Early Stage Calibration of a Formula SAE Engine 1-D Fluid Dynamic Model with Limited Experimental Data

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Abstract. This work addresses the early stage calibration of a Formula SAE engine 1-D fluid dynamic model starting from limited experimental data. The availability of an engine model since the early stages of the development of a new Formula SAE vehicle allows to carry out preliminary analyses or ECU calibration. A few experimental tests have been executed at wide open throttle and variable engine speed. Then, a 1D thermo-fluid dynamic engine model has been developed starting from the geometry data of the engine. A vector optimization problem has been then solved to calibrate the engine model. In particular, the error minimization between numerical and experimental values of the torque in different engine operating conditions has been set as objective of the optimization process. Finally, starting from the results of the proposed calibration methodology, a decision-making criterion allowed the identification of a single optimal solution within the Pareto optimal front together with the related values for the set of calibration parameters. The results highlight how the proposed calibration procedure could be usefully adopted to set an early stage engine model which could be properly adopted to preliminarily detect the effects of geometric changes or control parameters variations on the main engine performance.

Keywords: Thermo-fluid dynamic analysis, Experimental tests, 1D engine model calibration, Vector optimization algorithm.

1 Introduction

Purpose of this study is the set up and calibration of a 1-D thermo-fluid dynamic engine model since the early stage of development of the engine, when limited experimental data are available. This way, preliminary analyses or ECU calibration [1-3] could be carried out. The same engine model can be progressively updated and refined as the experimental investigation is performed. Object of investigation has been a Formula SAE engine developed by the Team UniNa Corse from the University of Naples and based on the Honda engine which equips the Hornet CB 600-F motorcycle model. Indeed, the preliminary 1D engine model has been then actually adopted to predict the engine behavior and evaluate possible improvements during the whole international FSAE championship. In fact, a wider

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and comprehensive experimental campaign has never been performed until the end of the championship due to lack of time. A few experimental tests have been carried out at wide open throttle and variable engine speed while torque and speed values were acquired. Steady-state testing has been performed and acquisitions carried out by mean of a load cell, several thermocouples and a phonic wheel speed sensor. In particular, mean values have been calculated for the engine speed and torque. A 1D thermo-fluid dynamic engine model has been then set up starting from the geometry data of the real engine. To calibrate the engine model starting from the few available experimental data, a vector optimization problem has been solved with the objective of minimizing the error between numerical and experimental values of the torque along the full load curve. To identify a set of values for the calibration parameters of the 1D engine model, a decision-making criterion has been applied to identify a single optimal solution among those belonging to the Pareto optimal front.

2 The Engine Prototype

As already mentioned, the engine object of the study is based on the Honda engine which equips the Hornet CB 600-F motorcycle model, whose main technical data are summarized in **TABLE 1**. However, the basis engine configuration has undergone significant modifications to comply with the Formula SAE championship regulation† before equipping the Formula SAE vehicle developed by the Team UniNa Corse.

TABLE 1. Main engine specifications

Number of cylinders, layout	4, in lines
Total displacement	599.3 cm^3
Type	4 strokes
Bore	67 mm
Stroke	42.5 mm
Compression ratio	12.0:1
Spark sequence	1-2-4-3
Injection	Port injection
RON	98

a) **b)** **c)**

FIGURE 1. 3D CAD model of the intake system, **a)**, exhaust system, **b)** and the whole engine, **c)**.

† 2017-18 Formula SAE® Rules. https://www.fsaeonline.com/content/2017-18%20FSAE%20Rules%209.2.16a.pdf.

Specifically, intake and exhaust systems, together with lubrication and coolant circuits, have been properly redesigned to comply with the stringent packaging requirements. The 3D CAD model of the new intake system is represented in **FIGURE 1 a)**. The main geometric characteristics of its components are summarized in **TABLE 2**.

TABLE 2. Geometric characteristics of the intake system components

Throttle valve diameter	36.5 mm
Venturi tube length / min diameter / max diameter	200 mm / 19 mm / 40 mm
Intake plenum volume	2300 cm^3
Runner Length / Inlet diameter / Outlet diameter	150 mm / 48 mm / 34 mm

In particular, it consists of the following parts: a throttle valve, a Venturi tube, a 2.3 l intake plenum volume, four intake runners supplying the cylinders. Composite materials (Nylon/Carbon fibers) were adopted for the intake system. Selective Laser Sintering technology has been used for its production due to the particular shape of the runners and the required stiffness requirements. The exhaust system, represented in **FIGURE 1 b)**, is characterized by a 4-2-1 layout with a terminal muffler. It is specifically designed to reduce the noise emissions according to the limitations imposed by the FSAE regulation. The main geometric characteristics of the exhaust system components are reported in **TABLE 3**.

