A study of turbocharged Diesel engine during sudden acceleration. Set up and exploitation of a specific test rig

P. Podevin ; G. Descombes
Conservatoire National des Arts et Métiers
Chaire de turbomachines
292 rue Saint Martin
75141 paris Cedex 03 France
Tel : 33 (0)1 30 45 87 35 Fax : 33 (0)1 30 45 87 73
e-mail : podevin@cnam.fr descombe@cnam.fr

P. MAREZ ; F. DUBOIS
PSA Peugeot Citroën
Moteurs Diesel
18, rue des Fauvelles 92250
La Garenne Colombes
Tel : 33 (0)1 56 47 25 04 Fax : 33 (0)1 56 47 87 69
e-mail : marez4@mpsa.com dubois17@mpsa.com

ABSTRACT

Knowledge of transient response of internal combustion engine is necessary to tune the vehicle's engine. Not only do comfort and performance depend on this response but also the compliance with future emission standards.

It is difficult to evaluate transient performance of the turbocharged diesel engine from steady tests, due to the "turbo lag" induced by the turbocompressor.

The object of this lecture is to present the procedure used to characterise the effect of different elements on the vehicle's acceleration :

Firstly, set up of a specific test rig : the vehicle's inertia is simulated by a flywheel. This wheel of adjustable inertia weighs about 400 kg at maximum, and is able to run at 5000 rpm.

Secondly, certification of the test rig and set up of the measurement means.

Finally, acceleration tests : on 2.1 liter engine, a wide test campaign has been conducted for sudden acceleration on 3rd gear. The study was mainly based on the following three points : The comparison of performance obtained with different turbocompressors, or with turbocompressors of the same family ; The influence of inlet and outlet ducts, and of valve timing ; and the effect of particular design (waste-gate position, threshold valve, ...) and of some adjustment (thermal state of the motor, fuel delivery, ...). The most significant experiments have been selected.

INTRODUCTION

The knowledge of engine characteristics during transient phases is of a major interest, because the behavior of the vehicle depends on this response in terms of :

- performances,
- pleasure of driving,
- pollution.

The term "performance" involves the maximum performance of the engine at full load, but also its ability to respond to sudden load variation. Acceleration characteristics are part of vehicle's performance but requirements could be very different depending on the vehicle use.

Pleasure of driving depends on the performance of the vehicle but also on many parameters, such as suspension, seat material or color etc. User demands are getting greater and greater because of the increase of time being spent in cars which induces a higher request for comfort.

Pollution is one of the major problems of the automotive industry. Because standard requirements are gettint higher and higher, it is necessary to investigate all the ways of reducing pollution.

During transient phases, emissions of pollutants are anarchic (Degobert,1994). So, we can hope that a better study and understanding of these transient phases will bring opportunities to reduce the overall pollution of the automotive vehicle.

Study of transient behavior of a reciprocating engine is particularly difficult because it accepts a wide range of speeds and loads. The knowledge of steady performances is not sufficient to estimate transient performances, especially for supercharged engines, because they depend on dynamic phenomena which are difficult to take into account (injection dynamic, turbo lag ...)

In order to study closely the variation of different parameters during acceleration we have set up a special test bench for studying performances of a 2.1 liter turbocharged engine.

The following work is the result of an agreement between PSA Peugeot Citroën and CNAM.

1. TEST FACILITIES

Various methods are available to study vehicle acceleration (Hiereth, 1986).

- Road tests
- Roller bench

They involve a vehicle, and are not entirely satisfactory when we want to concentrate on the functioning of the engine. So the more practical option is to use a specific test bench.

Usual test benches (engine + dynamometer) do not allow simulation of the vehicle acceleration.

The best way is to use a dynamic test bench, but this type of bench is very expensive and is in low supply.

Another solution is to use a standard bench on which a flywheel is added. This solution is demonstrated by Podevin et al (1997). It is possible to simulate acceleration on that sort of bench, provided that the vehicle's inertia can be represented and the necessary resistant torque can be created.

