ECOLE DES MINES DE PARIS
ARMINES
CENTRE D'ENERGETIQUE

Analysis of test bench results and calculations to forecast energy performance of CAT vehicles using MDI technology

Order from MDI (S. Vencat)

FINAL REPORT

All drawings and pictures of the CAT concept presented in the report are by the courtesy of MDI

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Contents

Summary

The global CAT car concept is based on several concepts:

- compressed air engine,
- versatility of the engine, which is running as a compressor for recharging the air tanks,
- light urban vehicles,
- car manufacturing at small scale.

The only purpose of this report is to evaluate the possible autonomy of the CAT vehicle based on calculations and available test data provided by MDI.

The design of the actual air engine, named 34p01-4, is a 3-stage air expansion engine having 2 heat exchangers to re-heat the expanded air after the two first expansions.

CAT car autonomy forecast

Based on calculations using accurate thermodynamics properties of air at high pressure, Part 1 of the report evaluates the impact on the CAT car autonomy of:

- isentropic and mechanical efficiencies of the air engine,
- leakage ratio of the engine,
- the air temperature,
- the heat exchanger effectiveness.

Those parameters are grouped in 4 sets permitting to define 4 levels of efficiencies of the compressed air engine. Evaluations have been realized in steady state conditions for 2 speeds of the CAT car: 20 (12.4mp/hr) and 50 km/hr (31mp/hr).

Gross autonomy

Table 1: Gross autonomy of the car for the four sets of efficiency at 20km/hr (12.4mp/hr)

Distance	Low efficiency system	Average efficiency system	Baseline system	High efficiency system
(km)	222	406	**509**	590
(miles)	138	252	**316**	367

The autonomies, calculated depending on the different efficiencies, are the gross autonomies because the impact of the electrical consumption of accessories is not taken into account.

Autonomy with electrical consumption of accessories

Electrical accessories comprise mandatory safety accessories: wipers, lights, warning, and also starting of the air compressed engine. 300W is the maximum electrical power considered to be needed for running the car at night under raining conditions.

Table 2: CAT car calculated autonomies depending on the speed and the electrical consumption.

Tank volume (liters)	Baseline system (km/miles)	Baseline system (km/miles)	Baseline + 300 W (electric) (km/miles)	Baseline + 300 W (electric) (km/miles)
	at 20km/hr (12.4mp/hr)	**at 50km/hr** (31mp/hr)	**at 20km/hr** (12.4mp/hr)	**at 50km/hr** (31mp/hr)
3 x 114	**509 / 316**	**115 / 71**	120 / 75	93 / 58
3 x 150	**670 / 416**	**143 / 89**	146 / 91	117 / 73

Table 2 shows the significant impact of electrical consumption of the car, leading to an **autonomy in between 117 to 146km (73 to 91miles) with 300W of electrical**

consumption, and for the 2 levels of the car speed. This autonomy is possible for the baseline case where:

- **the efficiencies of the engine are of 85%**,
- the **leakage ratio is of 2%**, and
- the **heat exchanger effectiveness is of 50%**.

This set of efficiencies corresponds to a good design and realization of the engine.

Special attention shall be paid to cabin heating in winter conditions. The choice of an electrical heater could compromise the car autonomy down to 35 to 45km (22 to 28miles) if the needed electrical power is of 2kW. A fuel burner for heating seems to be an appropriate solution to avoid such a high electrical consumption.

On the contrary, for the cabin cooling, it shall be underlined that the CAT car concept permits to use free cooling due to the air low temperature (-40°C) at the air exhaust.

Actual tested prototype

Part 2 of the report analyzes the effective performances reached by the actual prototype, named 34p01-1. Due to delay in the realization, the actual tested prototype is not the complete 3-stage air engine but only the last stage. Nevertheless the tests permit to evaluate the efficiencies and leakage of the actual prototype.

Table 3: Actual performances of the 34p01-1 prototype.

	Parameters
Isentropic efficiency (%)	0.70 to 0.75
Mechanical efficiency (%)	0.70 to 0.75
Leakage on the main air loop (%)	10
Leakage in the cylinder chamber (%)	4 / (6 for 1piston)
Pressure losses (MPa)	1 – 1.4

The actual efficiencies that have been measured are in the low range. Those levels of efficiencies require significant improvements in order to reach the forecasted efficiencies of the baseline system presented in the previous paragraphs.

In conclusion, the global concept of CAT cars using compressed air permits to drive small urban vehicles. The design of the 3-stage 34p01-4 engine of MDI permits to forecast a possible autonomy corresponding to urban usage (between 117 to 146km (73 to 91miles)) taking into account typical speeds from 20 to 50km/hr (12.4mp/hr to 31mp/hr). At high speed, the autonomy will be lower.

To move the project from the design stage to the manufacturing process, a lot of development work is needed in order to reach the level of efficiencies required for the forecasted autonomy.

Introduction

The objective of this report is to evaluate the energy performances of the compressed air engine developed by MDI.

The work program covers two main aspects:

- calculations and analysis of the expansion process,
- analysis of test bench results.

1. Calculations and analysis of the expansion process

Based on the actual design of the engine and the working conditions (number of expansion chambers, number of heat exchangers, air pressure inside the tanks, power to be developed by the engine to move the car at various speeds), the expansion process simulation will permit to evaluate the autonomy of the MDI cars for various driving conditions.

The simulations take into account various parameters such as engine and heat exchangers efficiencies, the volume of the tanks, and the air leaks in order to analyze their relative influence on the car performances.

2. Analysis of test bench results

MDI has performed various tests on their actual prototype and sent us the available results (power, rotation speed, pressures, temperatures and duration time for different running conditions). The analysis of these results permits to evaluate the energy performances of the actual prototype.

3. Visit of MDI facilities

J. Benouali and D. Clodic of ARMINES have visited MDI facilities in Carros near Nice, on June 2 and 3. Messrs. Guy and Cyril Negre, and their team have presented the different concepts of CAT cars. The visit has permitted to have a demonstration of the actual engine prototype on a test bench. Different workshops of the facilities have also been visited to present the realization of parts of the vehicle.

Test data on the actual prototype have been provided by MDI and are used in Part 2 of this document.

Note: Values for conversion		
1mile = 1.609km	**1kW = 1.359hp (ch)**	**1bar = 100kPa = 0.1MPa**

Part 1
Calculations and analysis of the expansion process

1.1 Engine presentation

MDI has developed various compressed air models of engines that can power little city cars. The late model is named 34p01-4 and is presented Figures 1.1 and 1.2.

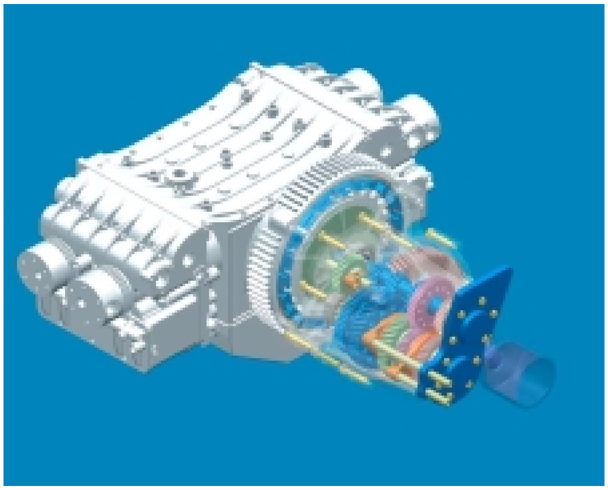


Figure 1.1:
Global view of the engine with its gear box and its alternator.

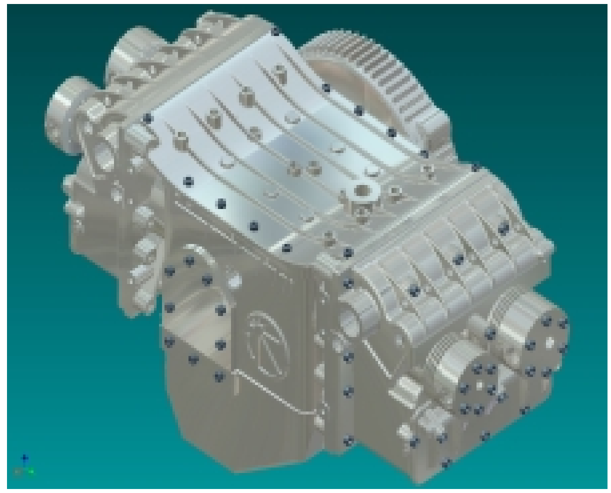


Figure 1.2:
View of the 34p01-4 engine.

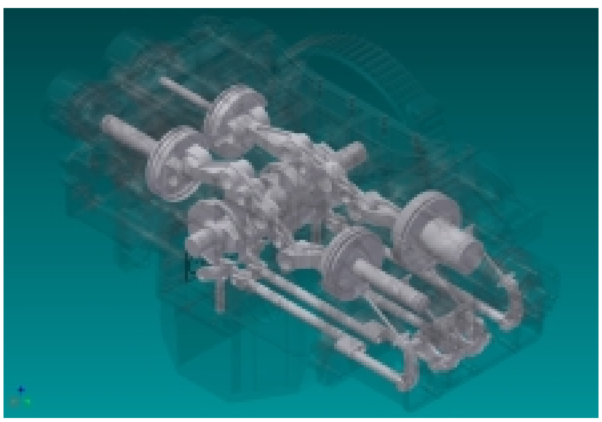


Figure 1.3:
Inner view of the engine.

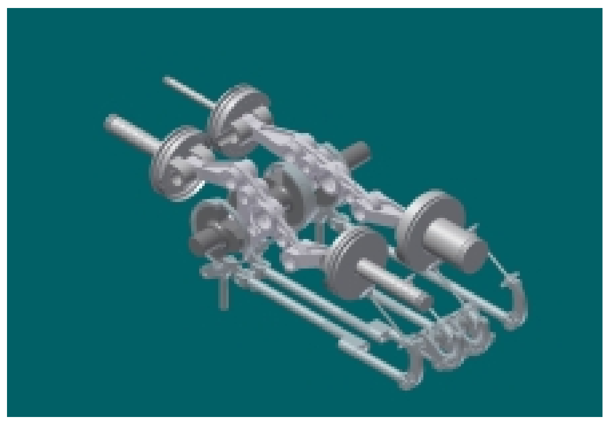


Figure 1.4:
View of the two-stage pistons and the variable distribution.

1.2 Expansion and reheat process

The actual design of the 34p01-4 engine is based on a three-stage expansion process coupled with two heat exchangers. The higher the number of stages in a compression / expansion processes, the higher the efficiency.

Two heat exchangers are used to reheat the air at the outlet of the first and the second expansion stages.

The engine operation is explained using Figures 1.6 to 1.8.

