Proceedings of the 23rd International Symposium for Air-Breathing Engines - ISABE 2017, 4-8 September 2017, Manchester, UK
Available online https://isabe2017.org/

The Impact of Clean Sky Technology on Future 3500 lb Single Engine Light Rotorcraft

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ABSTRACT
This manuscript describes a collaborative research effort between members of the Clean Sky Joint Technology Initiative (JTI), within the broader area of novel rotorcraft engine technology and rotorcraft operations. The Clean Sky JTI was created as a public/private partnership between the European Commission and the aeronautical industry. The paper assesses the impact of innovative engine technologies to be integrated into the next generation of rotorcraft and evaluates their potential towards meeting the ACARE 2020 goals. The focus is on the lower segment of the light helicopter class with a particular interest in the performance of two innovative powerplants: an advanced turboshaft with Lean Premixed Prevaporised (LPP) combustor design and a supercharged diesel cycle engine. In order to evaluate their benefits alongside other Clean Sky technologies, a multi-disciplinary rotorcraft performance analysis framework (PhoeniX) is employed. Two variants of the same light helicopter platform with year 2020 technology plus Clean Sky innovations are modelled, named hereafter as Single Engine Light (SEL) Y2020 and High Compression Engine (HCE) Y2020, respectively. A turboshaft engine-powered helicopter, representative of year 2000 technology (SEL Y2000) is also modelled and used as reference. Payload-Range diagrams (PR) of the three vehicles were generated. The HCE Y2020 reached a maximum range 83% greater than the SEL counterparts. The gaseous emissions of the helicopters were also evaluated over three notional scenarios representative of light helicopter activities. The HCE Y2020 emitted 60% less carbon dioxide (CO_2) and 63% less nitrogen oxides (NO_x) than the SEL Y2000. The SEL Y2020 emitted on average 19% and 49% less CO_2 and NO_x, respectively, compared with the SEL Y2000. It was also observed that the NO_x production rate of the LPP technology integrated in the SEL Y2020 combustor depends strongly on engine power setting. At certain power settings, the SEL Y2020 emitted less NO_x than the HCE Y2020 even though the HCE Y2020 emitted less NO_x over the complete mission. The direct comparison between SEL Y2020 and HCE Y2020 highlighted the superior performance of the HCE engine over the gas turbine for the mission types and rotorcraft class simulated.

Keywords: Clean Sky; piston engine; performance; emissions; combustion

NOMENCLATURE

ACARE	Advisory Council for Aeronautics Research in Europe
CO_2	Carbon dioxide
EHOC	European Helicopter Operator Committee
EUROPA	European Rotorcraft Performance Analysis code
EW	Empty Weight (kg)
GRC	Green Rotorcraft
HCE	High Compression Engine
HELENA	Helicopter Environmental Noise Analysis
HOGE	Hover Out of Ground Effect
ISA	International Standard Atmosphere
ITD	Integrated Technology Demonstrator
LPP	Lean Premixed Prevaporised
MTOW	Maximum Take-Off Weight (kg)
JTI	Joint Technology Initiative
NO_x	Nitrogen oxides
PhoeniX	Platform Hosting Operational & Environmental Investigations for Rotorcraft
PR	Payload-Range
RMEM	Rotorcraft Mission Energy Management model
SAGE	Sustainable and Green Engine
SL	Sea Level
SEL	Single Engine Light
SFC	Specific Fuel Consumption (µg/J)
SHE	Safran Helicopter Engines
TE	Technology Evaluator
V_r	Maximum Range speed (m/s)

1.0 INTRODUCTION

Rotorcraft are versatile vehicles involved in a plethora of activities, ranging from heavy duty cargo to emergency medical services. They are a quick and safe alternative for daily transportation of passengers and goods in isolated areas as well as densely populated ones. Global aviation traffic is expected to rise sharply in the near future following the current commercial aviation trend [1]. One particular activity forecasted to expand is the passenger transport/air taxi with a two to three-fold increase in the 2015-2020 period [2]. In this context, there is a growing concern over the environmental impact of such activities. Currently, the aviation industry is a relatively small contributor to the global man-made carbon dioxide (CO_2) footprint with 2% of the worldwide share [3]. The emission of this greenhouse effect gas is directly related to fuel consumption, thus fuel efficiency is one of the top concerns in the aerospace industry. Aircraft not only emit CO_2 but also nitrogen oxides (NO_x) which have negative effects on health. Ground noise impact is also seen as a concern. Indeed aircraft noise is the most significant cause of adverse community reaction related to the operation and expansion of airports [4].

The rising green philosophy is reflected in the environmental goals set by the Advisory Council for Aeronautics Research in Europe (ACARE) to be met by civil aviation to provide a sustainable aviation growth. These targets are summarised in the “Vision 2020” under the Strategic Research and Innovation Agenda and include reductions in CO_2 and NO_x emissions by 50% and 80% by 2020, respectively, relative to the year 2000 technology [2]. These targets were extended in the “Flightpath 2050” agenda, with a 75% reduction of CO_2 and 90% of NO_x emissions by 2050 relative to the year 2000 [5]. In order to meet these goals, the Clean Sky Joint Technology Initiative (JTI) was created as a public/private partnership between the European Commission and the aeronautical industry. Clean Sky aims to generate high-quality research within Europe with the ultimate goal of developing innovative environmentally friendly technologies.