TABLE 3. Main geometric characteristics of the exhaust system

Exhaust manifold Length / Int.	420 mm / 32
Secondary pipes Length / Int. Diameter	360 mm / 36
Final Pipe Length / Int. Diameter	550 mm / 48
Muffler Length / In.t Diameter	470 mm / 60

The pipes are made of AISI316 while the muffler has a titanium core with carbon fiber external cover. The injection system consists of four port fuel injectors (PFI) controlled by the ECU. Each injector is controlled independently to supply each cylinder with the correct fuel mass. The engine is also equipped with two heat exchangers: a first radiator is coupled to the lubrication circuit while the other is coupled to the engine cooling circuit. The 3D CAD of the whole engine including lubrication and cooling circuits is shown in **FIGURE 1 c)**.

3 Experimental Analysis

a) **b)** **c)**

FIGURE 2. a) Test bench operation of the engine. **b)** Monitoring (above) and control rack (below). **c)** Wiring terminal and temperature control panel.

To assess the engine brake performance, preliminary experimental tests were carried out (**FIGURE 2 a**) to acquire the main quantities which will be used in the calibration methodology. The test bench includes an eddy current dynamometer, a proper set of sensors and data acquisition system. In particular, the test bench control is carried out by mean of a dedicated rack (**FIGURE 2 b**) which regulates the engine speed through a closed loop control of the excitation current in the stator winding. Engine torque and speed signals are processed by the monitoring rack (**FIGURE 2 b**). Then these signals are amplified and sent to a PC through the DAQ. A dedicated software (**FIGURE 2 c**) is used to ensure a real time monitoring of the engine operation and to store the output signals from the electronic control unit (ECU) and test bench instruments. Instantaneous ambient temperature, pressure and relative humidity of the test room have been monitored during the experimental tests through a weather station. More specifically, the following acquisitions (measured quantity - sensor) were made from the test bench instruments:

- Exhaust temperatures - 4 thermocouple signals, one for each of the exhaust runners.
- Engine coolant temperature - 2 thermocouple signals at radiator inlet and outlet.
- Engine lubricant temperature - 2 thermocouple signals at radiator inlet and outlet.
- Brake dynamometer cooling water temperature - thermocouples signals.
- Ambient temperature, pressure and relative humidity - weather station.
- Dynamometer speed - encoder.
- Engine torque - load cell.

While the following acquisitions were made from main engine sensors managed by ECU:

- Engine speed - pick-up sensor.
- Throttle position - throttle position sensor, TPS.
- Manifold air pressure - MAP sensor.
- Intake air temperature - IAT sensor.
- Engine coolant temperature - ECT sensor;
- Engine lubricant oil temperature.
- Gear - gear sensor.
- Air-fuel ratio - λ sensor.

A scheme of the whole acquisition chain system is represented in **FIGURE 3**.

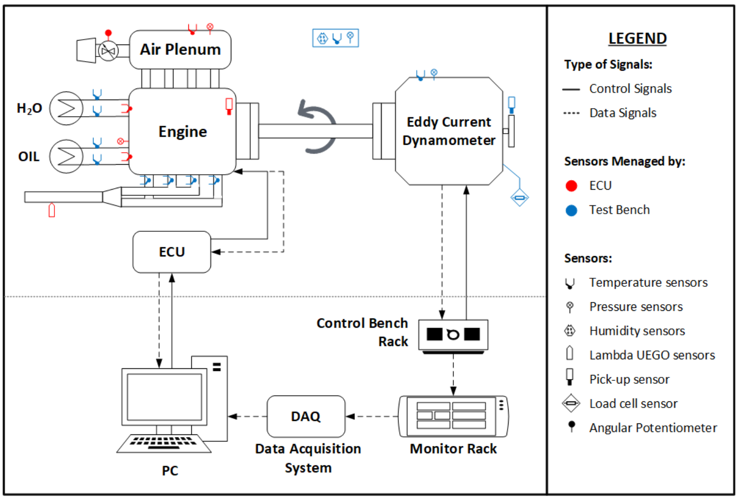

FIGURE 3. Acquisition chain scheme

As for the experimental activity, the operating points to be analyzed have been selected in the range between 3000 and 10000 RPM. Then, once engine stable operation is reached at WOT, all the measured quantities used for the engine model calibration (engine speed, torque, pressures, temperatures, etc.) have been stored via the acquisition system stores. This procedure was conducted from 3000 to 10000 RPM and vice versa, with step of 500 RPM. The effect of cyclic dispersion was taken into account by repeating the procedure 3 times. Therefore, 14 different engine operating conditions were acquired, and each of them is analyzed 6 times. The main results of the experimental activity are summarized in **TABLE 4**.