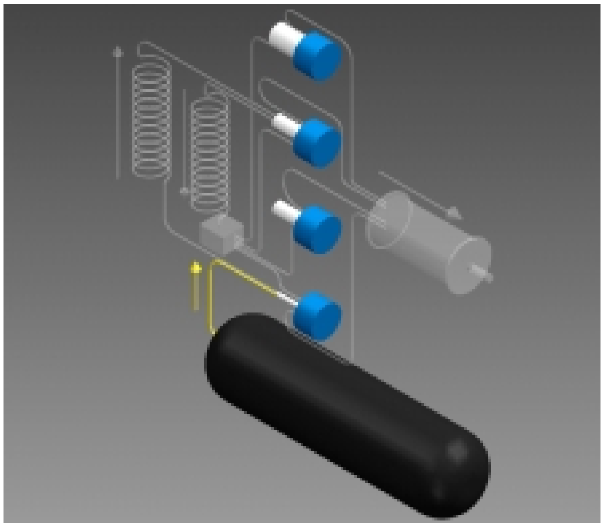


Figure 1.5:
Expansion process in the first stage.

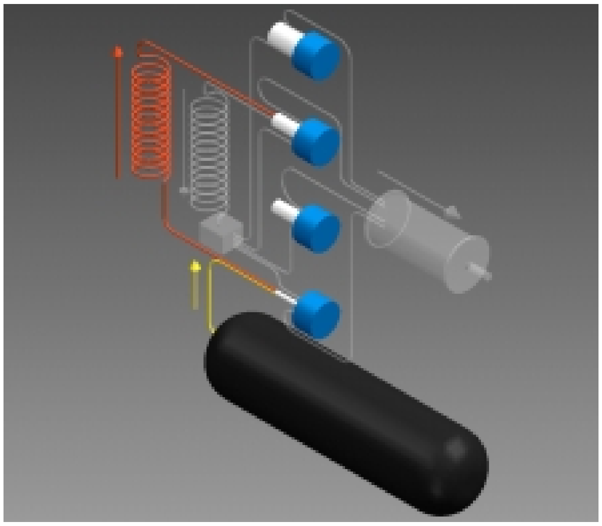


Figure 1.6:
Reheat of the air in the first heat exchanger and expansion process in the second stage.

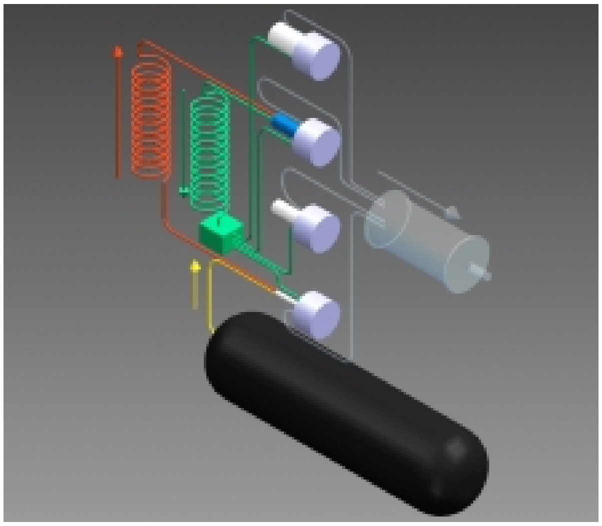


Figure 1.7:
Reheat of the air in the second heat exchanger and expansion process in the third stage.

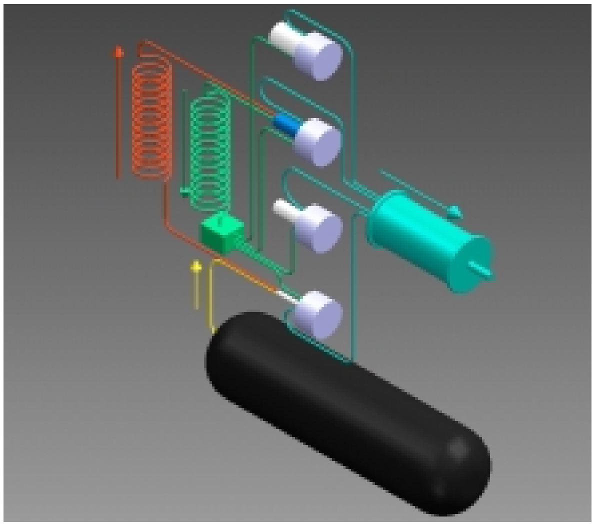


Figure 1.8:
End of the expansion process through the exhaust pipe.

The air reheat between each expansion stage is essential to realize an evolution as close as possible to an isothermal expansion and as far as possible from an adiabatic one. In fact an isothermal (expansion or compression) presents a better efficiency than an adiabatic one. In the case of the 34p01-4 engine the two heat exchangers aim at achieving the compression process closer to the isothermal expansion.

1.3 Thermodynamic evaluation of the 34p01-4 engine

The main objective of this study is the modeling of the expansion process of the compressed air from the high-pressure tank to the exhaust pipe. This modeling is not as simple as it can be imagined; in fact shown in Figure 1.10, above 3,8 MPa (which is the air critical pressure) the air is not a gas anymore, but a supercritical fluid.

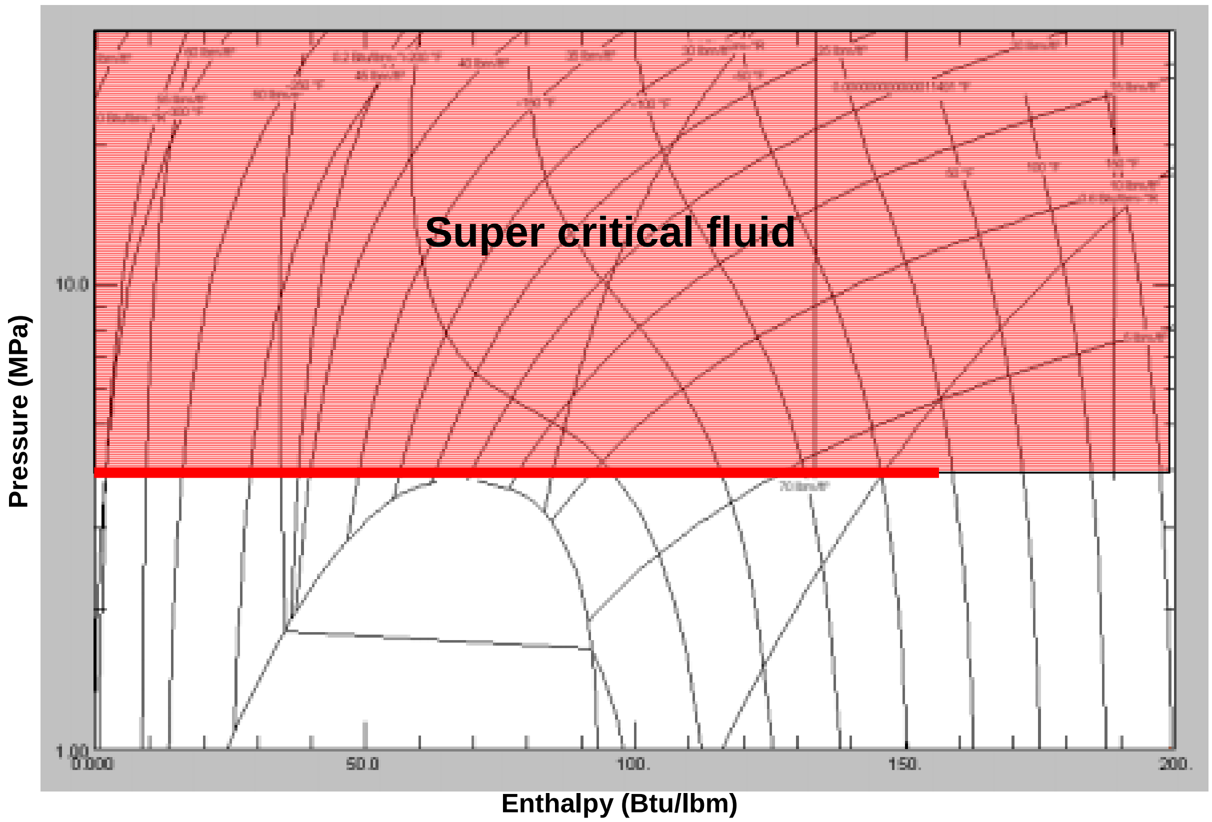


Figure 1.10: Pressure- enthalpy diagram of the air.

Since air above 3,8 MPa is a supercritical fluid, it is not possible to consider the air like an ideal gas; so it is not possible to use the following equation of state:

$$P = \rho . r . T \tag{1.1}$$

where :
P pressure (Pa),
ρ density (kg.m^{-3}),
T temperature (K),
r = 287.18

It is not even possible to use the polytropic expansion relation:

$$P . V^k = constant \tag{1.2}$$

where:
V volume (m^3),
k polytropic factor (comprise between 1 and 1.4).

The properties of the compressed air have been obtained using the software Refprop7, developed by the US NIST (National Institute of Science and Technology). All the properties have been plotted to be used in the software "Air_Expansion", developed by the Center for Energy Studies of Ecole des Mines de Paris, in order to evaluate the energy performances of the MDI engine.

The methodology used to solve the problem is based on the knowledge of the temperature, and the pressure before each expansion process. The enthalpy, the entropy and the density of the air are then calculated (using P and T). Knowing the volumetric ratio between the clearance volume and the chamber volume, it is possible to calculate the density at the end of the expansion process. With the density and the entropy, all the parameters can be evaluated for an isentropic process, and with an isentropic efficiency, all the real parameters can be calculated.

Figure 1.11 shows the main panel of the "Air_Expansion" software. All the parameters can be changed to evaluate various configurations.

