsheet approach was chosen to utilize data from various sources and formats without the expense of modifying standard Boeing tools and engine decks to achieve the same result.

Mission performance was evaluated with standard performance equations for hover, climb, and cruise at specific airspeed and altitude. Rotor cruise performance was modeled with table lookup routines of cruise efficiency versus rotor thrust coefficient and advance ratio, similar to VASCOMP. Rolls-Royce engine shaft horsepower available data was tabulated at MRP, IRP and MCP versus altitude and Mach number (all climb and cruise flight segments were at ISA conditions).

The installed engine power required for each LCTR2 sizing case was scaled to the greater of hover takeoff power or cruise power. Engine scaling assumed SFC was preserved for the same relative power, altitude and Mach number. Power required for LCTR2 cruise performance accounted for the Rolls-Royce engines' residual jet thrust. Fuel flow was obtained from referred fuel flow versus referred power, against Mach number and altitude. Mission fuel was calculated for each LCTR2 mission segment and summed up to total fuel required. Fuel was calculated at seven (7) climb altitudes, sequentially evaluated at the corresponding gross weight during climb, and at four (4) cruise segments.

The NASA mission profile for the LCTR2 was used to size all cases. No attempt was made to find or use a more optimum altitude, or cruise airspeed, or to evaluate other mission ranges. The LCTR2 sizing mission profile is described in Figure 14.

- 5 minute warm up at IRP power at 5,000'/ISA+20°C
- 2 minute hover takeoff at 5,000'/ISA+20°C
- Climb to 25,000' cruise altitude at MCP, ISA
- Cruise at 25,000'/ISA, 310 ktas to a range of 1000 nm
- Vertical descent (no time, no fuel, no distance)
- 1 minute hover landing at 5,000'/ISA+20°C
- 30 nm cruise allowance for alternate destination, Vbr (airspeed (velocity) for best range) at 25,000'/ISA
- 30 minute reserve fuel at Vbr, 10,000'/ISA

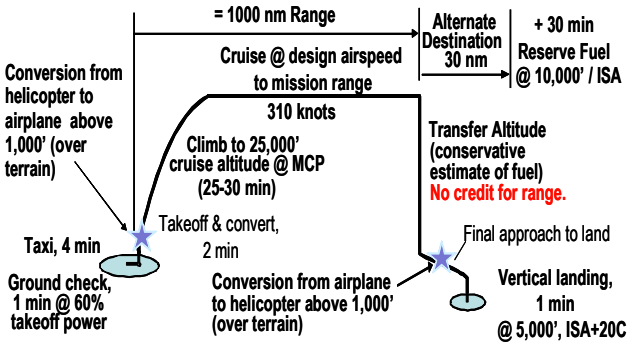

Figure 14: Mission Profile

VEHICLE SIZING RESULTS

All LCTR2 sizing cases were run with the NASA choice of a 650 fps rotor hover tip speed. The rotor cruise tip speed of 500 fps was obtained by either;

- A 2-speed gearbox (77%) with the engine at 100%RPM.
- A single-speed gearbox with the engine at 70% RPM.

The rotor cruise tip speed of 350 fps was obtained by either;

- A 2-speed gearbox (54%) with the engine at 100% RPM
- A 2-speed gearbox (70%) with the engine at 77% RPM
- A single-speed gearbox with the engine at 54% RPM.

Sizing With The 2015 Engine

Sizing results for the COTS engine study matrix are presented as bar graphs in Figure 15 and Figure 16. The three cases at 350 fps Vtip (54% of hover RPM) examines the effect of engine RPM reduction versus drive system RPM reduction. The engine was sized by hover power required, except for the case with the engine operating at 54% RPM, pointing out the need for an engine design with improved cruise performance at this low cruise RPM.

The gross weight at 54% engine RPM (350 fps rotor cruise Vtip) was driven up by an 11% increase in required fuel relative to the 100% engine RPM case. Notably, the engine was sized by cruise power required at this 54% engine RPM, and it required more installed SHP than either the 100% or the 77% engine RPM cases. The least takeoff GW for the 350 fps rotor cruise Vtip was at the intermediate condition of 77% engine RPM, although that did not demonstrate much improvement from the 100% engine RPM.

While the 650 fps rotor cruise Vtip had the second highest GW, it was in fact no worse than the result for the 350 fps case with a two-speed gearbox, even though the helical tip speed in cruise was 840 fps (M 0.82) at 650 fps Vtip and cruise airspeed. Installed SHP was still determined by the hover condition for this case, with a simple single-speed transmission. However, not surprisingly, it had the lowest rotor cruise efficiency and therefore required more mission fuel than most other cases.