Clean Sky is composed of several Integrated Technology Demonstrators (ITDs), each one developing a different technology at engine or vehicle level to satisfy the aforementioned ACARE goals. With respect to rotorcraft technology, the contributing ITDs are the Green Rotorcraft (GRC) and the Sustainable and Green Engine (SAGE), alongside the Technology Evaluator (TE). The TE is the central body within Clean Sky responsible for the assessment of the innovative technologies developed by the ITDs, GRC and SAGE in the context of rotorcraft. The GRC ITD has set specific environmental performance objectives as illustrated in Figure 1. These targets are designated specifically for the Single Engine Light (SEL) helicopter category.

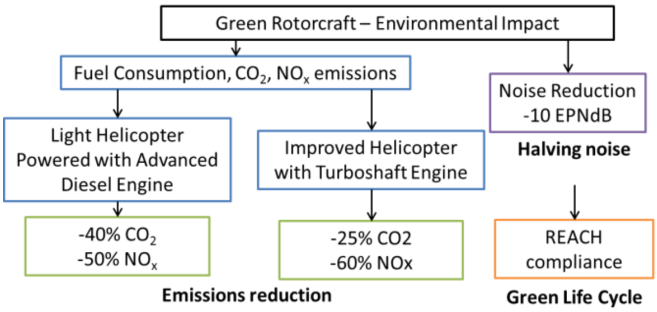

Figure 1 Expected GRC contribution for the light helicopter class [2]

In response to the aforementioned requirements, the GRC ITD took the lead on six distinct projects, representative of technical areas where improvements are envisioned. As shown in Figure 2, the GRC ITD research fields span from the development of innovative rotors to rotorcraft airframe ecological design, including the integration of a High Compression Engine (HCE). The HCE is a supercharged diesel cycle engine developed for light helicopter propulsion purposes. Despite its higher weight compared with conventional turboshaft engines, piston engines present a lower Specific Fuel Consumption (SFC), reducing the CO_2 emissions. Moreover, supercharging allows the design of an engine with constant power rating through the entire operational envelope as opposed to gas turbine engines, which require an oversized powerplant to operate under hot & high conditions. The potential benefits of piston-engine-powered light helicopters are explored in the present work as a part of the Clean Sky TE activity.

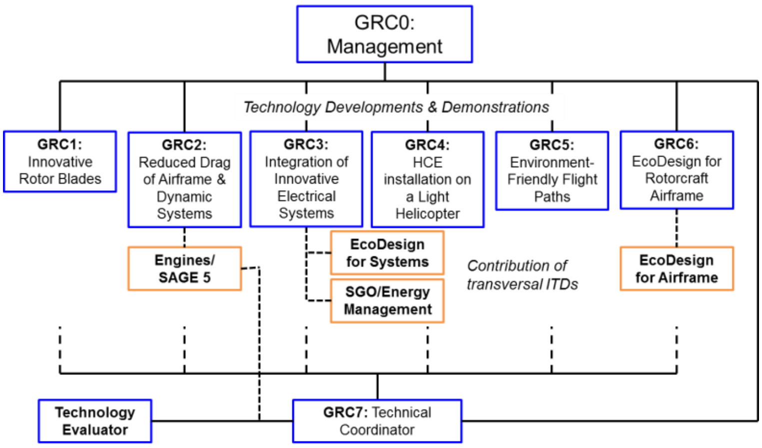

Figure 2 GRC technologies integration scheme

Since their invention, rotorcraft have been powered by fossil fuel-based powerplants. Reciprocating engines were initially employed until the advent of the gas turbine [6]. Due to their high specific power output, turboshaft engines are the preferred powerplant for most rotorcraft, whilst reciprocating engines are uniquely used to power small lightweight helicopters.

In order to bridge the gap between gas turbines and piston engines, Castor et al. [7] studied compound cycle engines more commonly known as turbocharged diesel engines. Three Brayton/diesel engine arrangements were investigated with three diesel engine designs. SFCs and engine weights were evaluated and their performances assessed over a nominal mission. The compound engine cycles were designed to conserve their power rating under hot and high conditions thanks to an increase of the trapped equivalence ratio and an increase of the gas generator speed to conserve the peak firing pressure of the piston cylinder. This process results in an increase of the engine SFC and more importantly in a flat-rated power. In comparison, a gas turbine engine must be oversized to alleviate altitude and temperature effects. This oversizing resulted in a 40% increase of the power rating at SL/ISA. The best compound cycle engine was then compared to the aforementioned gas turbine engine over a nominal mission. Reductions of 31% in fuel consumption and 16% in engine plus fuel and fuel tank weight were observed for the compound engine cycle in comparison with the gas turbine engine. Although the study did not assess the environmental impact of such technology, it highlighted the need to evaluate the powerplants at mission level.

As for turboshaft engines, SFC reductions can be achieved through efficiency improvement of individual turbomachinery components. Innovative engine cycles have the potential to further increase the overall engine efficiency. Recuperated gas turbines [8], regenerative powerplants [9], or reheat with interstage turbine burners [10] are currently considered for future engine designs.

Considerable NO_x emissions reductions are targeted along the fuel consumption savings. The NO_x formation is a result of high combustion temperatures produced by the formation of local "hot spots" where combustion takes place at nearly stochiometric conditions. Therefore, one of the mechanisms to reduce the NO_x production is a more homogeneous temperature distribution within the combustor. Lefebvre & Ballal [11] present several combustor concepts to effectively realise combustion out of stoichiometric conditions. Tacina et al. [12] also demonstrated the capabilities of low NO_x lean direct injection for turbofan engines, achieving large reductions in NO_x emissions when compared to conventional combustor designs.