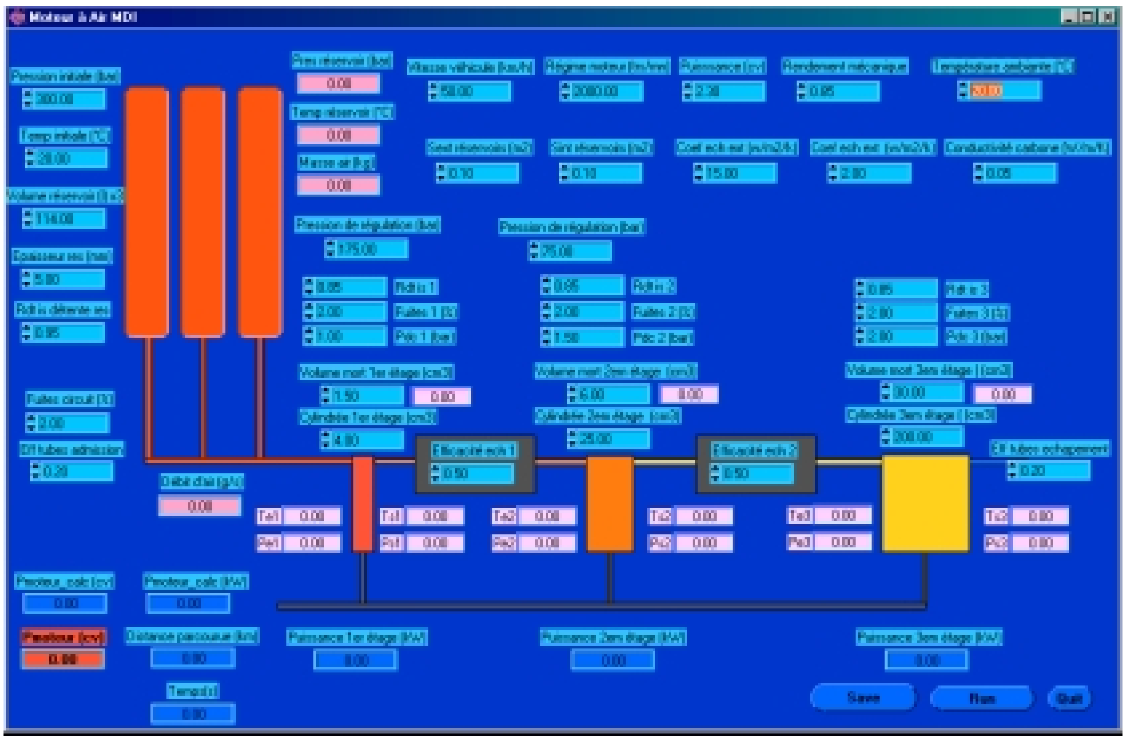


Figure 1.11: The "Air_Expansion" software – Panel 1.

1.4 Evaluation of the MDI car autonomy

Using the "Air_Expansion" software, it is possible to evaluate the autonomy of MDI City CAT car for different conditions.

It has been decided to run the tests for two steady state driving conditions:

- 20km/h (12.4mph),
- 50km/h (31mph).

Note: steady state conditions are not realistic for urban driving conditions, but are sufficient to evaluate the order of magnitude of the car autonomy.

According to the values given by MDI, the energy needed to run the City CAT is about:
- 110W (0.15hp) at 20km/h,
- 1,7kW (2.32hp) at 50km/h.

Table 1.1: Volumes used to perform the calculations

	Clearance volume (cm^3)	Volume chamber (cm^3)
Stage 1	1.5	5
Stage 2	6	25
Stage 3	30	300

1.4.1 Calculations at 20km/h

At 20km/h, the engine rotation speed is about 1000rpm.
For the calculations, the parameters listed in Table 1.2, have been used for the "baseline case".

Table 1.2: Parameters used for the baseline case

	Baseline
Isentropic efficiency (%)	0.85
Mechanical efficiency (%)	0.85
Leakage on the main air loop (%)	2
Leakage in the cylinder chamber (%)	2
Heat exchanger effectiveness (%)	0.5
Air tank pressure (MPa)	30
Air tank temperature (°C)	20
Ambient air temperature (°C)	20
Air tank volume (l)	114

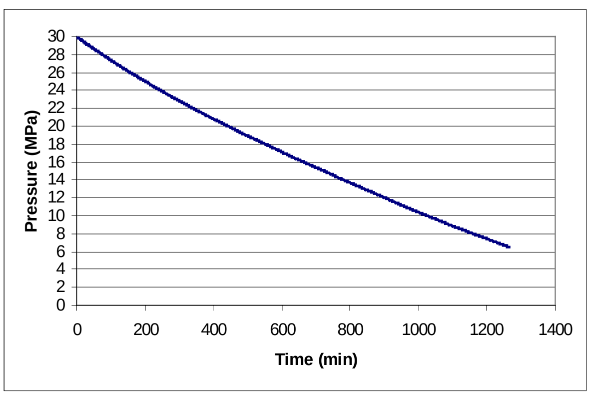


Figure 1.12: Evolution of the pressure of the compressed air inside the tank

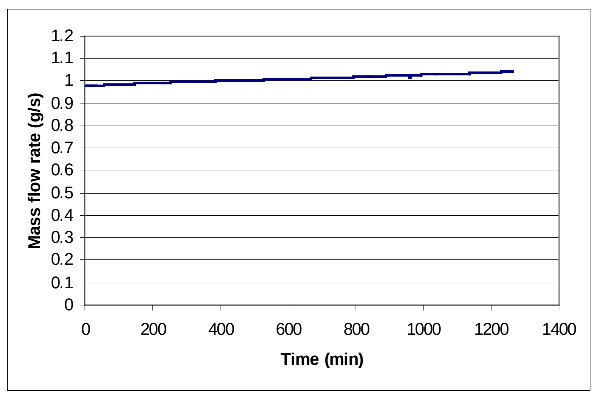


Figure 1.13: Evolution of the compressed air mass flow rate

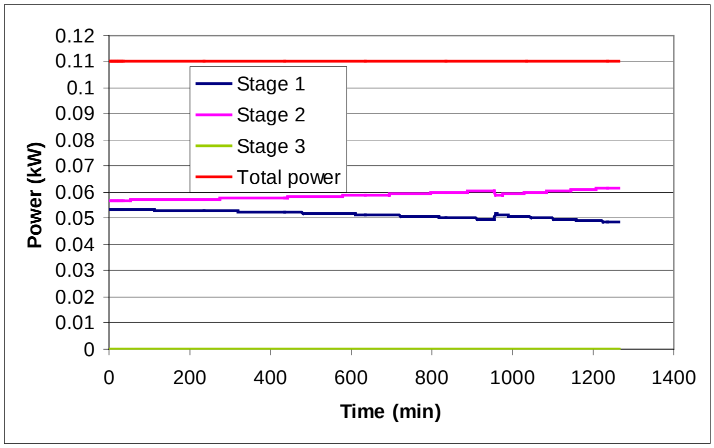


Figure 1.14: Evolution of the power supplied by each expansion stage

Figure 1.14 shows the evolution of the power supplied by each expansion stage. At low power, 0.11kW in this case (0.15hp), only two stages are used to develop the required power (stage 1 and stage 2). The third stage is not used because the air pressure at the outlet of the second stage is about 0.1Mpa, so no other expansion process can be performed. Figure 1.13 shows that the air flow rate varies slowly during the cycle, this is why the variation of the power supplied by the two first stages is not important.

The lower the pressure in the tank, the higher the mass flow rate to compensate the loss of mechanical power developed during the expansion process.

The higher the air flow rate, the lower the power available at the first stage. This is due to the fact that the ratio between the suction volume and the cylinder chamber is reduced, when the mass flow rate increases; so the expansion ratio falls down too and so does the power.

Whatever the evolution of each stage, the global power is constant along the test so the speed of the car can be controlled without problem.

The influence of various parameters has been studied to evaluate the autonomy of MDI cars. Tables 1.3 to 1.8 show the results obtained.

- *Energy efficiency*

Table 1.3: Influence of the isentropic efficiency

Isentropic efficiency (%)	Car Autonomy (km)	Car Autonomy (miles)
0.7	405	252
0.75	460	286
0.8	486	302
0.85	**509**	**316**
0.9	528	328
0.95	547	340

Table 1.4: Influence of the mechanical efficiency

Mechanical efficiency (%)	Car Autonomy (km)	Car Autonomy (miles)
0.7	428	266
0.75	458	285
0.8	484	301
0.85	**509**	**316**
0.9	531	330
0.95	551	342

The results presented in Tables 1.3 and 1.4 show that the influence of the isentropic and the mechanical efficiencies is very significant. The autonomy reduction is proportional to the efficiency level.

- *Leakage ratio*

Table 1.5: Influence of the leakage ratio on the air loop

Leakage on the air loop (%)	Car Autonomy (km)	Car Autonomy (miles)
0	519	322
2	**509**	**316**
4	499	310
6	489	304
8	478	297

Table 1.6: Influence of the leakage ratio on the cylinder chamber

Leakage in the cylinder chamber (%)	Car Autonomy (km)	Car Autonomy (miles)
1	531	330
2	**509**	**316**
4	461	287
6	408	254

Table 1.5 shows that at a low-level leakage rates on the air loop do not affect the autonomy of the car in an important way. On the contrary, Table 1.6 shows that a low airtightness for the pistons entails an important reduction in terms of performances.

- *Air temperature inside the compressed air tank*

When the air is compressed, its temperature increases. The higher the temperature, the lower the air density so the mass stocked in the tank is lower (for a given pressure); on the other hand, the higher the temperature, the higher the enthalpy (i.e. the energy per kg of air). So there is an optimum temperature, which in this case is 40°C.

Table 1.7: Influence of the air temperature in the tank

Air temperature in the tank (°C)	Car Autonomy (km)	Car Autonomy (miles)
20	**509**	**316**
40	518	322
60	467	290
80	458	285
100	454	282

- *Ambient air temperature*

Table 1.8: Influence of the ambient air temperature

Ambient air temperature (°C)	Car Autonomy (km)	Car Autonomy (miles)
-20	504	313
0	506	314
20	**509**	**316**
40	512	318

The influence of the ambient air is not very important but Table 1.8 shows that the higher the ambient temperature, the higher the autonomy.

♦ *Heat exchanger effectiveness*

Table 1.9: Influence of the heat exchanger effectiveness

Heat exchanger effectiveness	Car Autonomy (km)	Car Autonomy (miles)
0	245	152
0.1	281	175
0.2	325	202
0.3	382	237
0.4	499	310
0.5	509	316
0.6	514	319

As it can be seen in Table 1.9 when the heat exchanger effectiveness is lower than 0.4, any reduction of the effectiveness entails an important reduction of the car autonomy. On the contrary, when the heat exchanger effectiveness is higher than 0.4, any improvement does not yield to any significant improvement.

♦ *4 sets of efficiencies*

The parametric analysis performed previously has permitted to identify the most important parameters influencing the energy performances of the engine. To analyze the influence of a **set of parameters**, four sets have been chosen leading to:

- a low efficiency system,
- an average efficiency system,
- a baseline system,
- a high efficiency system.

The different efficiencies of those systems are summarized in Table 1.10.