The minimum GW solution occurred at the 500 fps cruise Vtip, not for the objective 350 fps cruise Vtip. Both of the 500 fps cruise Vtip cases resulted in lighter overall GW than the other four cases. The 500 fps rotor cruise Vtip had nearly the same rotor cruise propulsive efficiency as the 350 fps cases (0.839 vs. 0.845), and it gave the lightest EW and GW. The higher rotor tip speed (500 fps) had a 9% lower drive system weight than the 350 fps cases, reflecting about 30% less output torque required at the higher rotor tip speed. The lightest GW solution was for the 500 fps rotor cruise Vtip with a light weight single-speed drive system and the engine operating at 77% RPM, which did not carry the fuel flow penalty of engine operation at 54% RPM. It's GW was 2,600 lb lighter than the 350 fps rotor cruise Vtip case at 100% engine RPM.

In general, the following may be concluded from the study with the COTS engine.

- Gross Weight variation was less than expected at the different rotor cruise tip speeds.
- Sizing the engine SHP to hover resulted in smaller engines than the NASA LCTR2 (different criteria).
- Boeing transmission weights and rotor weights were generally higher than NASA LCTR2.
- Sensitivity to design cruise airspeed was found to have as much effect on GW as rotor cruise tip speed.
- Two-speed transmissions were a more efficient means of obtaining the 350 fps rotor Vtip than reducing the engine RPM.
- Reduced Engine RPM was equally as efficient as a 2-speed transmission for the 500 fps cruise Vtip.
- The 500 fps rotor Vtip resulted in lower GW than the 350 fps rotor Vtip, suggesting that the optimum rotor cruise tip speed may lie near 500 fps for a 310 ktas cruise airspeed, when engine fuel flow and drive system weights are properly accounted for.

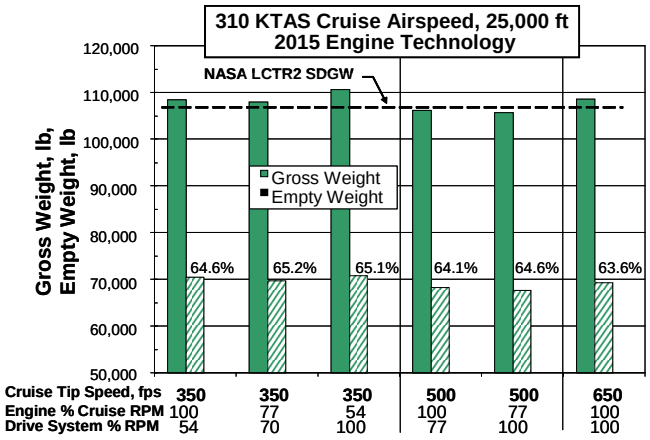

Figure 15: 2015 Engine - Effect of Rotor Tip Speed and Engine/Drive System RPM on GW

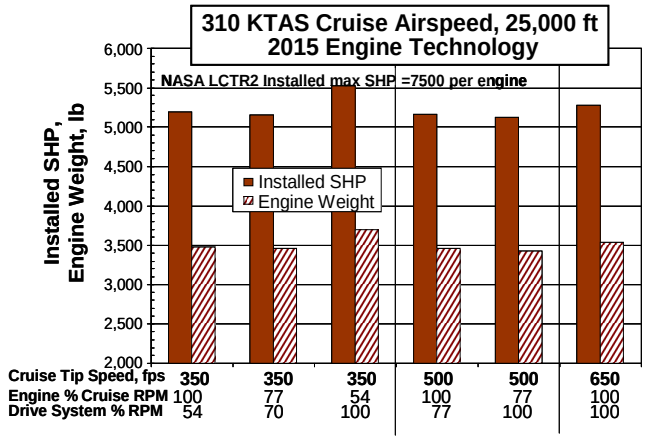

Figure 16: 2015 Engine - Installed SHP and Weight

Sizing With The 2025 Engine

The concept for the 2025 engine was to accept a relatively small increase in engine weight to gain a large expected benefit from more efficient fuel burn. The 2025 dry engine weighed more than the 2015 engine (Table 2), but its performance was a major improvement over the COTS engine for operations at reduced RPM. It displayed increased MCP power available and lower SFC at reduced RPM, whereas the COTS engine lost significant MCP power and suffered increased SFC at 54% RPM, typical of current engines, refer back to Figure 5.