The inertia of the vehicle and the inertia of the transmission gear are obtained via the flywheel. The resistance forces acting on the vehicle's movement can be set through the dynamometer controller.

Usually, the dynamometer controller permits work with a constant load. In our application, this possibility proved sufficient, but in practice it is possible to link the resistant torque with the engine speed.

Generally test benches with flywheel use a gear-box coupled to the engine. This solution allows the use of a flywheel of relatively small dimension and offers some facilities for the adjustment of the required inertia. Of course, in some cases this arrangement will allow study of gear changing.

The major disadvantage of this combination is that gear-box has to be set up. This one is not always available for the engine, or cannot be set up the bench because of space requirements.

The advantage of a test bench with a flywheel and without a gear-box is that this solution is adaptable most of the time on standard test benches and allows one to concentrate on the functioning of the engine only.

This solution which was recommended by PSA, has been studied an realized by the CNAM. At present it seems unique.

2. FLYWHEEL TEST BENCH

The conception of the flywheel depends on many parameters which have to be considered together in order to reach the best solution :

- range of application
- room available
- mechanical limits (stress and critical speed)
- simplicity of realization and use
- cost

The general arrangement of the test bench is presented in figure 1.

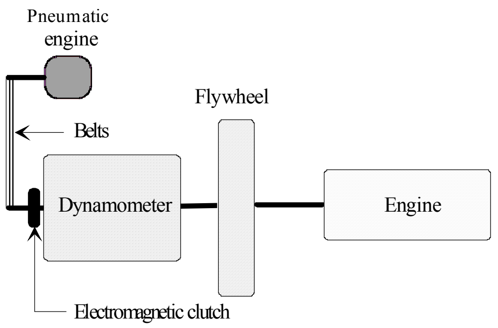

Fig. 1 - Sketch of flywheel test bench

The engine cannot start directly when coupled to a flywheel. So, an auxiliary power unit is used to run the flywheel until it idles before engaging the engine clutch.

The flywheel is composed of a shaft on which a set of ten removable plates can be fixed.

Inertia is adjustable by step of 1 kg.m² from 3.5 to 32.5 kg.m² .

So, it is possible to simulate the acceleration of a four door diesel saloon car for the 3rd,4th and 5th gear ratio as required by PSA.

In figure 2, the main parts of the flywheel can be seen.

Special care has been taken to mechanical dimensioning, knowing that the weight of the wheel can reach 400 kg and is able to run at 5000 rpm.

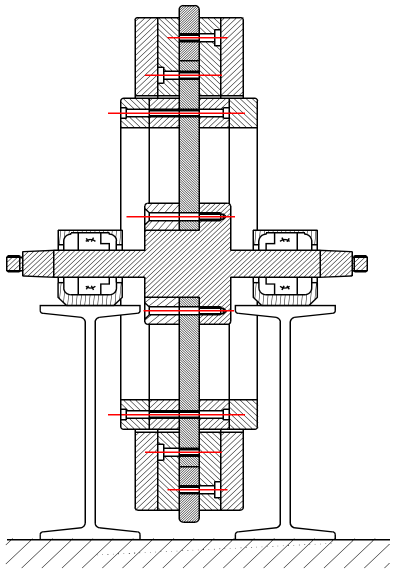

Fig. 2 - Sketch of the flywheel

3. TEST BENCH CERTIFICATION

A comparison between tests done by PSA Peugeot Citroën on a roller bench and tests on the flying wheel bench has been set up. This comparison concerns sudden acceleration from steady point to full load, based on the following schedule :

- short acceleration from 30 to 60 km/h in 3rd gear,
- short acceleration from 60 to 90 km/h in 4th gear,
- short acceleration from 80 to 120 km/h in 5th gear.
- long acceleration 1000 to 3000 rpm in 3rd,4th and 5th .

