

# DARE: A MATLAB Toolbox for Design and Analysis of Ramjet/scramjet Engines

Bora O. Cakir<sup>1\*</sup> and Ali Can Ispir<sup>2\*</sup>

<sup>1</sup> Department of Energy Sciences, Lund University, Sweden <sup>2</sup> Department of Mechanical Engineering, Eindhoven University of Technology, the Netherlands \* These authors contributed equally.

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## Summary

Advancing supersonic civil aviation with a focus on technical and environmental sustainability demands a comprehensive approach to the design and performance evaluation of supersonic aircraft. These designs must not only support the requirements of high-speed flight but also adapt to varying external conditions throughout their missions, making the optimization of aerodynamic and propulsion systems essential across diverse operating scenarios (Küchemann, 2012). Consequently, the configuration, optimization, and analysis of high-speed propulsion systems are critical for developing supersonic and hypersonic aircraft. Among the propulsion architectures suited for high-speed missions, ramjet engines offer significant advantages over rocket engines by eliminating the need for onboard oxidizer storage and rotating components. Despite their structural simplicity compared to turbo-based aero-engines, ramjets feature complex internal flow dynamics that require detailed investigation to ensure stability and optimal performance (Curran & Murthy, 2000). To address this, conceptual design methods employing zero- and one-dimensional approaches provide a cost-effective alternative to detailed numerical simulations, enabling the analysis of design parameters, operational variables, and propulsion performance metrics such as thrust, specific impulse, and fuel consumption.

## Statement of need

Since the 1960s, researchers have developed and evaluated reduced-order models for high-speed propulsion systems, including ramjet and scramjet engines. Early models concentrated on simulating fuel injection and mixing effects, using a two-shock approach to analyze flow through intake contours (Bauer, 1966). These efforts investigated critical combustion chamber parameters such as pre-ignition conditions, fuel mixing, and ignition techniques, while also assessing propulsion performance across varying altitudes and speeds. Later advancements introduced numerical methods that integrated finite-difference solutions with stirred reactor models and finite-rate chemistry, emphasizing design aspects like overall engine performance and weight optimization (Edelman et al., 1981; Harsha & Edelman, 1978). Subsequently, one-dimensional models incorporating Eulerian-Lagrangian frameworks were developed to study stable and unstable combustion modes and their influence on cycle performance (Bhatia & Sirignano, 1990). These models also evaluated thrust losses caused by incomplete combustion and entropy generated from irreversibility (Riggins & Clinton, 1995). Some approaches combined low-fidelity propulsion analysis with structural integrity considerations for hypersonic engines, enabling performance assessments under aeroelastic conditions (Bolender & Doman, 2007; Chavez & Schmidt, 1994). Despite these advancements, combustion modeling remained a limitation. To address this, Torrez et al. (2011) introduced a reduced-order engine model for ramjet and scramjet mixing and combustion, further enhancing the MASIV (Michigan Air Force Scramjet In Vehicle) tool with the Shapiro method to predict thermal choking positions

42 (Torrez et al., 2013).

43 In parallel with these domain-specific developments, several modern frameworks employing  
44 one-dimensional modeling techniques have emerged for propulsion and system-level modeling.  
45 NASA's OpenMDAO (?) provides a flexible, open-source Python framework for multidisciplinary  
46 design, analysis, and optimization, enabling coupling between aerodynamic, structural, and  
47 propulsion models. The Numerical Propulsion System Simulation (NPSS) (?) offers a modular,  
48 extensible environment for thermodynamic cycle simulation of gas turbine engines, while tools  
49 such as SUAVE (?) and PyCycle (?) extend this approach to open-source aircraft and engine  
50 analysis. Within the MATLAB/Simulink ecosystem, NASA's Toolbox for the Modeling and  
51 Analysis of Thermodynamic Systems (T-MATS) (?) provides a component-based library for  
52 general thermodynamic and turbomachinery systems.