Sizing results for LCTR2 with the 2025 EIS engine (PD646_11751) also reflect 2025 drive system technology that reduced drive system weight and had lower drive system losses. Sizing results, summarized in Figure 17, show the 2025 engine resulted in an overall 2% to 7% increase in aircraft gross weight, relative to the 2015 engine.

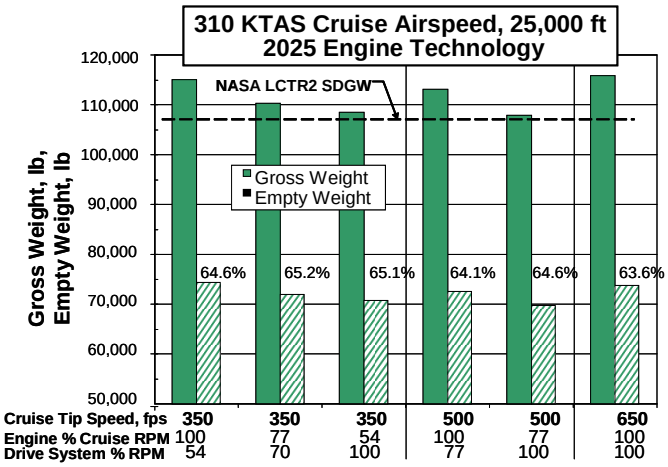

Figure 17: 2025 EIS Engine - Effect of Rotor Tip Speed and Engine/Drive System RPM on GW

The engine was sized by hover for all cases except for the 650 fps cruise Vtip case. Gross weight at 100% engine RPM is nearly the same for 650 fps cruise Vtip and for 350 fps cruise Vtip, reflecting the 2025 engine's significantly higher fuel flow at 100% engine RPM shown in Figure 17.

The GW trend at 350 fps rotor cruise Vtip was very different than the COTS engine. GW from the COTS engine cases increased with reduced engine RPM, but GW for the 2025 engine actually decreased with reduced engine RPM, owing to the significant fuel efficiency from the 2025 engine's variable geometry power turbine. The lowest GW solution came from the 500 fps Vtip rotor, with improved 2025 engine fuel efficiency at 77% engine RPM, coupled with a light weight single-speed transmission.

Installed SHP and engine weight for the 2025 engine are shown in Figure 18 with a trend similar to the GW trend. Engine weights are considerably more than for the 2015 engine, due to the double effect of more installed SHP due to the higher GW and the lower HP/weight ratio of the 2025 engines.

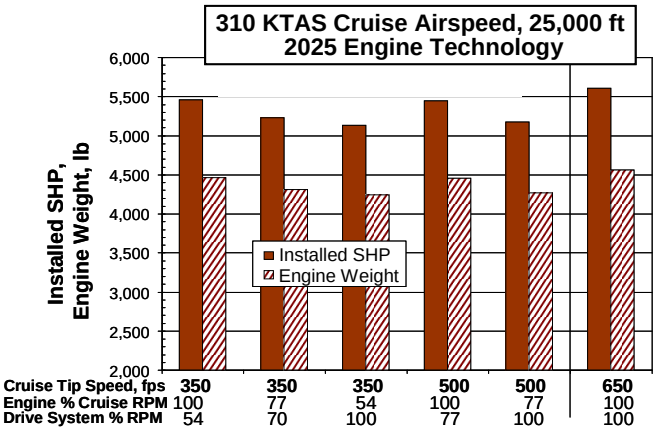

Figure 18: 2025 EIS Engine - Installed SHP and Weight

Sizing With The 2035 Variable Geometry VSPT Engine

The LCTR2 was resized again for the advanced Rolls-Royce 2035 EIS variable speed power engine (PD647-11772) with VAATE technology and its variable geometry power turbine. These cases applied the new engine performance and weight, and the estimated weight and efficiency for a 2035 drive system. Aircraft structural weights remained based on 2025 technology and the same three rotor designs were used. Results are shown in Figure 19 and Figure 20.

Fuel flow of the 2035 engine was significantly less than either the COTS engine or the 2025 engine at all operating RPMs. And the 2035 engine was significantly lighter; weighing 25% less than the COTS engine (per shp), and 34% less than the 2025 engine (per shp). The combination of reduced mission fuel and reduced engine weight had a dominant effect on LCTR sizing. Gross weight results from the 2015 engine (Figure 15) ranged from 105,700 to 110,600 lb, and results from the heavier 2025 engine (Figure 17) ranged from 108,000 to 114,700 lb. But the double benefit of reduced fuel and reduced engine weight for the 2035 variable geometry VSPT engine substantially reduced aircraft GW for all cases. GW for the lighter, more fuel efficient 2035 engine (Figure 19) ranged from 93,500 to 97,500 lb, a remarkable 14% average reduction in GW.