TABLE 4. Main results of the experimental activity

Environmental Temperature	Environmental Pressure	Throttle	Engine Speed	Engine Speed Variation	Spark Advance	Mean λ	Mean torque	Torque Variation
[°C]	[mbar]	[deg]	[RPM]	[RPM]	[deg]	[\]	[Nm]	[Nm]
24.0	1017	WOT	10076	109	26.3	≈0.88	48.2	1.8
24.0	1017	WOT	9578	309	27.0	≈0.88	50.9	2.6
24.1	1017	WOT	9091	272	27.6	≈0.88	53.2	1.5
24.1	1017	WOT	8578	223	23.2	≈0.88	56.9	1.8
24.5	1017	WOT	8076	333	18.8	≈0.88	60.6	1.3
25.1	1017	WOT	7561	321	21.5	≈0.88	62.3	1.9
25.5	1017	WOT	7061	283	28.1	≈0.88	59.4	2.9
26.5	1017	WOT	6024	424	31.4	≈0.88	50.6	1.1
26.5	1017	WOT	5578	629	36.0	≈0.88	49.3	2.9
27.0	1017	WOT	5048	166	27.7	≈0.88	52.2	1.0
27.5	1017	WOT	4574	245	37.3	≈0.88	43.5	5.6
27.5	1017	WOT	3947	457	37.0	≈0.88	42.2	2.7
27.5	1017	WOT	3665	206	33.4	≈0.88	43.6	1.2
27.5	1017	WOT	3048	115	26.2	≈0.88	42.4	2.0

In particular, the table shows average values of the ambient temperature and pressure, engine speed, air/fuel ratio, torque, etc., that have been adopted for the engine model calibration.

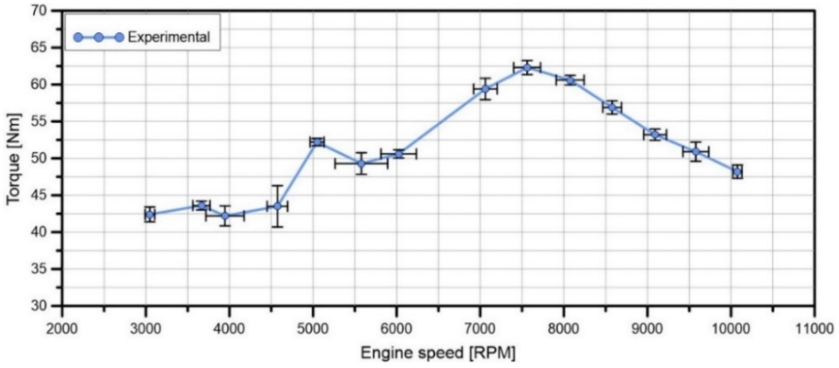

FIGURE 4. Experimental torque curve with details of the uncertainty range for each measurement

The stored measurements also consider torque and speed variations to take account of measurement uncertainties. **FIGURE 4** shows the mean values obtained for the torque with details of the uncertainty range for each measurement. The spark advance values have been obtained from the ECU after proper verification of the control unit circuit.

4 1D Engine Model

In this study, a mixed 0D-1D model of the engine has been set up and thermo-fluid dynamic analyses have been carried out based on a well-known turbulent combustion model [4-6]. **FIGURE 5** shows the 0D/1D schematization obtained for the engine object of investigation, whose main geometric data for the intake and exhaust systems, cylinders and combustion chambers are collected in **TABLE 1**, **TABLE 2** and **TABLE 3**.