Inertia is obtained by piling up the plates of the flywheel.

The resistant torque has been set as a constant for the following reasons :

- the main study will be carried out on short accelerations. Thus the resistant torque variation can be considered negligible,
- it avoids having to use a special device to vary resistant torque according to engine speed. Technologically this solution is available but it complicates the bench unnecessarily.
- comparison of engine performances are easier to do because a time dependent parameter is excluded.

For certification the following procedure has been established :

- the original value of inertia is determined by calculations taking into account the mass of the vehicle, the gear and some other parameters .
- an acceleration is done at the mean resistant calculated torque.

Then other experiments are carried out with a value of plus or minus 5 N.m, in order to straddle the acceleration curve of the vehicle. Tests are then continued with a new inertia value set at plus or minus 1 kg.m² depending on the previous results .

3.1 Short acceleration

A very good concordance is obtained for all tests. We will present here only the results obtained in 5th gear. See figure 3.

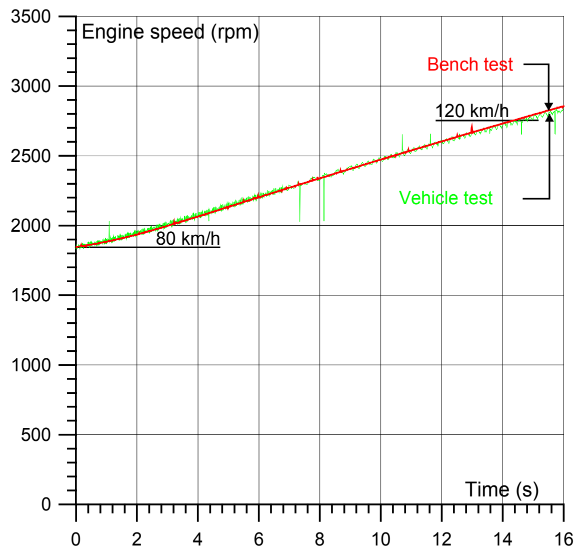

Fig. 3 - Short acceleration
from 80 to 120 km/h in 5th gear

3.2 Long Accélération

A quite good concordance is also obtained for 3rd and 4th gears. An example is given for 4th gear in figure 4.

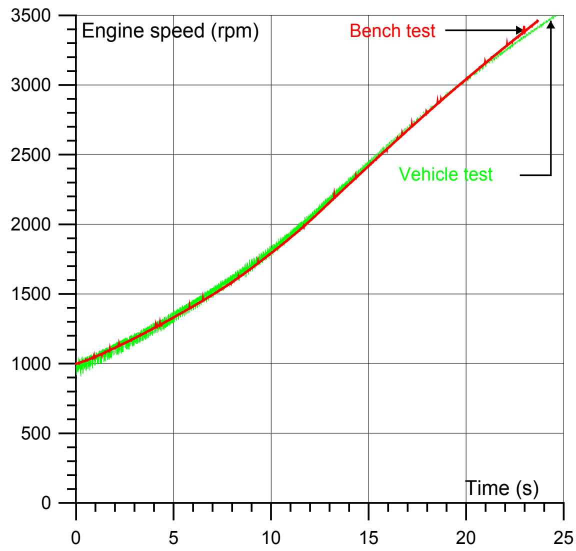

Fig. 4 - Long acceleration
from 1000 to 3000 rpm in 4th gear.

For 5th gear, see figure 5, a divergence appears around the 16th second. This event was foreseeable because the resistant torque is maintained constant on our test bench, although its variation is considerable for high gear with high engine speed variations.