Overall, the 2035 engine fuel flow was much less sensitive to operating RPM than either of the previous engines, resulting in very little variation in GW across the combinations of engine and drive system RPM. Once again, the lowest GW was for the 500 fps rotor Vtip with a 77% engine RPM and the lighter weight single-speed drive system. That was closely followed by the 350 fps rotor Vtip with a 54% engine RPM and a single-speed drive system.

Figure 20 displays installed SHP and the weight of one engine for the six combinations of rotor cruise Vtip, engine and drive system RPM. As with the other engine technologies, the trend of installed SHP follows the GW.

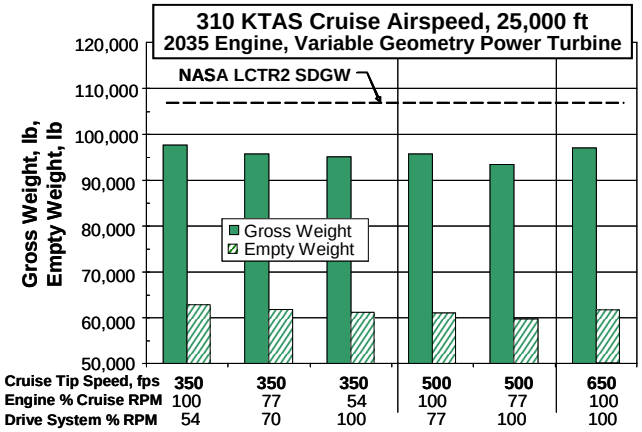

Figure 19: 2035 Variable Geometry Engine - Effect of Rotor Tip Speed and Engine/Drive System RPM on GW

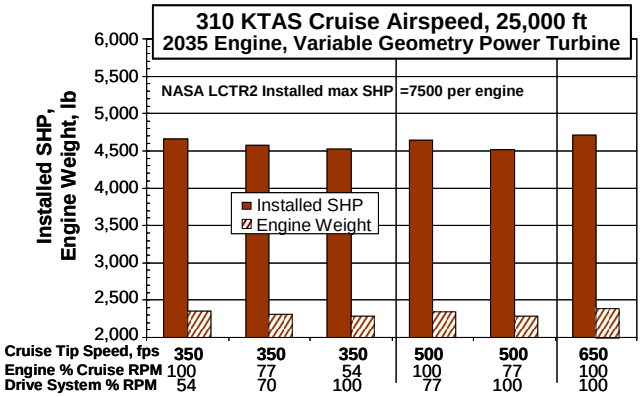

Figure 20: 2035 Variable Geometry Engine - Installed SHP and Weight

Sizing With the 2035 Fixed Geometry VSPT Engine

The fourth and final engine explored in this study was the Rolls-Royce's PD628, a 2035 EIS engine with a fixed geometry VSPT, previously discussed in this paper. This was the lightest engine of the four, with a HP/lb ratio of 10, while retaining very good specific fuel consumption.

Figure 21 compares the ratio of MCP cruise power available at 25,000 ft/ISA/Mach 0.5 to the Max Rated Power (takeoff) at SLS, across the spectrum of operating RPM for all four engines. Clearly the 2035 EIS engine with a variable geometry power turbine excelled in this measure, achieving more power at reduced RPM than it did at 100% RPM. And its excellent fuel consumption resulted in considerably lighter GW, evidenced in Figure 19. But the substantial cruise power available over-shot the LCTR2 need for cruise power. So, good as it is, it may not provide the ideal hover-cruise power match.

The PD628 engine with a fixed geometry VSPT provided about 12% more cruise power than the COTS 2015 engine at the very low 54% RPM, but far less than the 2035 engine with the variable geometry power turbine. Still, the PD628 turned out to be the best overall engine for LCTR2, providing sufficient cruise power with a very light engine (HP/lb = 10).