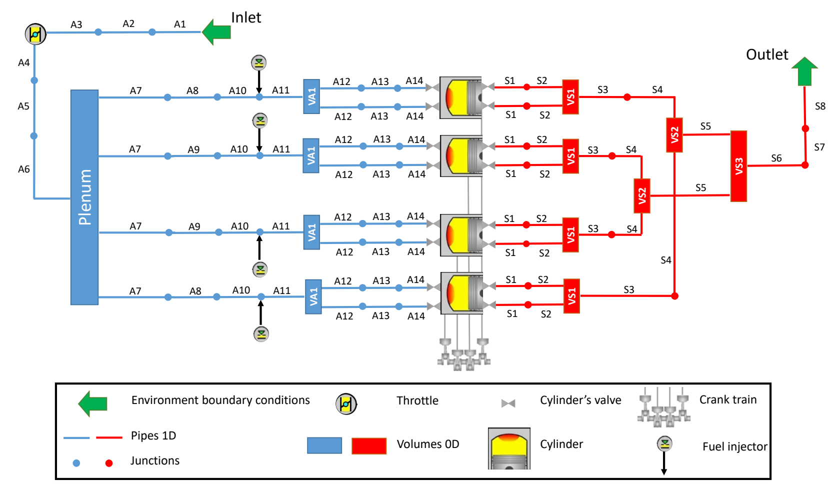

FIGURE 5. 0D/1D engine schematization

The 1D flow model is based on the solution of the one-dimensional continuity, momentum and energy equations which characterize the wave propagation phenomena.

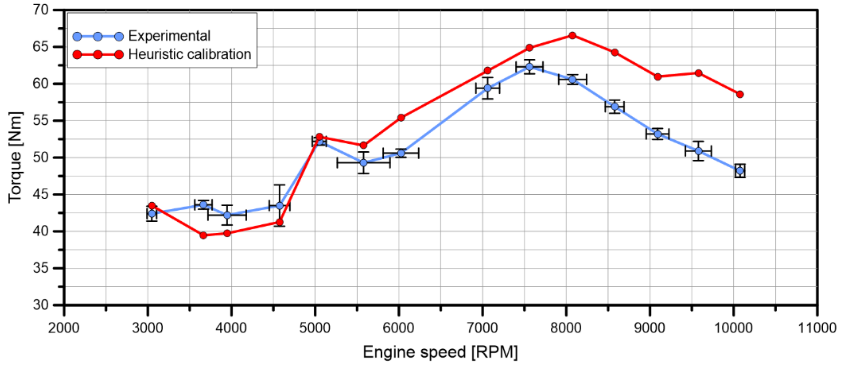

FIGURE 6. Comparison between simulated and experimental torque curve

Moreover, to reliably detect the effects of cylinders geometry, spark timing, air motion, valve timing and fuel properties on the engine performance, a predictive turbulent combustion model for the flame front propagation has been used. A more detailed discussion concerning flow equations or combustion and friction modeling can be found in [7-11]. With reference to the torque curve at WOT, **FIGURE 6** shows a first numerical-experimental comparison obtained after a first heuristic calibration of the engine model. The figure

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highlights that, although the trend is quite well reproduced, the 1D engine model requires further calibration effort before it could be reliably used to predict the engine behavior.

5 The Calibration Procedure

To identify the calibration parameters of the thermo-fluid dynamic engine model that mostly affect the simulation results, a preliminary parametric analysis was conducted. Since a simplified 0D model has been used for the intake plenum volume, the length of the intake manifold pipes has been selected as calibration parameters mainly to try to account for the complex wave dynamic phenomena occurring within the manifold plenum [12, 13], whose phenomenology has not been analyzed in detail in this paper. Three parameters concerning the flame front propagation and a flow coefficient multiplier were also considered. Specifically, a flow area multiplier, a flame kernel growth multiplier, a turbulent flame speed multiplier and a Taylor length microscale multiplier have been adopted as calibration parameters affecting the intake valves airflow and the combustion process. The Taylor length microscale multiplier influences the tail combustion by affecting the time constant of combustion. The flame kernel growth multiplier, instead, influences the ignition delay, thus varying the transition from laminar to turbulent combustion. The effect of variations of these parameters on the brake torque have been evaluated. **FIGURE 7**, **FIGURE 8** and **FIGURE 9** show only the results related to the three combustion parameters, as the effects of the other two calibration parameters are mainly negligible.