Table 1.10: Efficiencies chosen for four sets

	Low efficiency system	Average efficiency system	Baseline	High efficiency system
Isentropic efficiency (%)	0.75	0.8	**0.85**	0.9
Mechanical efficiency (%)	0.75	0.8	**0.85**	0.9
Leakage on the main air loop (%)	5	4	**2**	1
Leakage in the cylinder chamber (%)	5	4	**2**	1
Heat exchanger effectiveness (%)	0.3	0.4	**0.5**	0.6
Air tank pressure (MPa)	30	30	**30**	30
Air tank temperature (°C)	20	20	**20**	20
Ambient air temperature (°C)	20	20	**20**	20
Air tank volume (l)	114	114	**114**	114

Table 1.11: Gross autonomy of the car for the four sets of efficiency

Distance	Low efficiency system	Average efficiency system	Baseline system	High efficiency system
(km)	222	406	**509**	590
(miles)	138	252	**316**	367

Table 1.11 shows that depending on the combination of all efficiencies, the system can have a very different autonomy. A small reduction of all the efficiencies can lead to an important reduction in terms of autonomy (nearly 60% between the high efficiency and the low

efficiency systems). Table 1.11 presents the gross autonomy because the electrical consumption of accessories is not taken into account.

1.4.2 Energy consumption of accessories

A minimum electrical energy is necessary to operate safety accessories, wipers, lights, warning, and also for starting the air-compressed engine. In this study, 300W of electrical power is assumed as a minimum to cover the minimum electrical needs. Moreover, heating and, in many countries, cooling are considered as basic functions that need to be taken into account. The good news for the air-compressed system is the capability to use the cold air exhausted by the engine to cool the cabin. This is a significant advantage of this concept. On the contrary, heating is a constraint, and the heating needs shall be covered either by a burner or by an electrical resistance. The following calculations show that electrical heater compromises significantly the autonomy of the car.

In the following calculations, the typical alternator efficiency of 60% is taken as a reference.

Three cases are studied in this section:

- baseline system, without any production of electricity (not realistic),
- baseline system with a 300W electrical production,
- baseline system with a 2 kW electrical production.

To produce 300W of electricity, 500W of mechanical energy must be used (0.68hp).
To produce 2 kW of electricity, 3.33 kW of mechanical energy must be used (4.50hp).

Table 1.12: Influence of the electric production

Tank volume (liters)	Baseline system (km/miles)	Baseline + 300 W (electric) (km/miles)	Baseline + 2 kW (heating) (km/miles)
114	**509 / 316**	120 / 75	45 / 28
150	**670 / 416**	146 / 91	55 / 34

The effect of the electric production on the autonomy of the car is significant. For a 300 W production, the autonomy is about 75 miles compared to 316 miles without electrical production. This corresponds to a 75% reduction in terms of autonomy.

With a 2kW electrical production, the autonomy reduction is about 90% (at 31mph).
To limit the effect of the electric production, 150-liter tanks can be used instead of the actual 114 liters ones.

1.4.3 Calculations at 50km/h (31mph)

At 50km/h, the engine rotation speed is about 2000 rpm. The same work as performed in section 1.4.1, has been carried out in this section. The results are presented in the following tables.

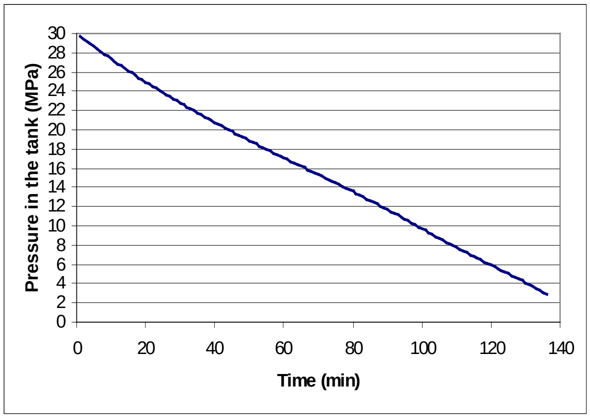


Figure 1.15: Evolution of the pressure of the compressed air inside the tank.

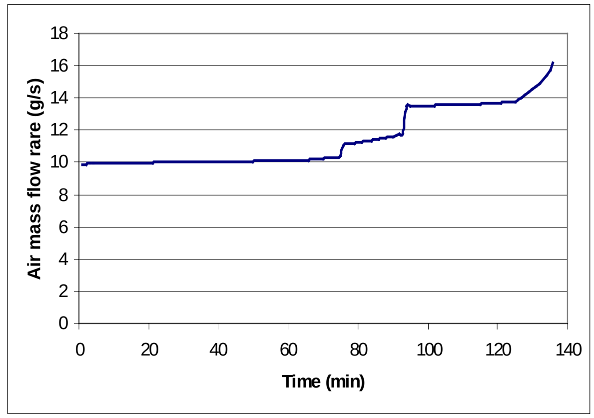


Figure 1.16: Evolution of the compressed air mass flow rate.

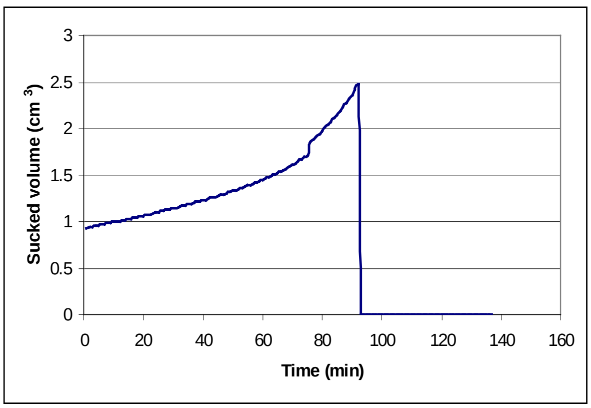


Figure 1.17: Evolution of the sucked volume in the first stage.

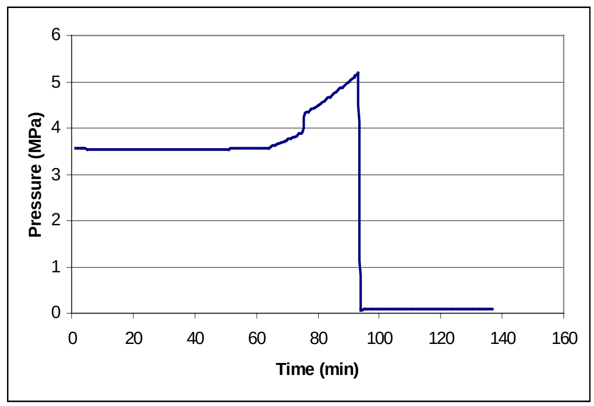


Figure 1.18: Evolution of the pressure at the outlet of the first stage.

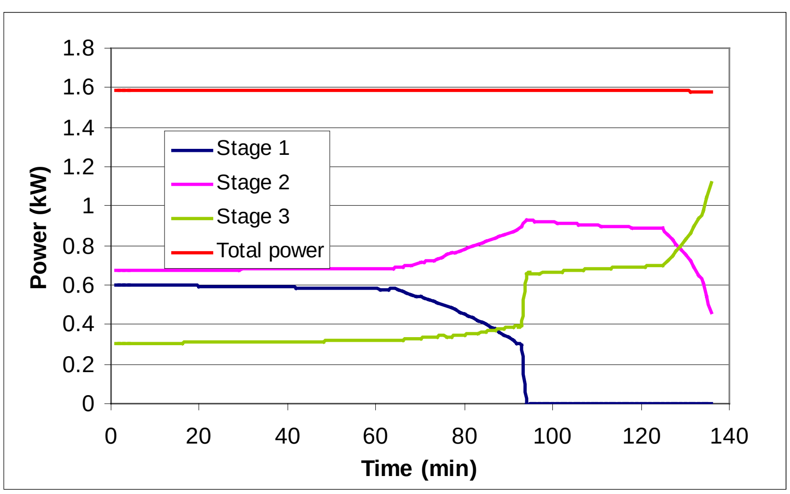


Figure 1.19: Evolution of the power supplied by each expansion stage.

Figure 1.19 shows the evolution of the power supplied by each expansion stage. At 1.6kW (2.30hp), all the stages are used to develop the required power, which was not the case when the power was equal to 0.11kW (0.15hp).

During the first 60 minutes, the way the engine works is stable. Figure 1.16 shows that the air mass flow rate is constant and equal to 10 g/s. When the tank pressure reaches 16MPa (approximately the half of the initial pressure), the engine needs a higher mass flow rate to compensate the decrease of the expansion ratio. This is particularly true for stage 1: the available power decreases, but since the ratio between the sucked volume and the cylinder volume decreases Figure 1.17), the pressure at the outlet of the first stage increases and thus the pressure at the inlet of stage 2 (Figure 1.18). So the power available at stages 2 and 3 increases.

Stage 1 is stopped for a pressure in the tank equal to 11MPa. After 90 minutes, the engine works only on stages 2 and 3.

When the pressure decreases in the tank, the power available on the stage 2 decreases whereas the power supplied by stage " increases. Whatever the evolution of each stage, the global power is constant along the test so the speed of the car can be controlled without problem.

Table 1.13: Parameters used for the baseline case

	Baseline
Isentropic efficiency (%)	0.85
Mechanical efficiency (%)	0.85
Leakage on the main air loop (%)	2
Leakage in the cylinder chamber (%)	2
Heat exchanger efficiency (%)	0.5
Air tank pressure (MPa)	30
Air tank temperature (°C)	20
Ambient air temperature (°C)	20
Air tank volume (l)	114

Table 1.14: Influence of the isentropic efficiency

Isentropic efficiency (%)	**Car Autonomy (km)**	**Car Autonomy (miles)**
0.7	97	60
0.75	103	64
0.8	110	68
0.85	**115**	**71**
0.9	118	73
0.95	123	76

Table 1.15: Influence of the mechanical efficiency

Mechanical efficiency (%)	Car Autonomy (km)	Car Autonomy (miles)
0.7	97	60
0.75	102	63
0.8	108	67
0.85	**115**	**71**
0.9	118	73
0.95	123	76

Table 1.16: Influence of the leakage ratio on the air loop

Leakage on the air loop (%)	Car Autonomy (km)	Car Autonomy (miles)
0	116	72
2	**115**	**71**
4	112	70
6	109	68
8	107	66

Table 1.17: Influence of the leakage ratio in the cylinder chamber

Leakage in the cylinder chamber (%)	Car Autonomy (km)	Car Autonomy (miles)
1	120	75
2	**115**	**71**
4	105	65
6	93	58

Table 1.18: Influence of the air temperature in the tank

Air temperature in the tank (°C)	Car Autonomy (km)	Car Autonomy (miles)
20	**115**	**71**
40	118	73
60	115	71
80	114	71
100	112	70

Table 1.19: Influence of the ambient air temperature

Ambient air temperature (°C)	Car Autonomy (km)	Car Autonomy (miles)
-20	109	69
0	112	70
20	**115**	**71**
40	117	73

Table 1.20: Influence of the heat exchanger effectiveness

Heat exchanger effectiveness	Car Autonomy (km)	Car Autonomy (miles)
0	80	50
0.1	85	53
0.2	87	54
0.3	99	62
0.4	109	69
0.5	115	71
0.6	120	75

Table 1.21: Efficiencies chosen for the four sets

	Low efficiency system	Average efficiency system	Baseline	High efficiency system
Isentropic efficiency (%)	0.75	0.8	**0.85**	0.9
Mechanical efficiency (%)	0.75	0.8	**0.85**	0.9
Leakage on the main air loop (%)	5	4	**2**	1
Leakage in the cylinder chamber (%)	5	4	**2**	1
Heat exchanger effectiveness (%)	0.3	0.4	**0.5**	0.6
Air tank pressure (MPa)	30	30	**30**	30
Air tank temperature (°C)	20	20	**20**	20
Ambient air temperature (°C)	20	20	**20**	20
Air tank volume (l)	114	114	**114**	114

Table 1.22 : Autonomy of the car for the four sets

Distance	Low efficiency system	Average efficiency system	Baseline system	High efficiency system
(km)	51	85	**115**	135
(miles)	32	53	**71**	84

Three cases are studied in this section:
- baseline system (without any production of electricity),
- baseline system with a 300W electrical production,
- baseline system with a 2kW electrical production to heat the cabin.