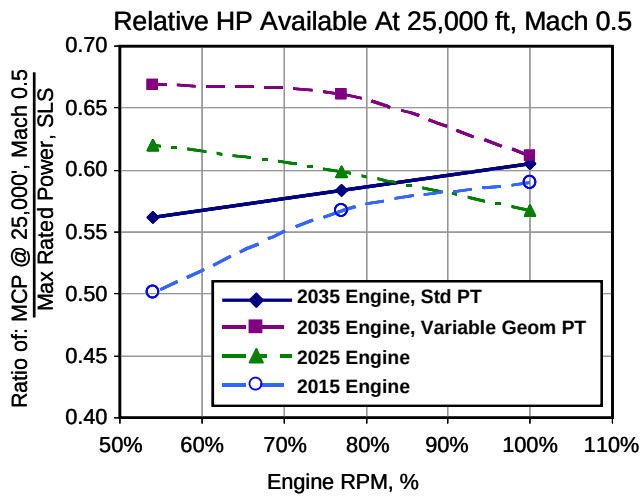

Figure 21: Relative MCP Cruise Power Available

That is a significant lesson to be taken from examining these multiple engines, drive systems and rotor tip speeds, even if not a surprising one. The best engine for the aircraft is the one that best fits the rotorcraft's particular hover and cruise requirements, while providing low fuel consumption. Features that provide excess cruise power that add to engine weight, which cannot effectively be used in flight, may not pay their way into the aircraft design.

The LCTR2 was resized with the PD628 engine to quantify the net benefit of reduced engine weight, improved fuel flow, and cruise power available. The six combinations of rotor tip speed, engine cruise RPM, and drive system speed reduction were run, and are shown in Figure 22 and Figure 23. Key points from the PD628 engine sizing cases are:

- The engine was sized by the hover condition in all cases, showing that the PD628 engine's MCP cruise power available was sufficient for the LCTR2.
- The 2035 advanced technology engine reduced fuel flow and engine weight significantly, reducing GW from about 106,000 lb GW for the 2015 engine down to about 92,000 lb for the 2035 PD628 engine. That GW difference is equivalent to another 53 passengers.

- The lightest GW design was 91,923 lb, and continued to be for the 500 fps cruise Vtip with a single-speed transmission and 77% engine RPM. This was 1540 lb lighter than with the 2035 engine with variable geometry power turbine.
- The second lightest GW design was 91,989 lb, also for the 500 fps cruise Vtip, but with a 2-speed transmission and 100% engine RPM.
- The 350 fps rotor Vtip cases sized very close to each other, between 93,900 lb and 94,900 lb GW, exhibiting little sensitivity to the combination of engine RPM-drive system RPM, reflecting the ability of the PD628 engine to operate efficiently over a broad RPM range.
- Installed SHP was nearly flat at about 4500 HP per engine, as shown in Figure 21. The installed SHP was between 0.192 and 0.195 times the aircraft GW for all six cases.

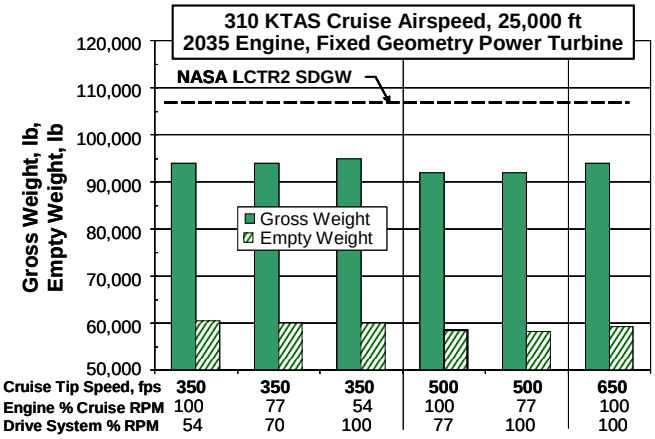

Figure 22: 2035 Fixed Geometry VSPT Engine – Effect of Rotor Tip Speed and Engine/Drive System RPM on GW

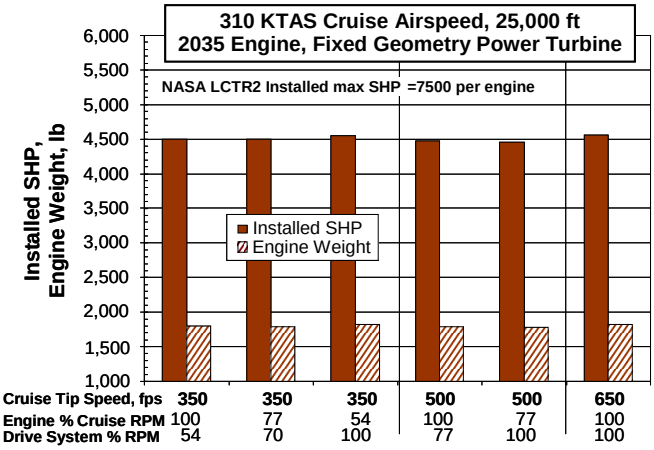

Figure 23: 2035 Fixed Geometry VSPT Engine - Installed SHP and Weight

Effect of Empty Weight, Fuel and Gross Weight

The ratio of empty weight/GW and fuel weight/GW are important indicators of aircraft overall efficiency. Together they constitute between 77% and 82% of GW. The designer has some control over these quantities, making them important measures of value. The sum of these two ratios plus the ratio of payload/GW and fixed useful load/GW must add up to 1.0, i.e. the whole GW.