Advanced gas turbines and diesel engines provide two solutions to comply with the stringent aforementioned ACARE goals; however, no thorough assessment of such technologies has been carried out. Therefore, Clean Sky JTI investigates the potential benefits of diesel piston engines and lean combustion turboshaft engines, for small helicopter applications. This paper elaborates on the comparison between these two technologies. Performance and environmental impact are assessed for both powerplants. Three Single Engine Light (SEL) rotorcraft are modelled: a turboshaft engine powered configuration with year 2000 technology (SEL Y2000), a conceptual configuration corresponding to a turboshaft engine powered vehicle with projected technologies up until the year 2020 with Clean Sky innovations (SEL Y2020), and a HCE derivate from the conceptual SEL (HCE Y2020) and powered by a supercharged diesel cycle engine.

The associated Payload-Range (PR) diagrams were generated for each vehicle and employed to assess the relative performance of each rotorcraft. The environmental impact assessment was carried out over three distinct missions, representative of typical lightweight helicopter applications i.e. passenger transport, police/law enforcement, and training. The gaseous emissions produced by each helicopter are computed herein and discussed.

2.0 METHODOLOGY

In order to effectively evaluate the environmental impact of the technologies developed by the GRC ITD, a method capable of estimating fuel burn, gaseous emissions, and ground noise impact for any designated rotorcraft mission is required. An integrated multi-disciplinary rotorcraft performance framework, named PhoeniX (Platform Hosting Operational & ENvironmental Investigations for Rotorcraft) was deployed [13]. PhoeniX is composed of a rotorcraft flight mechanics code (EUROPA), an engine performance simulation and gas emissions calculation code (Safran Helicopter Engines deck), a rotorcraft environmental noise analysis tool (HELENA), and a rotorcraft mission energy management module (RMEM). These individual tools were linked together using a simulation framework toolkit called OPTIMUS [14]. A brief description of the code is provided below.

2.1 European Rotorcraft Performance Analysis code (EUROPA)

EUROPA [15] was developed to determine helicopter steady state (trim) and dynamic (manoeuvre) performance. Steady-state linear blade element momentum theory is utilised to model the rotor as an infinitely thin disk. Elastic phenomena are not accounted for, blades are considered rigid instead. The validation of the code was completed using flight test data for trim performance and dynamic response in [16]. For the purpose of the present work, the helicopter is handled dynamically during take-off and landing phases whilst it is assumed to be operating in trim during cruise and climb/descent segments.

2.2 Safran Helicopter Engines Deck

The Safran Helicopter Engines (SHE) deck is able to evaluate the performance of gas turbine engines in steady-state and transient conditions. It is built on a zero-dimensional component analysis based on discrete maps modelling the thermodynamic processes occurring within the different engine components. For the concern of this work, the SHE deck was employed to calculate the engines steady-state off-design performance to evaluate the fuel burn, CO_2 and NO_x emissions.

2.3 Helicopter Environmental Noise Analysis (HELENA)

The HELENA [17] platform is able to compute helicopter noise footprints from experimental and numerical helicopter noise databases [18]. HELENA evaluates the noise perceived in terms of Sound Exposure Level, which is the parameter commonly used for cumulative exposure. Further discussion over helicopter noise emissions can be found in [19]. However, noise emissions analysis is out of the scope of the paper, therefore further elaborations shall be omitted.

2.4 Rotorcraft Mission Energy Management Model (RMEM)

With the developments in avionics, helicopters are getting more and more electric, and secondary systems are playing a greater part in the vehicle performance. The RMEM [20] simulates the rotorcraft subsystems requiring engine shaft-power and bleed off-takes. The RMEM comprises a series of analytical methods representing the actuation, electrical, fuel, and environment control systems. The operation of these helicopter subsystems results in time-dependent shaft-power and engine bleed air off-takes along the mission [20]. For the vehicles of interest, no bleed air off-take was considered.

2.5 PhoeniX Platform

Phoenix, as represented in Figure 3, integrates the above individual tools into a common simulation environment. In order to simulate complete helicopter missions, the mission profile is truncated into discrete segments based on user-defined time steps. Different time steps can be set for manoeuvres or dynamic task, and trimmed flight conditions. To start the calculation process, the on-board fuel supply is guessed to set the initial All-Up-Mass (AUM) of the vehicle. For each time step, EUROPA calculates the power required and updates the position of the rotorcraft following the flight path defined by the user. The SHE deck retrieves this information and calculates the engine off-design operating point taking into account the shaft-power off-take estimated by RMEM. The engine fuel flow and the emission indices for the segment are then evaluated. The AUM is subsequently updated, deducting the fuel burn on the segment in order to simulate the gradual weight reduction of the vehicle along the mission. Once the mission is completed, the overall fuel burn estimate is compared to the initial guess. If the discrepancy between the two values is above a certain margin, the numerical process reiterates with a new initial AUM. As soon as convergence is reached, the gaseous emissions are compiled. The trajectory data are also transferred to HELENA in order to determine the noise footprints for the given flight conditions.

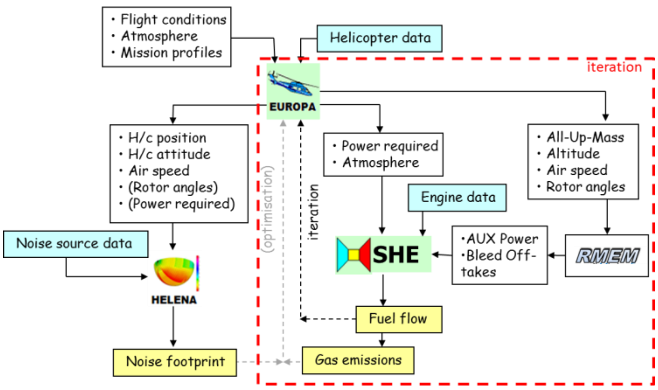

Figure 3 PhoeniX architecture overview

2.6 Rotorcraft configurations

The focus in this paper is on the lower segment of the light helicopter class, representing helicopters with a Maximum Take-Off Weight (MTOW) below 4000 lb (1800 kg). Three rotorcraft configurations are modelled for the present analysis. The ACARE goals are relative to year 2000 technology, therefore a reference turboshaft powered light helicopter representing year 2000 technology is modelled. This platform is referred to as Single Engine Light Year 2000 (SEL Y2000). A single engine light helicopter with year 2020 technology including the GRC ITD technologies is also modelled. It includes two variants, one denoted as SEL Y2020 and powered by a turboshaft engine and the other named HCE Y2020 and powered by a supercharged diesel engine.