Table 1.23 : Influence of the electric production

Tank volume (liters)	Baseline system (km / miles)	Baseline + 300 W (electric) (km / miles)	Baseline + 2 kW (heating) (km / miles)
114	**115 / 71**	93 / 58	35 / 22
150	**143 / 89**	117 / 73	46 / 29

The calculations show the same trends for 12.4mph (20km/h) and 31mph (50km/h). Nevertheless, it can be noticed that the relative influence of the electrical production (300W and 2 kW) is less important at higher speed (31mph vs. 12.4mph) and at higher rotation speed (2000rpm vs. 1000rpm).

1.4.4 Conclusions

The calculations performed at 20km/h and 50km/h (steady state conditions) show that the engine performances depend highly on the efficiencies. For the baseline system with efficiencies as defined in Table 1.2, the autonomy is of:
- 316 miles at 12.4mph (20km/h),
- 71 miles at 31mph (50km/h).

But if the efficiencies are low, the autonomy can fall to very low values:
- 138miles at 12.4mph (20km/h) ,
- 33miles at 31mph (50km/h).

Those values do not take into account the electrical power needed for the City CAT car. Taking into account actual energy efficiency of alternators (60%), the car autonomy with a baseline engine, including electrical power production of 300W, is reduced from 316 (509km) to 75 miles (120km).

To cover the heating needs, the use of a burner seems to be a good solution.

As seen in the parametric evaluation, the heat exchanger effectiveness presents a significant impact on the autonomy, and particularly when **the effectiveness is lower than 40%**.

The heat exchangers chosen by MDI are cross-flow air-to-air heat exchangers. Since the temperature of the air after the expansion process is very low (less than –100°C), the humidity of the external air will be frosted on the heat exchanger surface. The clogging of the heat exchanger by the icing process will entail very low heat exchange efficiency, thus here also the use of external heat coming from a burner permits to avoid such a drawback.

1.5 General conclusions

MDI has developed the global design of the 34p01-4 engine, which is not running yet. A significant work for optimization and control is still necessary to lead to an available prototype. Moreover, the electrical consumption of accessories needs a specific design. Nevertheless, the global concept permits a significant autonomy of the MDI compressed air car.

Part 2
Analysis of test bench results

2.1 Test bench presentation

Figure 2.1 presents the test bench on which MDI tests its engines.
It is composed by:

- three tanks of 132 liters at 20 MPa,
- the instrumented engine,
- a magnetic break to simulates the engine charges.

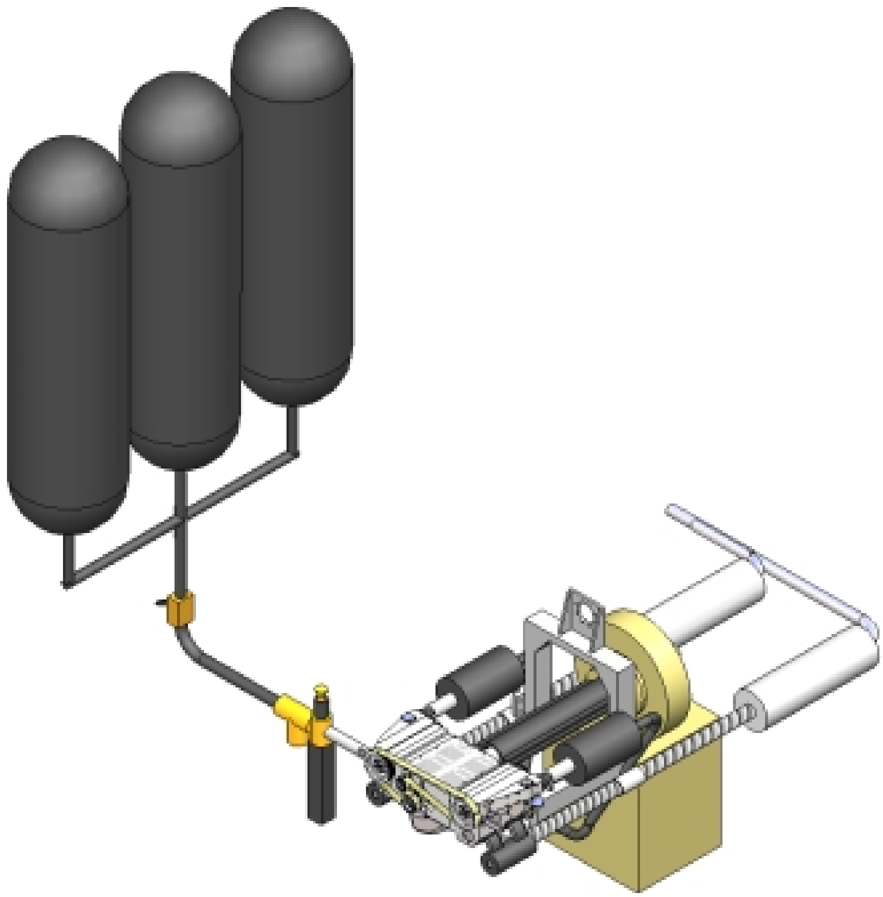


Figure 2.1: Test bench layout

2.3 Engine presentation

The engine tested during June 2003 is the 34p01-1 engine.
This engine has only one expansion stage and its pressure is limited to 2 MPa.
The engine is fed with air at 2 MPa thanks to the yellow expansion valve (Figure 2.1).

Figures 2.2 to 2.4 show various views of the engine.

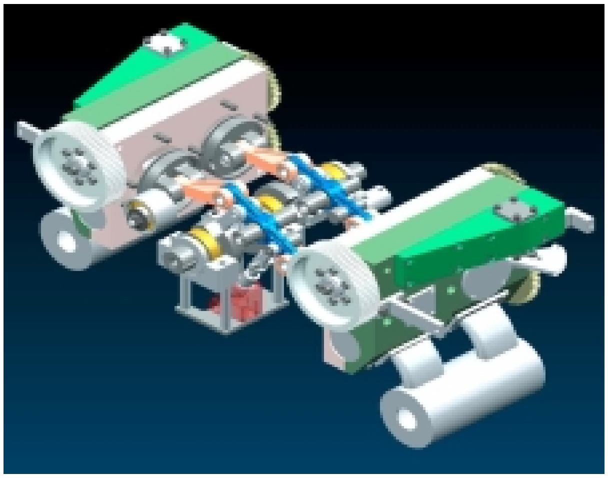


Figure 2.2:
34p01-1 engine

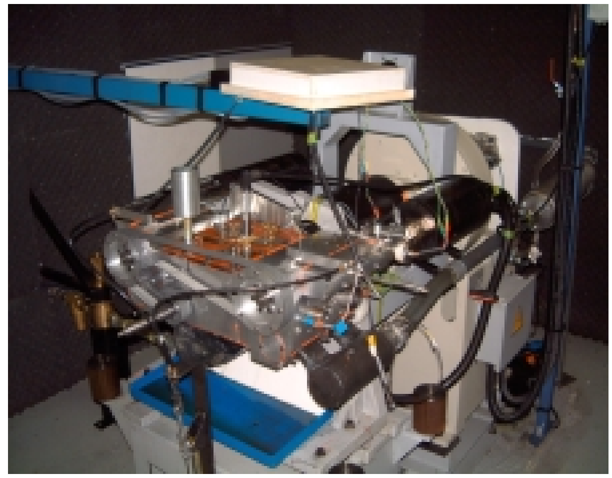


Figure 2.3:
34p01-1 engine on the test bench

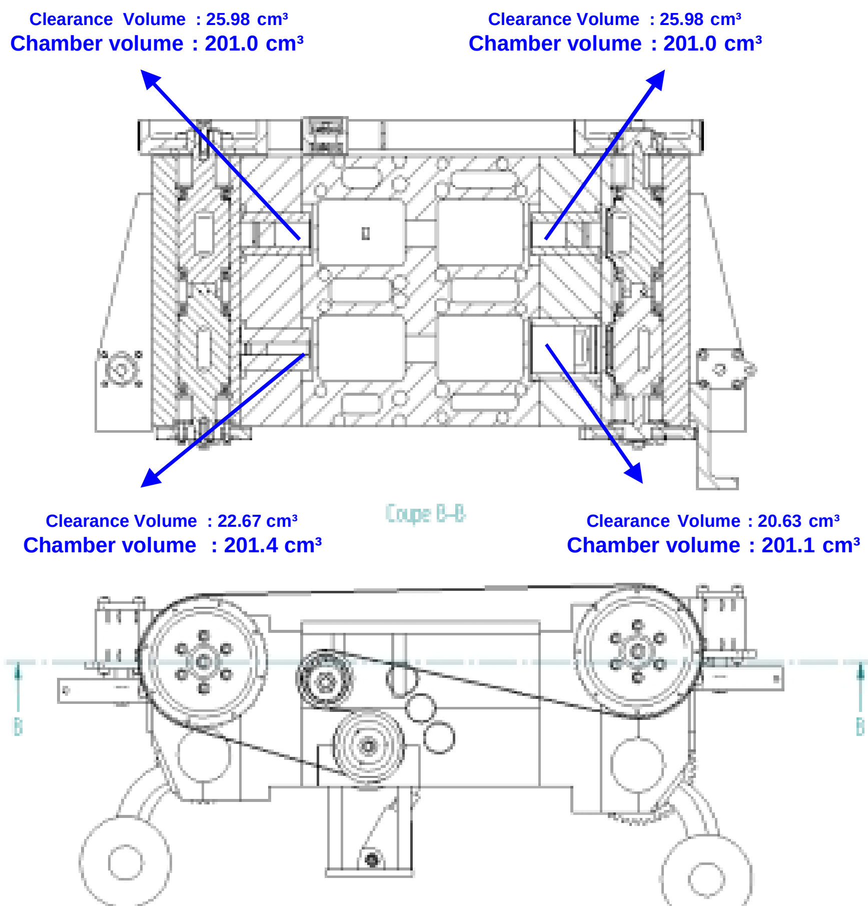


Figure 2.4:
Clearance and chamber volumes

2.3 Presentation of the test bench results and their analysis

MDI has carried out various tests to simulate two working conditions and have sent the results to ARMINES (Figures 2-5 to 2.7):
-12.4mph (20km/h) at 110W (0.15hp),
-31mph (50km/h) at 1,7kW (2.30hp)