The LCTR2 mission fuel is dominated by the long 1000 nm cruise segment. A typical distribution of mission fuel is: 7.2% for taxi, takeoff and landing segments, 6% for climb, 75.3% for cruise and 11.5% for the 30 nm alternate destination and 30 min reserve fuel segments. So LCTR2 mission fuel is dominated by the combined cruise efficiency of the prop-rotor, engine, and drive system. The ratio of total mission fuel/GW is a good measure of these combined efficiencies in cruise, reflecting more fuel efficient engines or improved prop-rotor propulsive efficiency. Table 5 summarizes this fuel/GW ratio at all combinations of prop-rotor cruise Vtip, engine and drive system RPM, for all four engines. It also shows the EW/GW ratio for all cases. For comparison, the NASA LCTR2 design has a fuel/GW ratio of 0.183, a fallout of the engine characteristics NASA used.

Table 5: Ratio of Mission Fuel / Gross Weight

Rotor Cruise Vtip	350 fps			500 fps		650 fps	
Engine Cruise	100%	77%	54%	100%	77%	100%	
Dr.Sys Cruise	54%	70%	100%	77%	100%	100%	
2015 COTS Engine							*Avg*
Fuel / GW	0.154	0.156	**A** 0.168	0.157	0.159	0.167	*0.160*
EW / GW	0.650	0.647	0.640	0.643	0.640	0.637	
2025 Advanced Technology Engine							
Fuel / GW	**B** 0.169	0.156	0.153	0.171	**C** 0.157	0.181	*0.165*
EW / GW	0.646	0.652	0.651	0.641	0.646	0.636	
2035 Variable Geometry VSPT Engine							
Fuel / GW	0.138	0.132	0.133	0.140	0.134	**D** 0.148	*0.138*
EW / GW	0.645	0.646	0.643	0.638	0.639	0.633	
2035 Fixed Geometry VSPT Engine							
Fuel / GW	0.131	0.134	0.143	0.133	0.136	**E** 0.141	*0.136*
EW / GW	0.643	0.640	0.633	0.636	0.633	0.632	

The right hand column of the table shows the average Fuel/GW ratio of the six cases for each engine technology. The 2025 engine shows a slightly higher average ratio than the 2015 engine. Even though advanced technology gave the 2025 engine better performance at reduced RPM, 3 of the 6 cases were operating at 100% RPM in cruise where it lost performance. The two 2035 engines with VSPT technology had similar Fuel/GW averages, much better than either the 2015 or the 2025 engine.

Several points in Table 5 are selected as examples. Point A is a particularly high Fuel/GW ratio. The 2015 engine was operating at its worst condition, 54% RPM, resulting in a high GW, over 110,000 lb. But Figure 15 showed the empty weight was nearly the same as the other cases at 350 fps Vtip, so the GW increase came from the engine's high fuel demand at a low cruise RPM. The (relatively) high Fuel/GW ratio for point A validates the value of the metric.

Another observation from Table 5 is that the sum of Fuel/GW and EW/GW fall in a narrow band, since they must add up to the total fraction of (Fuel+EW)/GW. When fuel fraction increases, the empty weight fraction generally decreases, and vice-versa. Interpretation requires some knowledge of what physical or performance attributes changed from one case to another, i.e. did engine fuel flow decrease or did engine dry weight increase? For instance, the Fuel/GW ratio decreased significantly at point C because the 2025 engine was so much more efficient at that 77% RPM than it was at the point B 100% RPM.

As expected, improved performance of the two 2035 VSPT engines show much lower Fuel/GW ratios than the 2015 or 2025 engines, at all operating RPMs. Also expected, the VSPT engines display higher Fuel/GW ratios at 650 fps Vtip (points D and E) than at lower Vtip cases, driven by the low rotor cruise efficiency at 650 Vtip, and similar to the pattern for the 2015 and 2025 engines.