The SEL Y2000 must be representative of the year 2000 technology level. The most typical vehicles representative of such technology are the Bell 206 (B III Jet Ranger and L3 Long Ranger), the Airbus Helicopter AS350 BA and the Hughes 500D. They account for most of the annual flight hours of helicopters with the technology level of interest. The SEL Y2000 model characteristics were therefore defined to be representative of the technology implemented in these vehicles. The Y2020 platforms (SEL and HCE) incorporate the innovative technologies developed within the GRC ITD [2] as listed below:

- Passive Optimised Blades
- Active devices/vortex generator on blunt fuselage, improved landing skids, hub cab and dynamic air intake
- Integration of innovative electrical systems
- Structural weight saving

The implementation of these technologies results in a lighter and slender vehicle platform than the SEL Y2000. The engine model integrated into the SEL Y2020 intends to drastically reduce the NOx emissions with a Lean Premixed Prevaporised (LPP) combustor design. The combustion is completed in a lean environment with a uniform mixture to avoid locally stoichiometric zones of high temperature. The technology is widely used for ground-power application but not for aircraft. This is due to the higher pressures and temperatures and the wide range of duty cycle associated with aero-engines that may result in risks of auto-ignition and flow reversal in the premix zone [12]. However, the low rating power required for the SEL Y2020 (see Table 1) greatly lessens these risks. In order to avoid weak extinction in case of spontaneous reduction of engine power, the LPP system also integrates a pilot stage. The SHE deck takes into account the behaviour of the two injection systems (LPP and pilot stage) and the distribution of fuel injection between pilot and LPP stages [19].

As for the HCE Y2020, the vehicle platform is shared with the SEL Y2020, but the installed powerplant becomes a supercharged piston engine. Although it is a diesel cycle (constant pressure combustion), the fuel remains kerosene-type Jet-A. The model of the HCE follows the testing of a demonstrator engine flown on an Airbus Helicopter EC120. The engine model is provided by Siemens PLM Software and is integrated into Phoenix in a similar fashion as the SHE deck. Although the HCE is 28% heavier than the SEL Y2020 powerplant, HCE Y2020 and SEL Y2020 have the same MTOW. The fuel capacity of the HCE Y2020 is thus reduced by 21% in comparison to the SEL Y2020 in order to maintain the maximum payload capability. As previously mentioned, the power of the HCE can be maintained under higher/hotter conditions thanks to supercharging. Therefore, the engine can be sized to the main gearbox torque limitation. This design approach results in a 7.5% reduction of the HCE Y2020 take-off power at ISA/SL when compared to the SEL Y2020. Table 1 summarises the main features of the three vehicles.

Table 1 RC main characteristics

Parameter	Unit	SEL Y2000	SEL Y2020	HCE Y2020
MTOW (internal load)	[kg]	1765	1596	1596
Empty weight fraction	[%]	55.0	54.4	57.4
Useful load (Payload +Fuel)	[kg]	412+292	412+232	412+183
Take-off power @ ISA/SL	[kW]	377	318	294

3.0 RESULTS

In this section, the payload-range capabilities of the three light helicopters are first compared in order to appreciate the merits and drawbacks of the Clean Sky helicopter concepts. Then, in order to complete the analysis, the environmental impact of each rotorcraft is analytically assessed at mission level. CO_2 and NO_x emissions are evaluated and statistically compared.

3.1 Payload-Range comparison

The Payload-Range (PR) diagrams built for the three helicopters are defined by three points: maximum useful load (A), maximum range at maximum payload (B), and maximum range without payload (C). The point A is directly taken from the useful load of each vehicle given in Table 1. Points B and C require the definition of a mission procedure for each vehicle in order to establish the maximum range reachable with their respective fuel allowance. Thus, every mission is run following the same routine for take-off, climb, descent and landing. These segments are defined by GRC5. The mission is a single leg with a cruise altitude of 2500 ft. The reserve is defined as the fuel needed to realise a 60kts loiter for 20 minutes at 2000 ft. The cruise speed is set as the best range speed (V_r), defined as the speed that minimises the ratio engine fuel flow over airspeed and so, maximises the range attainable. Max Range point and V_r are graphically defined in Figure 4.