2.3.1 Tests presentation

MDI	**ESSAI MOTEUR SUR BANC** **34P01-1**	
E3401120603-3.xls		Date de compilation: 13-06-03

Fichier	**E3401120603-3**	**Date**	**12/06/03**	**T° salle**	**25 °C**	**P salle**	**1008.3 mbar**	**Humidité**	**48 %**

Régime maxi	**488 tr/min**
Régime mini	**302 tr/min**
Régime moyen	**371 tr/min**
Couple lu moy.	**0.39 kgb**
Puissance corrigée moy.	**0.15 cv**
Vitesse correspondante	**20.00 km/h**

Tps:	**3h08' ***
Volume réserves	**79200 Nl**
Pression init.	**205.25 bar**
Pressionj finale	**24.24 bar**
Conso	**71680 Nl**
Distance	**62.94 km**

Vidange à 2.30 cv moyen (20km/h)

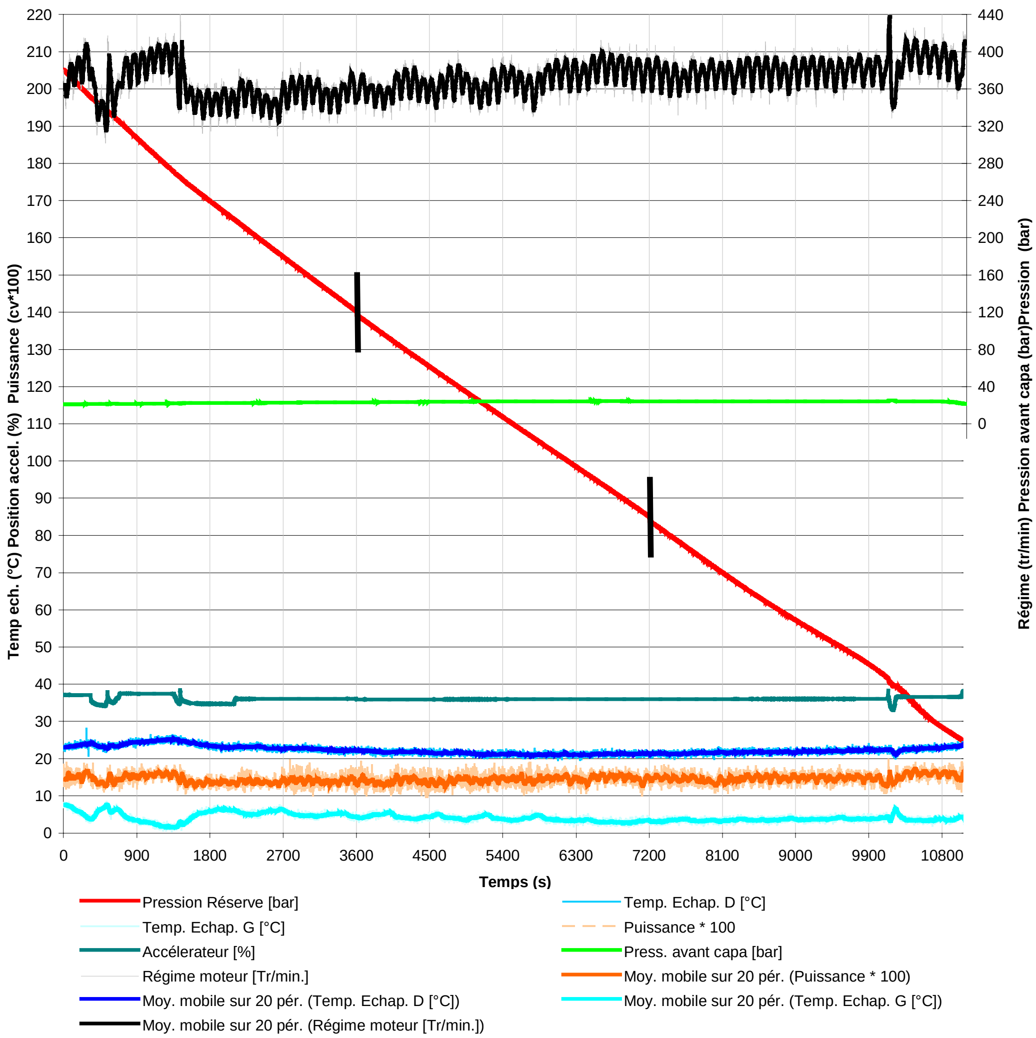
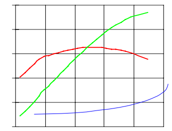


Figure 2.5: Evolution of the parameters along the test (12.4mph and 0.15hp at 371rpm)

E3401120603-2.xls	**ESSAI MOTEUR SUR BANC** **34P01-1**	 Date de compilation: 12-06-03

Fichier	E3401120603-2	Date	12/06/03	T° salle	25 °C	P salle	1008.3 mbar	Humidité	58 %

Valeurs lentes au point considéré			
Régime	386 tr/min	Température échappement D	21.02 °C
Couple	0.39 kgb	Température échappement G	15.23 °C
Puissance	0.15 cv	Temp. cana av det [°C]	26.62 °C
Pression réserves	211.3 bar	Temp. avant capa [°C]	20.21 °C
Tension batterie	11.1 V	Temp. Culasse D [°C]	26.02 °C
Position accélérateur	37.13 %	Temp. Culasse G [°C]	25.64 °C
Durée de l'essai	29"	Temp.admission D [°C]	24.85 °C
Volume réserves	79200 Nl	Temp. admission G [°C]	24.91 °C
Temp. Salle [°C]		23.72 °C	

Pressions internes

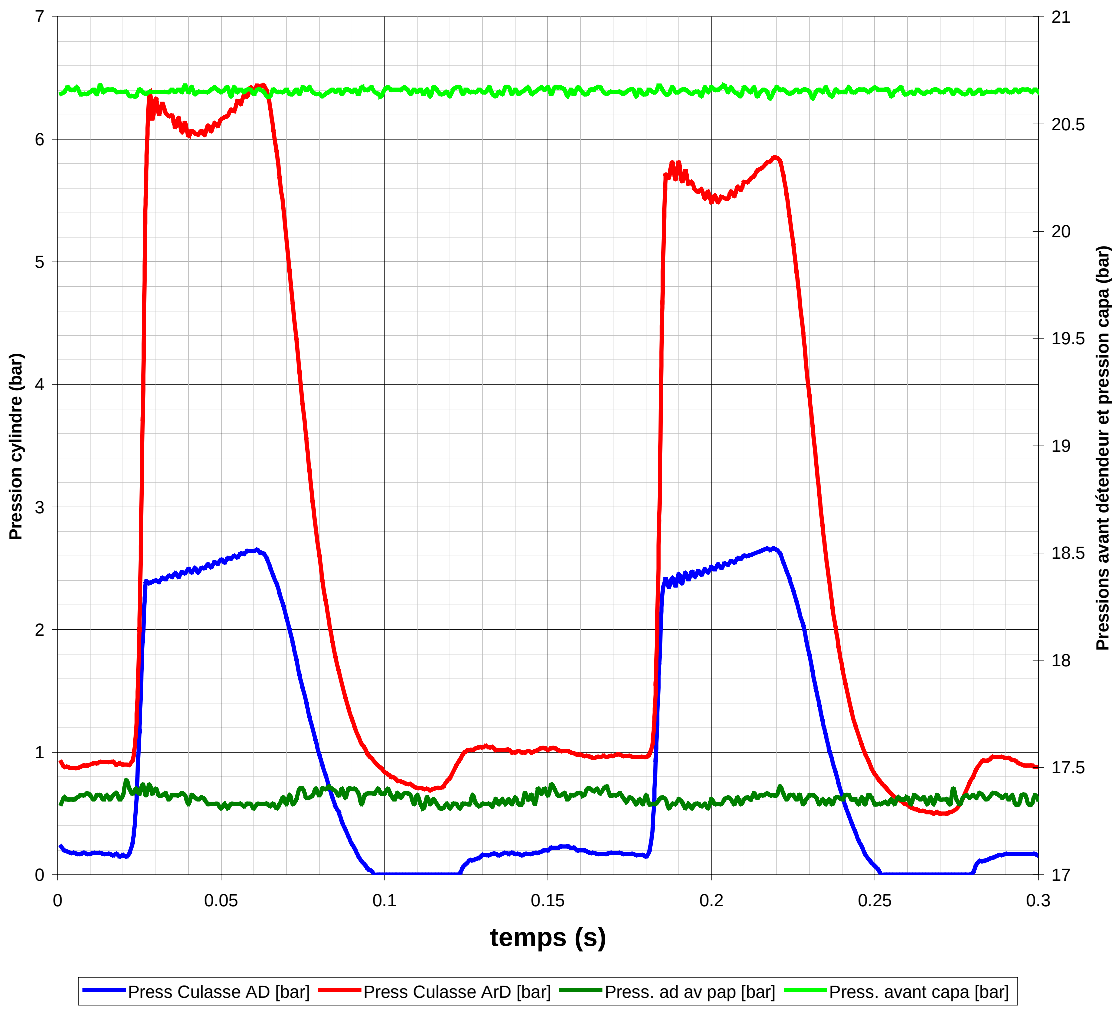
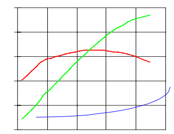


Figure 2.6:
Evolution of the pressures inside the expansion chamber (12.4mph and 0.15hp at 371rpm)

	ESSAI MOTEUR SUR BANC 34P01-1	
E3401110603-2.xls		Date de compilation: 11-06-03

Fichier	E3401110603-2	Date	11/06/03	T° salle	24.7 °C	P salle	1008.5 mbar	Humidité	55 %

Régime maxi	1153 tr/min
Régime mini	956 tr/min
Régime moyen	1048 tr/min
Couple lu moy.	2.17 kgb
Puissance corrigée moy.	2.30 cv
Vitesse correspondante	49.90 km/h

Tps:	36'32"
Volume réserves	79200 Nl
Pression init.	198.57 bar
Pressionj finale	20.74 bar
Conso	70421 Nl
Distance	30.39 km