COMPARISONS AND CONCLUSIONS

Study objectives highlighted in this paper were three-fold;

- Validate the benefit of reduced rotor cruise tip speeds for large civil tiltrotor (LCTR2) performance.
- Assess the tradeoffs between operating at reduced engine RPM versus employing a 2-speed gearbox to achieve reduced rotor tip speeds in cruise.
- Evaluate the potential of different engine cycles and advanced technology to improve power available at reduced engine RPM and to quantify the benefit of improved fuel flow.

Figure 21 compares the four engines' ability to achieve that objective, in terms of power. In order of their time entry into service (EIS) dates, the 2015 engine lost the most power at reduced RPM, down to half of the takeoff power at 54% rpm. That low speed was the only condition where the LCTR2 engine was sized by the cruise power required, rather than the hover power, and cruise only required about 5% more power. The 77% rpm case was still sized by hover.

The 2025 engine showed a very substantial improvement in cruise power available, up to 62% of the takeoff power. This engine was sized by LCTR2 hover power requirements for both the 54% and 77% rpm design cases. However, the 2025 engine had slightly less cruise power at 100% rpm than the 2015 engine, causing the engine to be sized by cruise at the 100% RPM design. There is obviously a fine line in achieving the right balance of cruise power available and hover power available, and that balance depends on the unique power requirements of the individual aircraft.

The 2035 engine with variable geometry VSPT achieved remarkable results. It improved the ratio of cruise power available at 100 % RPM, and it excelled at reduced RPM, providing 66% and 67% power ratios at 77% RPM and 54% RPM, respectively. This 2035 technology engine was sized by LCTR2 hover in all the sizing cases, with considerably more cruise power available than was needed for LCTR2. These results again point out the importance of tailoring the ratio of cruise power available to takeoff power available in future studies.

Lastly, the 2035 engine with fixed geometry VSPT (PD628) maintained a high ratio of cruise power available at 100% RPM (60.5%), nearly the same as the 2035 engine with the variable geometry VSPT. But it dropped off in power as RPM decreased – to about 58% at 77% RPM and 56% at 54% RPM. These fractions of MCP cruise power available at reduced RPM were higher than the 2015 engine, but far less than either the 2025 EIS or the 2035 variable geometry PT engines. The advanced technology made this engine 20% lighter weight than the advanced PD647 and 40% lighter than the 2015 engine, and it offered substantially reduced fuel flow.

LCTR2 sizing with the 2035 PD628 engine also included drive system weight reductions and improved efficiency projections for 2035, as for the previous 2035 PD647 engine. All sizing cases were run at a 25,000 ft cruise altitude and 310 ktas, matching the original NASA LCTR2 design.

- Average GW for five of the six LCTR2 sized cases with the 2015 engine was nearly equal to the NASA LCTR2 structural design GW of 107,124 lb. The one outlier was the 110,570 lb GW at the 350 fps rotor cruise Vtip operating at 54% engine RPM.
- The cases at 500 fps rotor cruise Vtip consistently sized to a slightly lower GW than any of the 350 fps cases for all four engine technologies. Additional investigation is suggested for rotor cruise tip speeds between 350 and 500

fps to determine the optimum rotor cruise tip speed from a vehicle sizing perspective.

- LCTR2 gross weight and empty weight with the EIS 2035 PD628 engine were significantly less than any case with the 2015 COTS engine, and for most cases less than the 2035 PD647 engine with the variable geometry VSPT.
- Considering the engines configured at the narrow (engine) speed range, the 2015 COTS and the 2035 fixed geometry VSPT, variation in the sizing cases for each engine was 3% or less. This suggests that the benefits of reduced speed operation for the mission, operating conditions and vehicle configurations is a relatively small effect, whereas the benefits for engine technology from the COTS engine to the 2035 engine were dramatic. Fuel efficiency and engine weight differences between those engines resulted in a 13% reduction in vehicle size cases (at 500 fps Vtip)
- Examination of the results for the 2015 COTS and the 2035 fixed geometry VSPT (PD628), at 500 fps and 350 fps rotor cruise Vtip at 100% engine RPM, showed the engine weight was 48% less with the PD628 and the resized aircraft needed 25% less fuel.
- Essentially equivalent benefits, as shown in the sizing results (GW), are derived from reduced engine RPM as from a 2-speed transmission for the 500 fps Vtip for either the 2015 engine or the 2035 engine with fixed geometry VSPT. Results for the other two engines favored 100% engine RPM with the single speed transmission.
- Additional criteria such as operating ecomonics or development cost may also affect investment decisions and determine future direction for VSPT and variable speed drive system technologies, where they provide equivalent performance benefits.