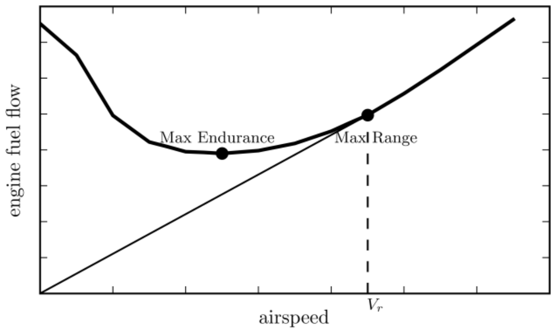

Figure 4 Definition of the best range speed

The engine fuel flows of the three vehicles are plotted versus airspeed for AUM equals MTOW and Empty Weight (EW) in Figure 5. It is observed that V_r tends to decrease with a reduction of the AUM. However, the effect of the AUM on V_r differs for each helicopter platform; whilst AUM has a relatively low effect for the SEL Y2020, it has a large impact for the HCE Y2020. Note also that the SEL Y2020 has the highest V_r out of the three vehicles. The missions simulated to generate the PR were run at constant cruise speed. This speed was defined as the V_r for the average AUM during the cruise segment. Once the maximum range is mathematically evaluated, a mission file is created to be run by PhoeniX. An iterative process over the mission range follows to adjust the maximum range evaluation to take into account all the mission segments and the gradual weight reduction of the vehicle. The same method is employed for the three vehicles.

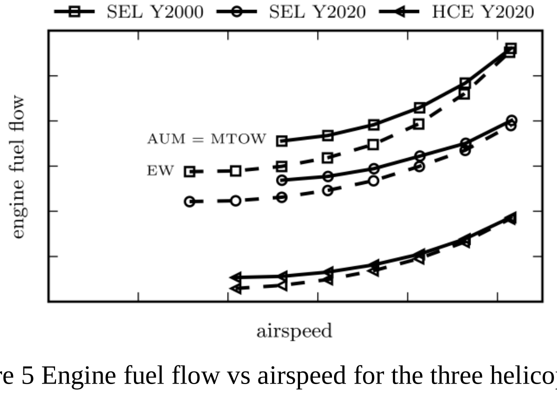

Figure 5 Engine fuel flow vs airspeed for the three helicopters

The SEL Y2020 was flown at the same speed for the two points of the diagram: B and C. The best range speed of the SEL Y2020 was 7% and 19% faster than the average V_r of the SEL Y2000 and the HCE Y2020, respectively. 3% and 10% differences were found between the V_r at maximum payload and no payload of the SEL Y2000 and the HCE Y2020, respectively. Finally, the PR diagrams of the three vehicles are shown in Figure 6.

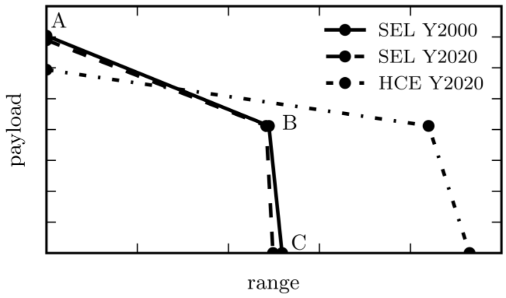

Figure 6 Lightweight helicopters Payload-Range comparison

The PR diagrams of the two turboshaft-powered vehicles are similar. This highlights the method deployed in the design of the SEL Y2020 where the benefits of the GRC ITD technologies were translated into reduced fuel consumption rather than increased performance. It results in a 20% reduction of the fuel capacity of SEL Y2020 compared to the SEL Y2000. Due to its higher empty weight, the HCE Y2020 has a theoretical 15% and 14% reduction in useful load compared to SEL Y2000 and SEL Y2020, respectively. However, the diesel engine powered helicopter presents greater ranges than the turboshaft-powered vehicles and depending on the real use of the helicopter, the payload penalty may never be seen. A 73% and 83% increase in range was found for points B and C, respectively, compared with the turboshaft powered SEL.

3.2 Mission analysis

As previously mentioned, the environmental impact assessment is carried out at mission level over three distinct missions representative of typical lightweight helicopter applications: passenger transport, police/law enforcement, and training. The profiles of these missions were designed following European Helicopter Operator Committee (EHOC) and Clean Sky partners' advice with regard to flight procedures. As shown in Figures 7-8, the passenger mission is a succession of four pick-up & drop-off segments. The helicopter takes off from the helipad to pick-up the designated passenger(s) from a secondary location and transfers them to a drop-off point. This procedure is repeated four times before the vehicle returns to the initial helipad. The hypothetical law enforcement scenario in Figures 9-10 represents a high altitude surveillance role over five adjacent areas. The scenario of the training mission is a combination of hover, climb, and level flight at various speeds and altitudes as illustrated in Figures 11-12. The different scenarios considered in the mission analysis cover the range of roles light helicopters perform.