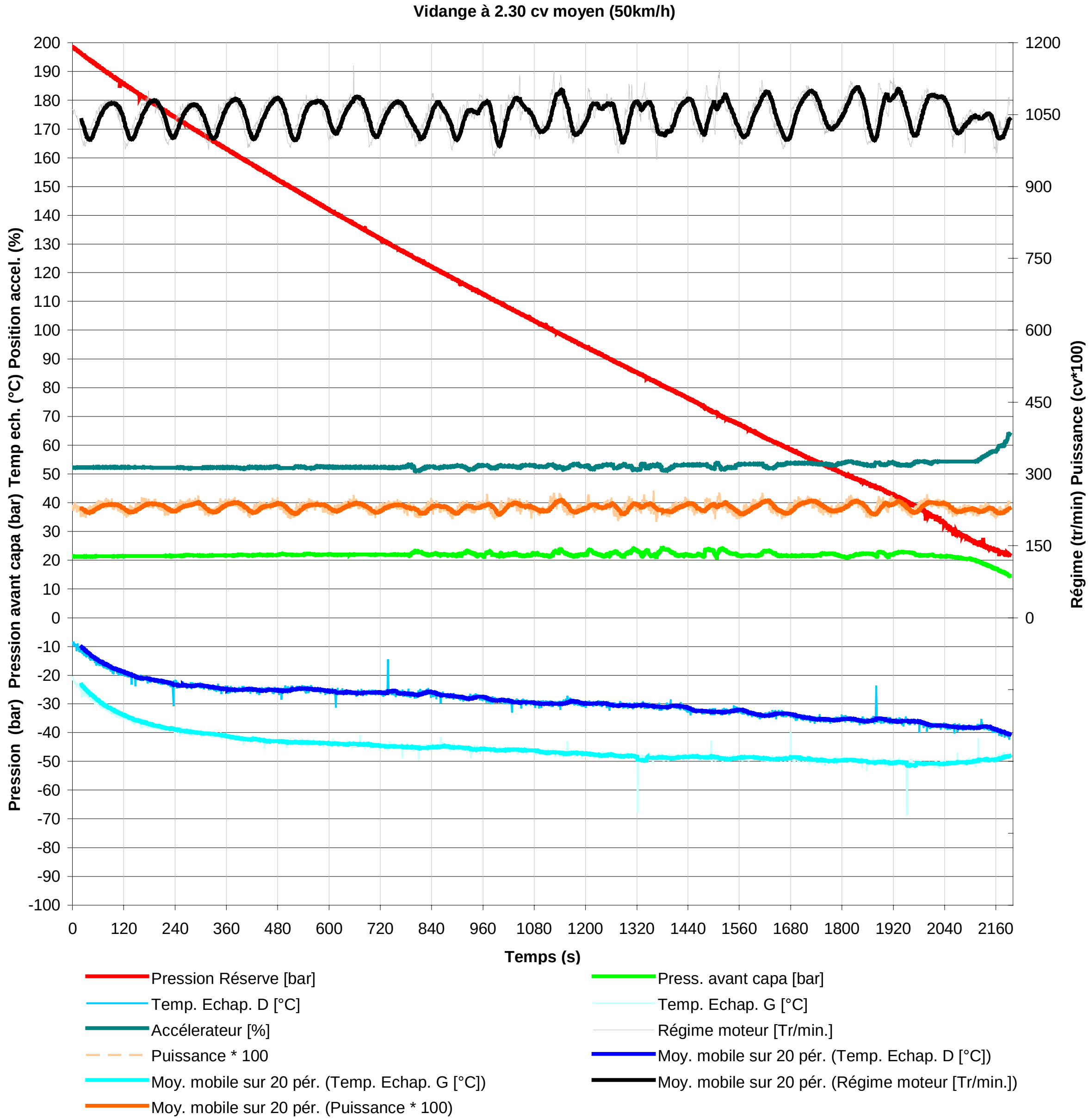
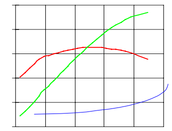


Figure 2.7:
Evolution of the parameters along the test (31mph and 2.30hp at 1048rpm)

	ESSAI MOTEUR SUR BANC **34P01-1**	
E3401110603-1.xls		Date de compilation: 11-06-03

Fichier	E3401110603-1	Date	11/06/03	T° salle	26.3 °C	P salle	1007.5 mbar	Humidité	58 %

Valeurs lentes au point considéré			
Régime	985 tr/min	Température échappement D	-16.44 °C
Couple	2.36 kgb	Température échappement G	-25.65 °C
Puissance	2.37 cv	Temp. cana av det [°C]	-
Pression réserves	195 bar	Temp. avant capa [°C]	17.49 °C
Tension batterie	11.5 V	Temp. Culasse D [°C]	-
Position accélérateur	52.35 %	Temp. Culasse G [°C]	-
Durée de l'essai	30"	Temp.admission D [°C]	22.54 °C
Volume réserves	79200 Nl	Temp. admission G [°C]	22.43 °C
Temp. Salle [°C]		24.23 °C	

Pressions internes

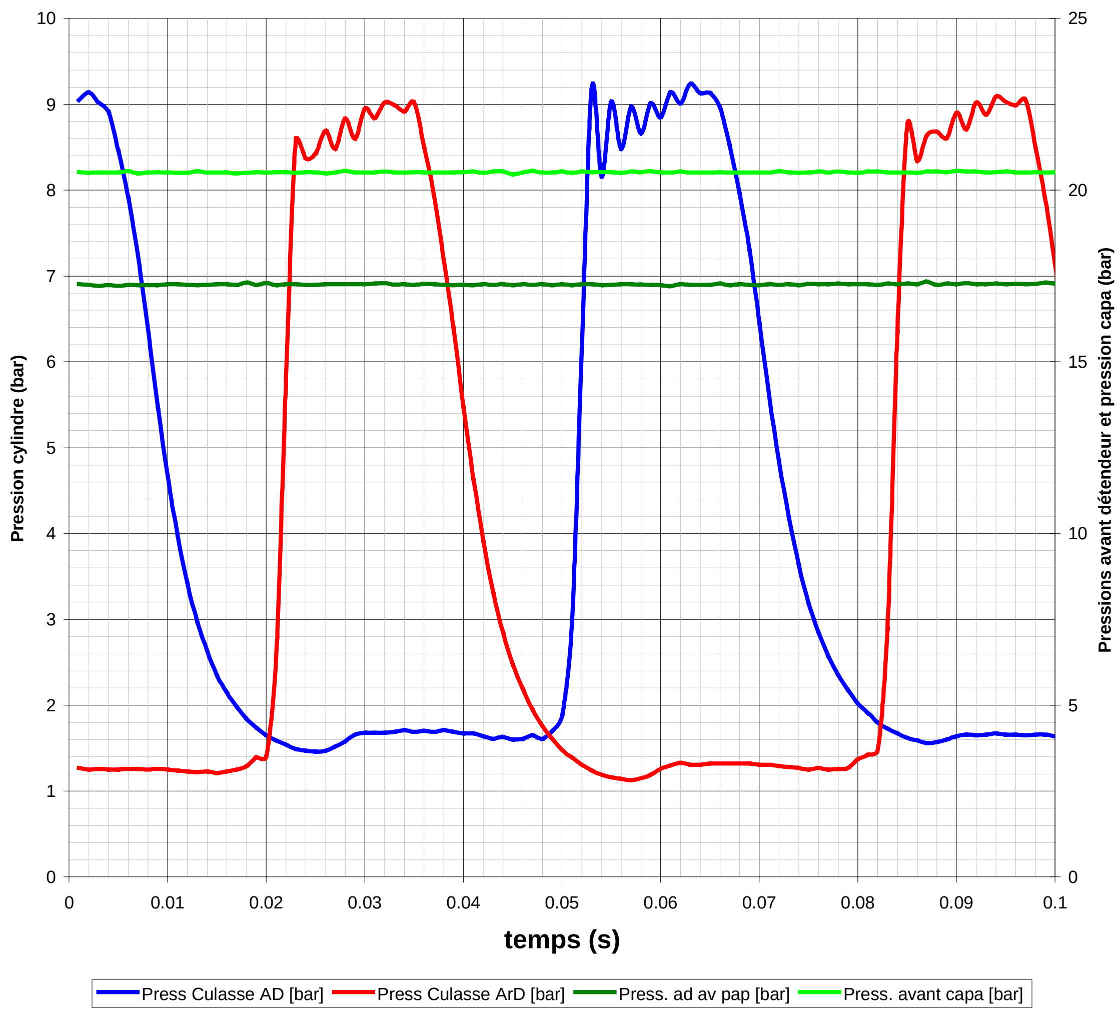


Figure 2.7:
Evolution of the pressures inside the expansion chamber (31mph and 2.37hp at 985rpm)

2.3.2 Tests analysis

According to MDI designers, the 34p01-1 prototypes have still many development problems that are being solved or will be solved in the near future.

- Air leaks at different points of the engine exist
  - accelerator,
  - one of the pistons,
  - various seals….
- Oil leaks are also noticed.
- Some components of the engine have to be changed because of machine finishing.
- The air flow pattern has not been optimized.
- The actual air distribution needs a torque, which ranges from 0.7 to 0.9kg.m.

For MDI, the main objective of this prototype is to estimate the mechanical liability and the thermodynamic performances of the last stage of the 34p01-1 engine.

Tests conditions are as follows:

- after the expansion valve, the air pressure is about 2 MPa, but in the chamber before the expansion process, the pressure is much lower:
  - around 900kPa at 1048rpm and 1.7kW (2.30hp),
  - around 600kPa at 371rpm and 110W (0.15hp).

  The pressure losses are important between the tanks and the cylinders.

- For the tests performed at 371rpm and 110W, the pressure inside the pistons is different (600kPa vs. 250kPa); this is due to air leaks before the cylinder and at the piston seal.

To analyze the tests performed by MDI and to evaluate the efficiencies and leakage rates, a specific model has been developed in Air_Expansion software to compare the calculation to the experimental results.