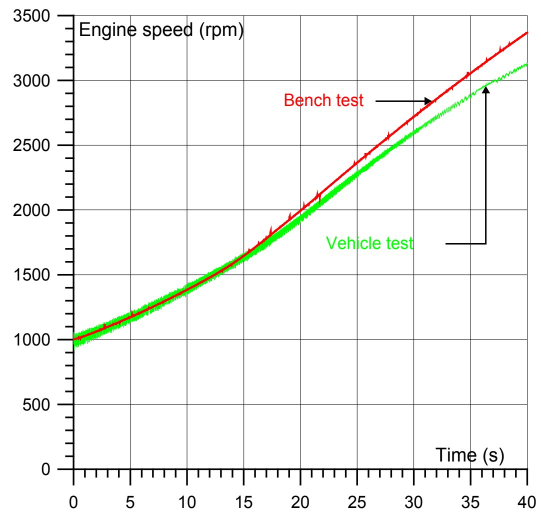

Fig. 5 - Long acceleration
from 1000 à 3000 rpm in 5th gear.

4 MEASUREMENT DEVICES

Only measurements taken during acceleration are set out. Typical results are shown in figure 6.

4.1 Measurements

4.1.1 Temperature

Metal sheathed thermocouples K are used. Some tests were carried out with bare wire thermocouples but their life time was too short. So, we use thermocouples of 0.5 mm external diameter with grounded junction. Response time is then affected, but this device has proven sufficient for comparison tests. The following temperatures are measured :

T_{AVC} : temperature before compressor
T_{APC} : temperature after compressor
T_{MOT} : temperature at engine inlet
T_{AVT} : temperature before turbine
T_{APT} : temperature after turbine

4.1.2 Pressure

Two piezo-resistive sensors are used close to the measuring points :

P_{MOT} : pressure at engine inlet
P_{AVT} : pressure at turbine inlet

Instantaneous pressure being not necessary for this study average values are calculated.

4.1.3 Rotation speed

Engine speed determination uses a 60 toothed wheel coupled with an inductive sensor.

Turbocompressor speed determination uses a one paint spot on impeller wheel coupled with an infra-red sensor.

Both output signals are treated by specific converters which allow a time delay equal to 0.003 second.

4.1.4 Smoke

The usual smoke meter with paper filter method cannot be used for acceleration tests. So, we have set an opacity meter immediately behind the turbine. This device is water-cooled because gas temperature can reach 600 °C.

4.1.5 Waste-gate displacement

It is interesting to know when the opening of the waste-gate occurs, because this waste-gate limit the power given to the turbine during engine acceleration.

An LVDT sensor has been linked to the actuator connecting rod.

4.1.6 Inertia

The inertia of the flywheel can be calculated with sufficient accuracy. However auxiliary inertia are to be taken into account, as for example dynamometer inertia, coupling etc. So, inertia is experimentally determined by runs at zero load.

4.1.6 Torque

The resistant torque, Cr, is given by the dynamometer actuator.

The driving torque, Cm, can be obtained by :

$$\frac{d\,\omega_m}{dt} = \frac{Cm - Cr}{I}$$ with:

I : inertia

$d\omega_m$: engine's acceleration during time dt

Using this formula we get a good estimation of the driving torque, except at the end of acceleration when dw_m becomes small. So we have set a strain gage on the drive shaft in order to get more accuracy on driving torque. Strain gage stress is transmitted by a telemetry system.

4.2 Data Acquisition

All the signals delivered by the sensor are amplified and converted to voltage and sent to a computed guided Hewlet Packard HP 3852A data acquisition unit.

The computer and the data acquisition unit are linked by a IEEE 488 communication.

Here are the main characteristics of the data acquisition unit :

- 13 bit high-speed voltmeter,
- 100 Khz maxi acquisition rate,
- 24 voltage channel multiplexer
- 24 temperature channel multiplexer

During acceleration tests, data acquisition is set to 1 Khz. Typically , acceleration duration time is set to 15 seconds and 24 channels are scanned, so 360 000 measurement points are recorded during one test. These measurements are transmitted in numeric format via a GPIO link at 33 Khz rate and stored on a computer hard disk. Then a specially developed software is used to translate measurements in mean physical values every 0.1 second.