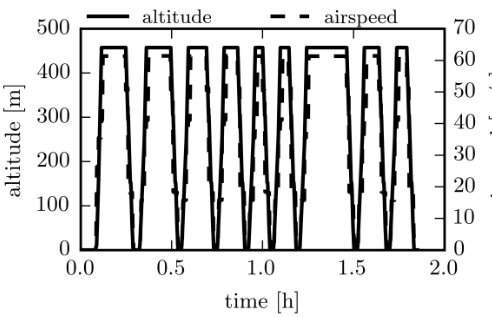

Figure 7 Passenger mission altitude and airspeed profiles

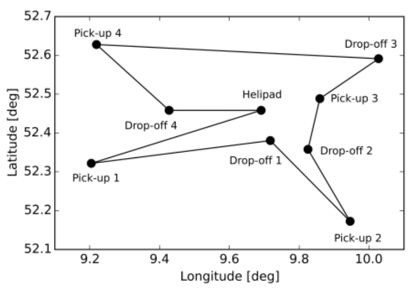

Figure 8 Passenger mission trajectory

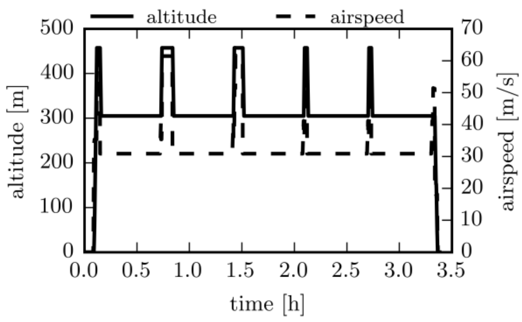

Figure 9 Police mission altitude and airspeed profiles

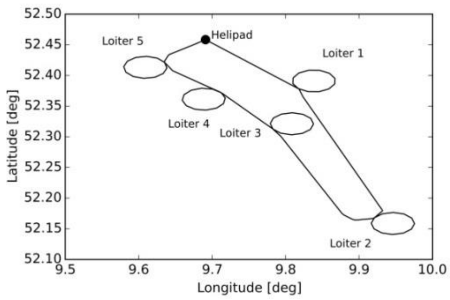

Figure 10 Police mission geographical trajectory

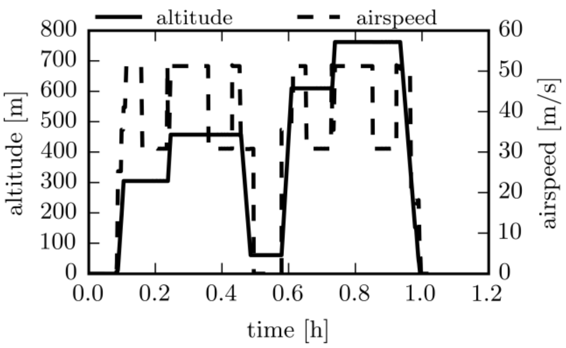

Figure 11 Training mission altitude and airspeed profiles

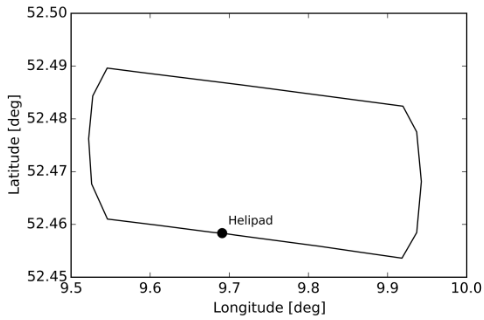

Figure 12 Training mission geographical trajectory

The overall emissions results for each helicopter platform are summarised in Table 2 to Table 4, where CO_2 and NO_x emissions are compared and then statistically analysed. The NO_x rate emission vs Power are also evaluated at SL/ISA conditions. The delta in CO_2 emissions between the turboshaft-powered helicopters is consistent over the three scenarios, with 20% reduction achieved by the SEL Y2020 compared with the SEL Y2000. This is not the case for the NO_x emissions, where the standard deviation is high (14%). An average 49% reduction in NO_x emission is achieved by SEL Y2020. With regards to the HCE Y2020 gaseous emissions, CO_2 and NO_x emissions are 63% lower than the SEL Y2000 ones. The HCE Y2020 CO_2 emissions are on average 53% lower than the SEL Y2020. The NO_x emissions are once again largely dependent on the mission scenario with a standard deviation of 18%. On average, the HCE Y2020 emits 23% less NO_x than the SEL Y2020 counterpart.

Table 2 CO_2 and NO_x emissions comparison at Passenger mission

Passenger	**SEL Y2020 vs SEL Y2000 [%Δ]**	**HCE Y2020 vs SEL Y2000 [%Δ]**	**HCE Y2020 vs SEL Y2020 [%Δ]**
CO_2 [kg]	-21.5	-60.5	-49.8
NO_x [kg]	-61.7	-65.3	-9.3

Table 3 CO_2 and NO_x emissions comparison at Police mission

Police	**SEL Y2020 vs SEL Y2000 [%Δ]**	**HCE Y2020 vs SEL Y2000 [%Δ]**	**HCE Y2020 vs SEL Y2020 [%Δ]**
CO_2 [kg]	-18.5	-63.5	-55.3
NO_X [kg]	-33.9	-62.6	-43.5

Table 4 CO_2 and NO_x emissions comparison at Training mission

Training	SEL Y2020 vs SEL Y2000 %Δ	HCE Y2020 vs SEL Y2000 %Δ	HCE Y2020 vs SEL Y2020 %Δ
CO_2 [kg]	-18.0	-64.0	-56.1
NO_X [kg]	-52.1	-61.1	-18.8

Figure 13 and Figure 14 show the CO_2 and NO_x production rates respectively for the police scenario. As expected, the HCE Y2020 presents the minimum CO_2 production rate in all the flight segments. The regions observed with higher CO_2 emission rates correspond to the flight legs where the helicopter transits between surveillance areas at high speed and altitude. As for the NO_x emissions, the HCE Y2020 produces clearly less NO_x at low power settings. However, during the transition segments, the SEL Y2020 NO_x production rates are lower than during the surveillance segments. NOx emissions of the Y2020 vehicles cannot be put apart in the transition segments.