53 Numerous low-fidelity design and analysis studies have been conducted to characterize the  
54 performance of ramjet engines. However, most of these tools focus on individual propulsion  
55 system components rather than providing a holistic methodology. To date, there has been  
56 no significant effort to integrate intake design approaches with combustion analysis modules,  
57 and only a limited number of studies consider the combined effects of flight conditions and  
58 design parameters across the entire propulsion flow path. While analyzing the performance  
59 of individual components is crucial for understanding the physical phenomena that influence  
60 various design considerations for ramjet and scramjet engines, a thorough exploration of  
61 the design envelope is essential. This approach ensures an accurate definition of mission  
62 requirements and enables the effective optimization of design choices for high-speed aircraft.

63 The DARE (A MATLAB Toolbox for Design and Analysis of Ramjet/scramjet Engines) tool is  
64 introduced as a design and analysis framework that integrates individual approaches for high-  
65 speed propulsion components into a unified low-fidelity methodology. This tool aims to enable  
66 cost-effective characterization of the design space for high-speed propulsion systems. The  
67 ramjet/scramjet propulsion flow path comprises four primary components: the intake, isolator,  
68 combustor, and nozzle. The proposed analytical tool provides a fully integrated flow path  
69 analysis divided into three main modules. The first module focuses on the intake, facilitating  
70 the necessary freestream flow modulation before entering the isolator. For ramjet configurations,  
71 this module incorporates a normal shock assumption. The resulting flow properties are then  
72 used in the second module, which models combustion. This module calculates flow evolution  
73 within the combustion chamber using one-dimensional steady, inviscid flow equations coupled  
74 with detailed chemical kinetics and JANAF tables, employing the SUNDIALS code (Hindmarsh  
75 et al., 2005), developed by Lawrence Livermore National Laboratory. The third module  
76 addresses nozzle design and analysis, simulating flow expansion across various expansion ratios  
77 and nozzle geometries using one-dimensional steady, inviscid flow equations under cold flow  
78 conditions. Key performance metrics, including thrust, fuel consumption, and specific impulse,  
79 are then calculated to evaluate engine performance for each design.

## 80 Research application

81 DARE has been primarily used within the EU funded Stratofly and More&Less projects to focus  
82 on the design, analysis, and optimization of ramjet and dual-mode ramjet/scramjet propulsion  
83 systems, which are critical for supersonic and hypersonic vehicles operating beyond Mach 3  
84 (Zhang et al. (2016); Laboratory (2024); Cakir et al. (2022)]. DARE provided assessments  
85 for flow development, combustion performance, and overall propulsive characteristics such as  
86 thrust, fuel consumption, specific impulse, and efficiency are analyzed under varying conditions,  
87 including flight Mach number, altitude, intake geometry, and fuel-air equivalence ratio (Cakir  
88 & Ispir, 2025; Ali Can Ispir et al., 2024). Sensitivity analyses, including Shapley Additive  
89 Explanations (SHAP) and feature importance studies, identify key design parameters influencing  
90 engine performance. These methodologies are demonstrated to efficiently explore the design  
91 space, generate performance maps, and quantify propulsion system feasibility for high-supersonic  
92 cruise vehicles at an affordable computational cost. DARE has also been used in conjunction with

machine learning techniques to support data-driven modeling of high-speed propulsion systems. In these studies, artificial neural networks were applied to both operational and design variables of ramjet and dual-mode ramjet/scramjet engines to enable a comprehensive exploration of the design space. The resulting machine learning models were trained to predict and represent the propulsive performance of these engines with improved computational efficiency (Cakir et al., 2023; A. Ispir et al., 2022). Furthermore, efforts were made to enhance the capabilities of DARE, including the addition of a fuel-air mixing model in the combustor. This was achieved by modeling the mixing efficiency as a function of fuel injector configuration parameters along the scramjet propulsion system duct axis, using machine learning applied to a CFD database (Ali C. Ispir et al., 2023).

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