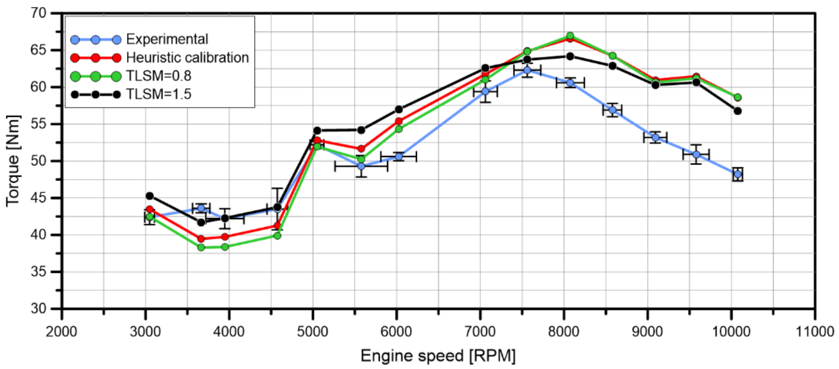

FIGURE 7. Torque curve for different values of the Taylor length microscale multiplier

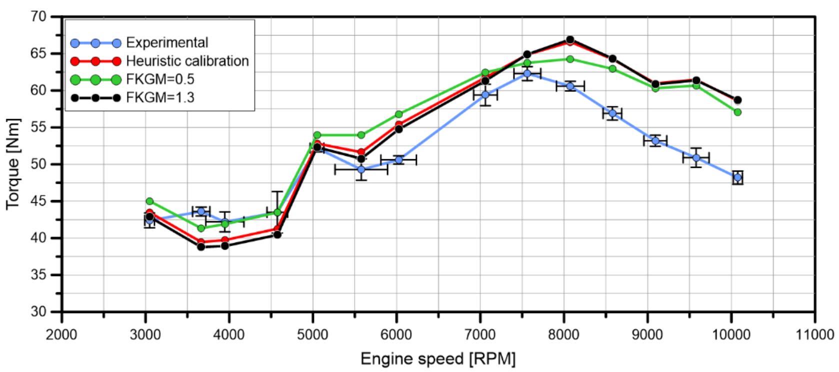

FIGURE 8. Torque curve for different values of the flame kernel growth multiplier

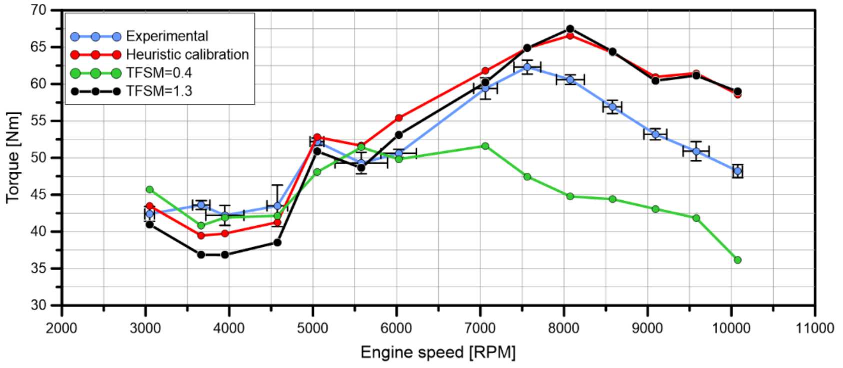

FIGURE 9. Torque curve for different values of the turbulent flame speed multiplier

Starting from the limited available experimental data, to obtain a quite reliable 1-D fluid dynamic engine model, a calibration procedure based on a vector optimization approach has been used [13-16]. The methodology adopted is schematized in **FIGURE 10**. The five model calibration parameters described above have been set as decision variables of a vector optimization problem and their range variation defined according to the values reported in **TABLE 5**.

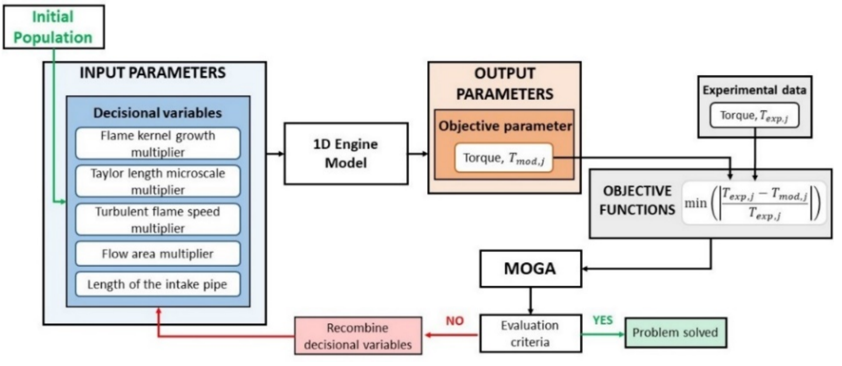

FIGURE 10. Vector optimization procedure

Objective of the optimization problem has been set the minimization of the error between numerical and experimental torque values in the 14 engine operating conditions considered during the experimental activity, as formalized in eq. (1). A genetic optimization algorithm has been used to solve the optimization problem [14, 15].