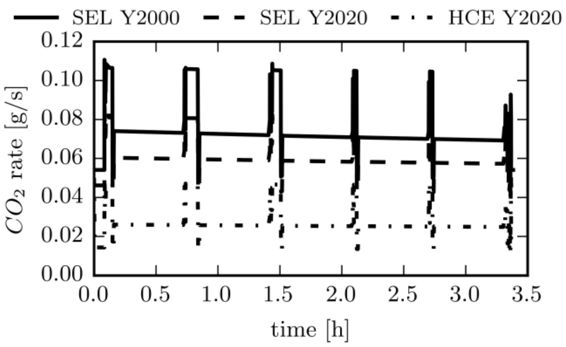

Figure 13 CO_2 production rate comparison at Police mission

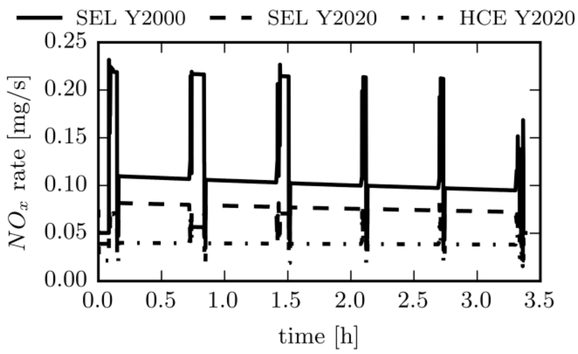

Figure 14 NO_x production rate comparison at Police mission

Figure 15 represents the NO_x production rate of each vehicle over the first leg of the passenger mission. It shows that the SEL Y2020 presents a lower NO_x production rate than the HCE Y2020 at cruise but the opposite is observed on the idle, take-off, and landing segments. Therefore, as 9 take-off and landing manoeuvres are performed during the passenger mission, the production rates at take-off and landing prevail over the cruise ones and, as a result, the NO_x emissions for the SELY2020 are 9.3% higher compared to the HCE Y2020 at mission level. It demonstrates the dominant impact of the take-off and landing segments on the NO_x emissions. The engines NO_x production rates versus shaft power are plotted in Figure 16 to explain the aforementioned result. In this graph, it is noticeable that, whilst SEL Y2000 and HCE Y2020 NO_x rates are essentially proportional to shaft power, the SEL Y2020 NO_x production oscillates. These fluctuations are a direct cause of the presence of a pilot stage along the LPP ones (for low power rating) and the gradual distribution of the airflow to a number of stages when the power rating increases. The SEL Y2020 combustor is, therefore, more effective at certain power settings from the NO_x production rate point of view. In particular, it is observed that for certain range of engine shaft power, the NO_x rate of the HCE Y2020 is higher than the SEL Y2020 one. This fact explains that at cruise conditions, where the engine power demand is relatively high, the HCE Y2020 produces more NO_x than the SEL Y2020 operating at same conditions.

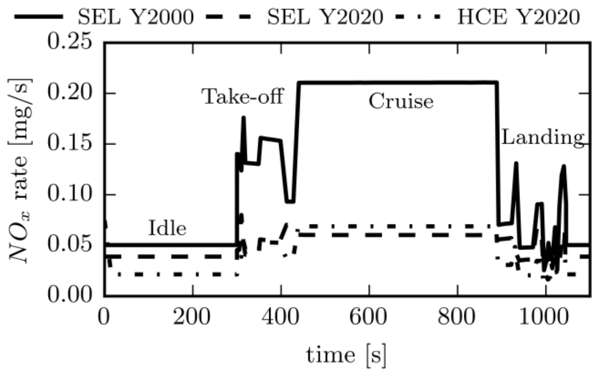

Figure 15 NO_x production rate comparison at passenger mission 1st leg

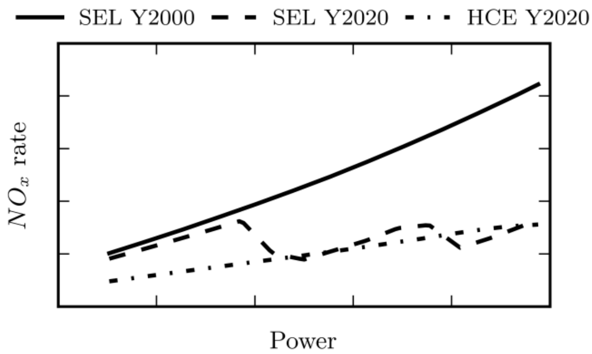

Figure 16 NO_x production rate vs. Power at ISA/SL

4.0 CONCLUSIONS

An analytical method was presented to assess the benefits linked with the integration of the GRC ITD technologies in terms of rotorcraft performance and environmental impact. This methodology was employed to evaluate the environmental benefits of the integration of advanced powerplant into light helicopters. Three vehicles were modelled: a turboshaft engine powered configuration with year 2000 technology, a conceptual configuration corresponding to a turboshaft-engine-powered vehicle with projected technologies up until the year 2020 with Clean Sky benefits, and a supercharged diesel cycle engine powered helicopter derivate from the conceptual SEL.

The PR diagrams of the two turboshaft-powered helicopters demonstrate the method followed to design and integrate the Clean Sky technologies into the SEL Y2020 model, as the performances of these two vehicles are similar. As previously mentioned, the HCE Y2020 platform is based on the SEL Y2020 one, adapted to integrate the diesel engine. It signifies an increase in vehicle empty weight at a cost of a lower fuel available in order to maintain the MTOW. Despite the lower fuel available, the HCE Y2020 demonstrates a maximum range 83% greater than the turboshaft-powered models.

The gaseous emissions of the vehicles were evaluated over three scenarios representative of the activities of light helicopters. On these missions, the HCE Y2020 surpasses the goals set by GRC, achieving over 60% reduction in both NO_x and CO_2 emissions when compared to the SEL Y2000. The SEL Y2020, on the other side, just reaches the designated goals with emissions cut by 19% and 49% for CO_2 and $NO_{x,}$ respectively, when compared to SEL Y2000. However, the SEL Y2020 performs greater over shorter scenarios when compared to SEL Y2000 as seen in reference [20]. The direct effect of the LPP technology implemented in the SEL Y2020 was also discussed. The NO_x production rate is fluctuating with the engine shaft power, resulting in regions where the LPP turboshaft emits less NO_x than the HCE. Finally, the direct comparison between SEL Y2020 and HCE Y2020 highlighted the superior performance of HCE engine over the conventional gas turbine for the simulated missions.