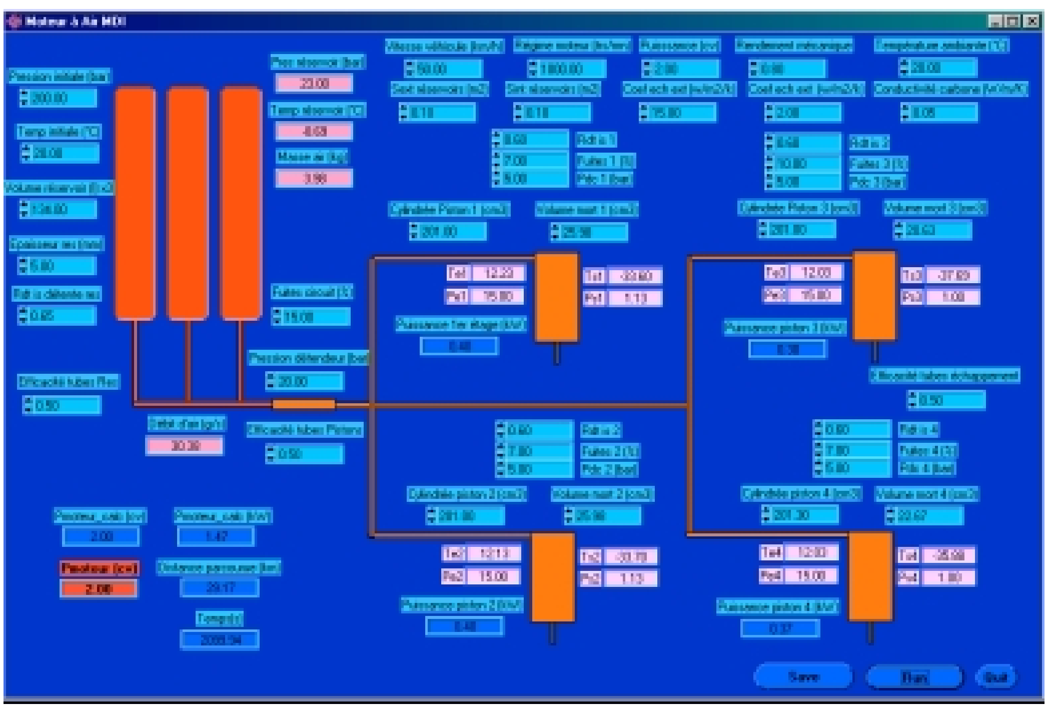


Figure 2.8: Prototype analyzer developed by the Center for Energy Studies

For the test performed at 371rpm, 110W (0.15hp) is the power absorbed by the magnetic break of the test bench. The engine produces more power since it is known that the rotative air distribution consumes a torque of about 0.7kg.m. Finally, the power produced by the engine is 309W (0.42hp).

Table 2.1 : Parameters used for the calculations (371rpm and 110W)

	Parameters
Isentropic efficiency (%)	0.7
Mechanical efficiency (%)	0.7
Leakage on the main air loop (%)	10
Leakage in the cylinder chamber (%)	4 / (6 for 1piston)
Pressure losses (MPa)	1.1
Pressure after the expansion valve (MPa)	2
Air tank pressure (MPa)	20
Air tank temperature (°C)	20
Ambient air temperature (°C)	20
Air tank volume (l)	132
Vehicle speed (km/h / mph)	50 / 31
Engine rotation speed (rpm)	1048
Power developed by the engine (hp)	3.25

Table 2.2 : Comparison between experimental results and calculations (371rpm and 110W)

	Experiments	Calculations
Duration of the test (min)	188	189.5
Equivalent distance (km)	62.94	63.17

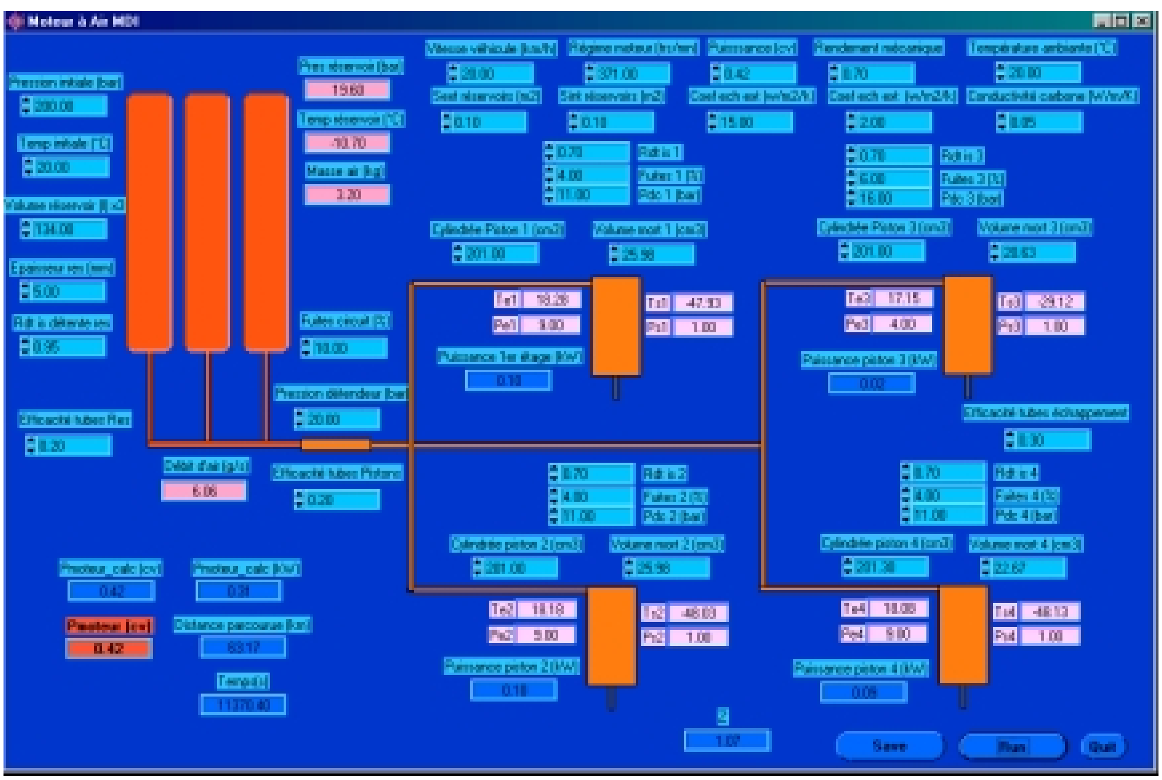


Figure 2.9 : Calculations panel (371rpm and 110W)

For the test carried at 1048rpm, 1.7kW (2.30 hp) is the power absorbed by the magnetic break of the test bench. The engine produces more power since it is known that the rotative air distribution consumes a torque of about 0.9kg.m. Finally, the power produced by the engine is 2.32kW (3.15hp).

Table 2.3 : Parameters used for the calculations (1048rpm and 1.7kW)

	Parameters
Isentropic efficiency (%)	0.75
Mechanical efficiency (%)	0.75
Leakage on the main air loop (%)	10
Leakage in the cylinder chamber (%)	4 / (6 for 1piston)
Pressure losses (MPa)	1.4
Pressure after the expansion valve (MPa)	2
Air tank pressure (MPa)	20
Air tank temperature (°C)	20
Ambient air temperature (°C)	20
Air tank volume (l)	132
Vehicle speed (km/h / mph)	50 / 31
Engine rotation speed (rpm)	1048
Power developed by the engine (hp)	3.15

Table 2.4 : Comparison between experimental results and calculations (1048 rpm and 1.7kW)

	Experiments	Calculations
Duration of the test (min)	36'30	37
Equivalent distance (km)	30.39	30.83

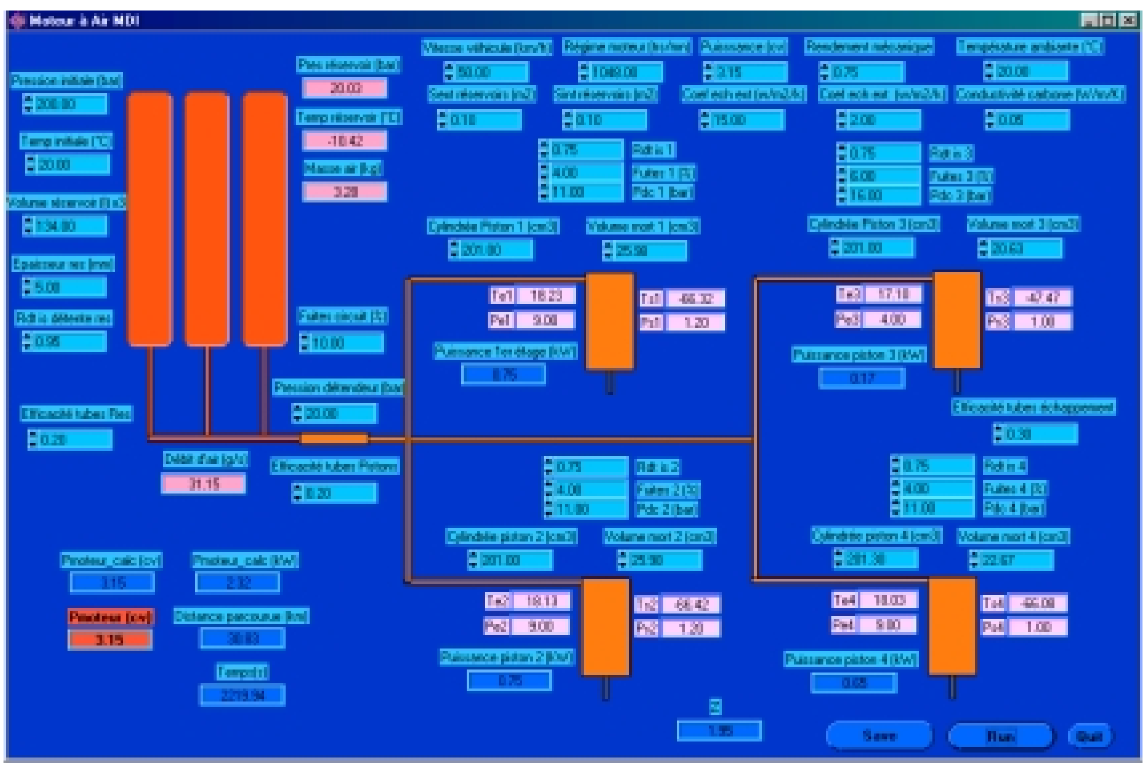


Figure 2.10: Calculations panel (1048 rpm and 1.7kW)

The calculations show little differences when compared to the experimental data. It is possible to say that the actual performances of the 34p01-1 prototype are as follows:

Table 2.5 : Actual performances of the 34p01-1 prototype

	Parameters
Isentropic efficiency (%)	0.70 to 0.75
Mechanical efficiency (%)	0.70 to 0.75
Leakage on the main air loop (%)	10
Leakage in the cylinder chamber (%)	4 / (6 for 1piston)
Pressure losses (MPa)	1 – 1.4

A lot of work remains to do especially to improve the leak tightness of the air loop and the cylinder (values lower than 2% must be obtained).

The pressure losses are very high too, and an important work must be done to lower these values (lower than 0.15MPa or 0.2MPa).

The isentropic and mechanical efficiencies are correct but it would be better to have higher values to obtain higher car autonomy.