A summary comparison of GW and EW for the 2015 and the two 2035 advanced technology engines is shown in Figure 24. The 2035 technology engines clearly provide significant reductions in gross weight, resulting from both their reduced fuel flow and reduced engine weight.

The 2035 engine with variable-geometry VSPT gave the lowest GW solution when operating at the lowest engine RPM that was analyzed, because it provided plenty of power at lower operating RPM while maintaining good SFC. And, those cases benefited from a lighter single-speed gearbox.

But the LCTR2 aircraft, with its relatively high cruise L/D, did not need or use the high MCP cruise power available from the variable-geometry VSPT at reduced RPM. LCTR2 suffered the weight penalty of the variable geometry engine, gaining little if any benefit from the engine's much improved cruise performance. For contrast, the higher weight variable-geometry power turbine engine resulted in 31% higher installed engine weight and 10% more fuel than the 2035 with a fixed-geometry power turbine (for the 500 fps Vtip with 100% engine RPM and 77% drive system RPM).

The lighter weight 2035 advanced engine with a fixed-geometry VSPT gave the lowest aircraft gross weight of any engine for all six combinations of rotor cruise Vtip and engine and drive system RPM.

The 500 fps Vtip cases continued to show up as the best rotor cruise tip speed in terms of aircraft gross weight and empty weight although the effects of reduced rotor speed operation is small compared to the effect of high efficiency engine technology.

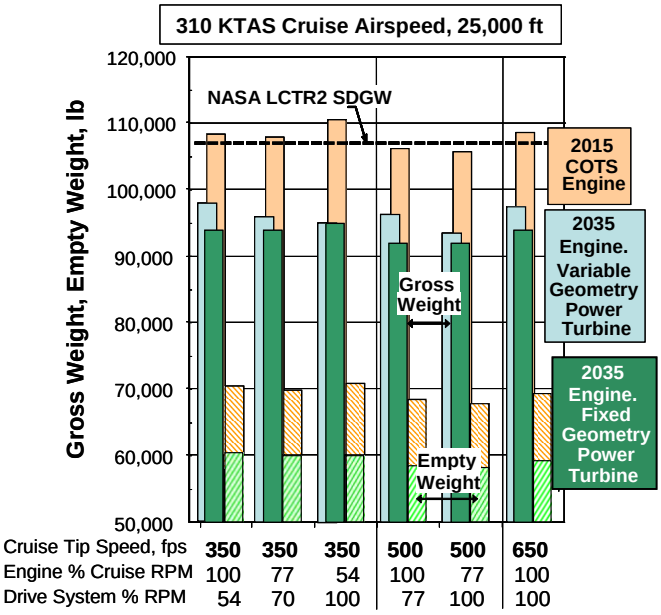

Figure 24: LCTR2 Gross Weight and Empty Weight Comparison for 2015 and 2035 Engines

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13. SUPPLEMENTARY NOTES

14. ABSTRACT

Boeing, Rolls Royce, and NASA have worked together to complete a parametric sizing study for NASA's Large Civil TiltRotor (LCTR2) concept 2nd iteration. Vehicle gross weight and fuel usage were evaluated as propulsion and drive system characteristics were varied to maximize the benefit of reduced rotor tip speed during cruise conditions. The study examined different combinations of engine and gearbox variability to achieve rotor cruise tip speed reductions down to 54 percent of the hover tip speed. Previous NASA studies identified that a 54 percent rotor speed reduction in cruise minimizes vehicle gross weight and fuel burn. The LCTR2 was the study baseline for initial sizing. This study included rotor tip speed ratios (cruise to hover) of 100, 77, and 54 percent at different combinations of engine RPM and gearbox speed reductions, which were analyzed to achieve the lightest overall vehicle gross weight (GW) at the chosen rotor tip speed ratio.Different engine and gearbox technology levels are applied ranging from commercial off-the-shelf (COTS) engines and gearbox technology to entry-in-service (EIS) dates of 2025 and 2035 to assess the benefits of advanced technology on vehicle gross weight and fuel burn. Interim results were previously reported. This technical paper extends that work and summarizes the final study results including additional engine and drive system study accomplishments. New vehicle sizing data is presented for engine performance at a single operating speed with a multispeed drive system. Modeling details for LCTR2 vehicle sizing and subject engine and drive sub-systems are presented as well. This study was conducted in support of NASA's Fundamental Aeronautics Program, Subsonic Rotary Wing Project.

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