ACKNOWLEDGMENTS

The authors would like to thank all the GRC leaders/participants for their valuable contributions as well as the Clean Sky JTI for funding this research activity. Special thanks to Safran Helicopter Engines for their helpful comments.

REFERENCES

[1] "Air Transport Action (ATAG)," [Online]. Available: http://atag.org. [Accessed June 2016].

[2] "Clean Sky innovation takes off," Clean Sky, [Online]. Available: http://cleansky.eu. [Accessed June 2016].

[3] Royal Comission on Environmental Pollution, [Online]. Available: http://www.rcep.org/uk/reports/sr-2002-aircraft/documents/aivation-report.pdf. [Accessed June 2016].

[4] J. Clarke, “The role of advanced air traffic management in reducing the impact of aircraft noise and enabling aviation growth,” *Journal of Air Transport Management,* vol. 9, no. 3, pp. 161-165, 2003.

[5] European Commission, “Flightpath 2050 Europe's Vision for Aviation,” 2011. [Online]. Available: ec.europa.eu/transport/sites/transport/files/modes/air/doc/flightpath2050.pdf. [Accessed November 2016].

[6] K. M. Rosen, “A Prospective: The Importance of Propulsion Technology to the Development of Helicopter Systems With a Vision for the Future The 27th Alexander A. Nikolsky Lecture,” *Journal of American Helicopter Society,* vol. 53, no. 4, pp. 307-337, 2008.

[7] J. Castor, J. Martin, and C Bradley, “Coumpound Cycle Engine for Helicopter Application,” NASA, NAS3-24346, 1987.

[8] C. F. McDonald, A. F. Massardo, C. Rodgers, A. Stone, “Recuperated gas turbine aeroengines. Part III: engine concepts for reduced emissions, lower fuel consumption, and noise abatement,” *Aircraft Engineering and Aerospace Technology,* vol. 80, no. 4, pp. 408-426, 2008.

[9] F. Ali, K. Tzanidakis, I. Goulos, V. Pachidis, R. d'Ippolito, “Multi-Objectie Optimization of Conceptual Rotorcraft Powerplants: Trade-Off Between Rotorcraft Efficiency and Environmental Impact,” *Journal of Engineering for Gas Turbines and Power ,* vol. 137, no. 7, p. 071201, 2015.

[10] Q. Li, W. Fan, “Parametric Cycle Analysis of Dual-Spool Mixed-Exhaust Turbofan with Interstage Turbine Burner,” *45th AIAA Aerospace Sciences Meeting and Exhibit, Reno, Nevada,* January 2007.

[11] D. R. Lefebvre, & A. H. Ballal , “Polutants Reduction by Control of Flame Temperature,” in *Gas Turbine Combustion- Alternative Fuels and Emissions*, CRC press, 2010, pp. 391-428.

[12] R. Tacina, C. Wey, P. Laing, A. Mansour, “A Low NOx Lean-Direct Injection, Multi Integrated Module Combustor Concept for Advanced Aircraft Gas Turbines - NASA/TM-2002-211347,” *Conference on Technologies and Combustion for a Clean Environment,* 2001.

[13] I. Goulos, V. Pachidis, R. d’Ippolito, J. Stevens, and C. Smith, “An Integrated Approach for the Multidisciplinary Design of Optimum Rotorcraft Operation,” *Journal of Engineering for Gas Turbines and Power,* vol. 134, no. 9, pp. 091701-091701-10, 2012.

[14] “NOESIS-OPTIMUS, the Industry-Leading PIDO Software Platform,” Noesis Solution, [Online]. Available: http://www.noesissolutions.com/our-products/optimus. [Accessed June 2016].

[15] C. Serr, J. Hamm, F. Toulmay, G. Polz, H.J. Langer, M. Simoni, M. Bonetti, A. Russo, C. Young, J. Stevens, A. Desopper, D Papillier, “Improved Methodology for Take-Off and Landing Operational Procedures, the RESPECT programme,” in *25th European Rotorcraft Forum*, Rome, 1999.

[16] C. Serr, G. Polz, J. Hamm, J. Hughes, M. Simoni, A. Ragazzi, A. Desopper, A. Taghizad, H. Langer, C. Young, A. Russo, A. Vozella and J. Stevens, “ Rotorcraft Efficient and Safe Procedures for Critical Trajectories,” *Air Space Eur.*, vol. 3, no. 3, pp. 266-270, 2001.

[17] FRIENDCOPER consortium, “Final Report - FRIENDCOPTER (Integration of technologies in support of a passenger and environmentally friendly helicopter),” 2009.

[18] M. Gervais, V. Gareton, A. Dummel, R. Heger, “Validation of EC130 and EC135 Environmental Impact Assessment using HELENA,” in *American Helicopter Society 66th Annual Forum*, Phoenix, 2010.

[19] C. Smith, V. Pachidis, A. Castillo Pardo, E. Gires, J. Stevens, L. Thevenot, R. d'Ippolito, “Achieving Rotorcraft Noise and Emissions Reduction for "Clean Sky" - The Measurement of Success,” *Challenges in European Aerospace, 5th CEAS Air & Space Conference,* 2015.

[20] J. Ortiz-Carretero, J. Enconniere, V. Pachidis, J. Stevens, C. Smith, L. Thevenot, and R. Ippolito, “Clean Sky Technology Evaluator Green Rotorcraft Mission Environmental Performance Analysis,” in *AEGATS 2016,* Paris, 2016.