$$S_j\ (\%) = \min\left(\left|\frac{Torque_{exp,j} - Torque_{mod,j}}{Torque_{exp,j}}\right| \cdot 100\right) \tag{1}$$

TABLE 5. Decision variables ranges

Decision variables	Lower bound	Upper bound	Calibrated values
Flame Kernel Growth Multiplier	0.5	1.3	1.29
Turbulent Flame Speed Multiplier	0.4	1.3	0.51
Taylor Length Scale Multiplier	0.8	1.5	0.82
Flow Area Multiplier	0.9	1.05	1.05
Length of the intake pipe, mm	85	95	95.00

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As the solution of the problem leads to the identification of a set of optimal solution (Pareto frontier), a decision-making problem has been solved to identify a single set of calibration parameters. The identification criterion, expressing the minimum distance from the axes origin, is formalized in eq. (2). The optimized values of the calibration parameters have been reported in **TABLE 5**.

$$\min\left(\sqrt{\sum_{j=1}^{n}\left(S_j\right)^2}\right) \tag{2}$$

6 Results and Discussion

Once the optimization problem has been solved, the optimized values of the calibration parameters have been used to simulate the engine torque curve at WOT. The result is represented in **FIGURE 11**.

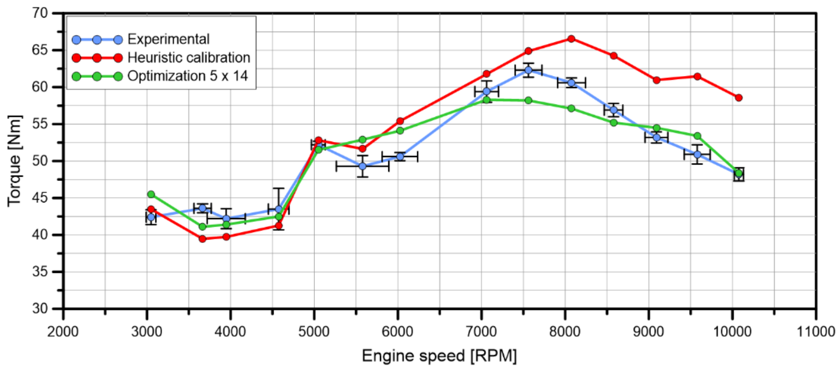

FIGURE 11. Comparison between default, experimental and optimized torque curve

Finally, **TABLE 6** shows the error comparison between numerical and experimental torque when the heuristic and the proposed approach are used. The table highlights a significant reduction of the error when the proposed methodology is used. This is an important result because the error magnitude can highly affect the reliability of the 1D engine model. However, further calibration improvements may be achieved through a detailed 1D model of the intake plenum, in replacement of the simplified 0D model, to take account of the wave dynamic effects on the engine volumetric efficiency. Moreover, a proper calibration of the engine friction model may be also useful to enhance the prediction capability of the engine model.

TABLE 6. Error comparison between heuristic and proposed approach

Torque error	Heuristic approach	Proposed approach
Maximum error	21%	7.2%
Mean error	9%	3.9%
Minimum error	1.2%	0.5%

7 Conclusion

This work addresses the set up and calibration of a 1-D fluid dynamic engine model through a limited number of experimental data available since the early stage of development of a new Formula SAE vehicle. The obtained engine model allowed the Team UniNa Corse of the University of Naples Federico II to evaluate possible improvements during the international FSAE championship. Firstly, the experimental activity has been conducted at WOT on the engine object of investigation. Then, a preliminary parametric analysis was carried out to identify possible calibration parameters to be used within the proposed calibration procedure. The calibration parameters were set as decision variables of a vector optimization problem, while the errors between numerical and experimental values of the brake torque have been defined as objective function. The results highlight a significant improvement of the model calibration when the proposed methodology is used, with the mean error falling from 9 to 3.9% if compared to a reference heuristic approach. This is a promising result because the error magnitude gives a measure of the reliability of the 1D engine model. Moreover, further calibration improvements may be achieved through a detailed 1D model of the intake plenum, a proper calibration of the engine friction model and an ad hoc design of the few experimental tests in future activities.

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