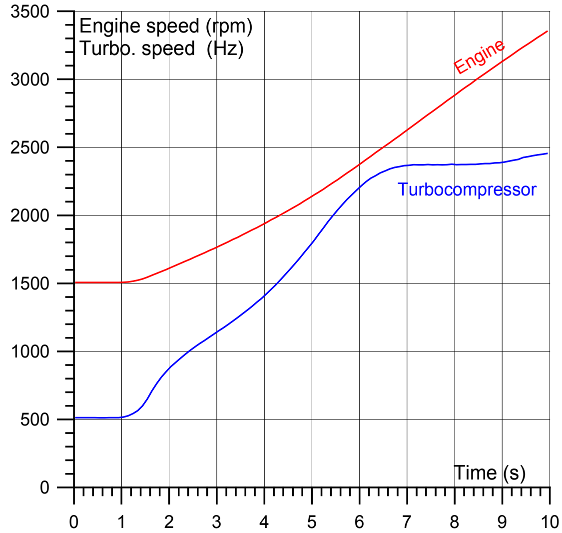

Fig. 6 - Engine and turbocompressor rotation speed

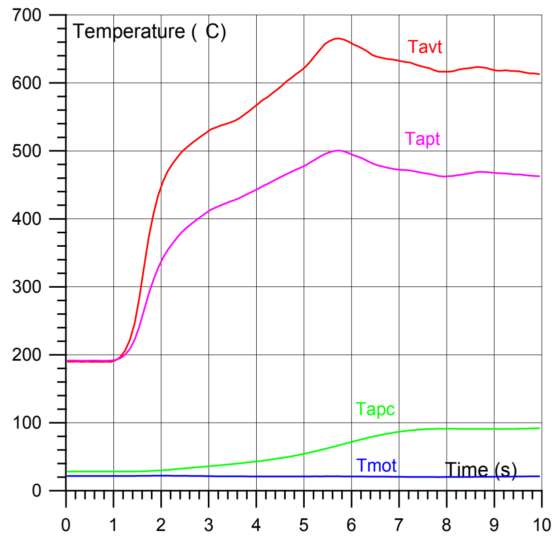

Fig. 7 - Temperature

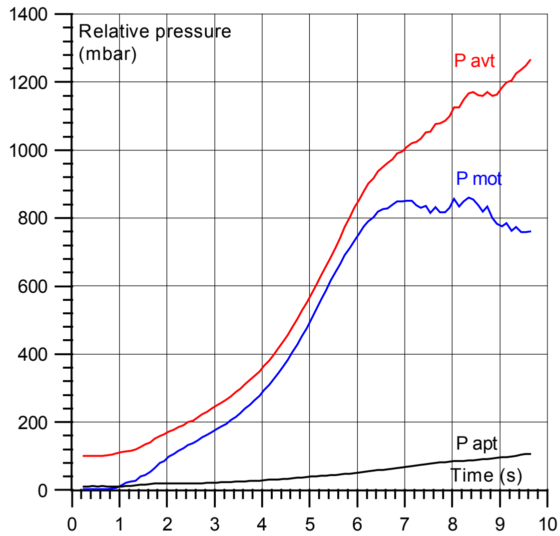

Fig. 8 - Pressure

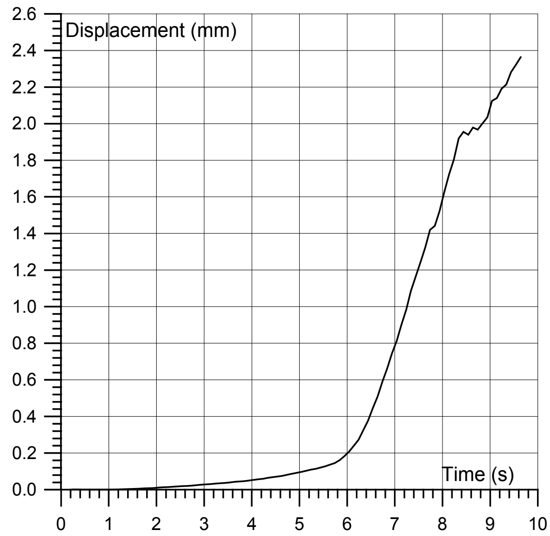

Fig. 9 - Waste-gate displacement

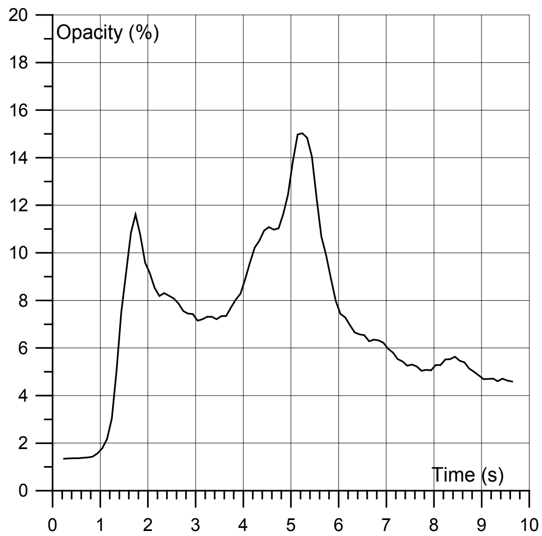

Fig. 10 - Smoke opacity

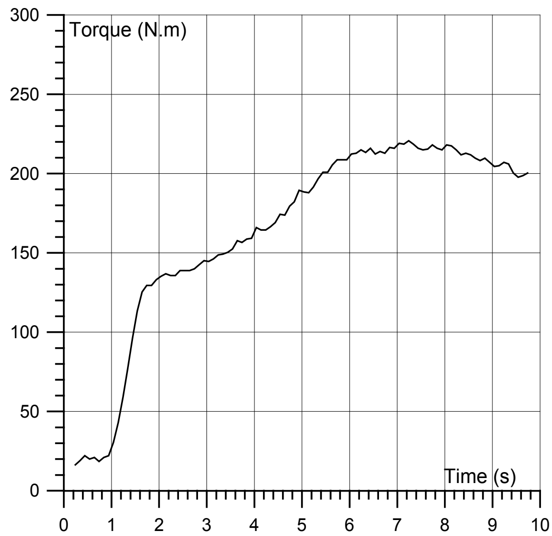

Fig. 11 - Engine torque

5 EXPERIMENTATION

A great number of experiments have been carried out the flywheel test bench on a 2.1 liter engine dealing with :

- turbocompressor performance,
- effect of inlet or oulet ducts, valve timing,
- particular design (waste-gate position, threshold valve, ...)

The difference between results are sometimes very small and are only interesting for the automotive manufacturer for the best tuning up of their engine.

Here, we will only give some examples which could lead to general conclusions for diesel engines.

5.1 Influence of exhaust duct.

Diesel engine tests, are carried out with a "test bench exhaust duct", usually made of a large sectional duct equipped with a vane in order to adjust the counter-pressure at the required value. It is commonly admitted that the performances of a turbocharged diesel engine are not deeply affected by the exhaust system layout but by the counter-pressure. However, during acceleration phases exhaust system arrangement can modify the acceleration curve of the turbocharger. Test have carried out made with test bench exhaust duct, an original exhaust duct system, and a free exhaust. In figure 12, the differences of turbocharger accelerations can be seen. Variations of engine acceleration are small and due to the effect of distinctive counter-pressure. This fact has been established by additional tests .

So, a modification, without effect on steady performances of the engine, can alter the working of the engine during transient phases. It can be considered that the gap in turbocharger acceleration curve noticed with a test bench exhaust system can have a minor influence on the vehicle's acceleration, but it may have a noticeable effect on the pleasure of driving.

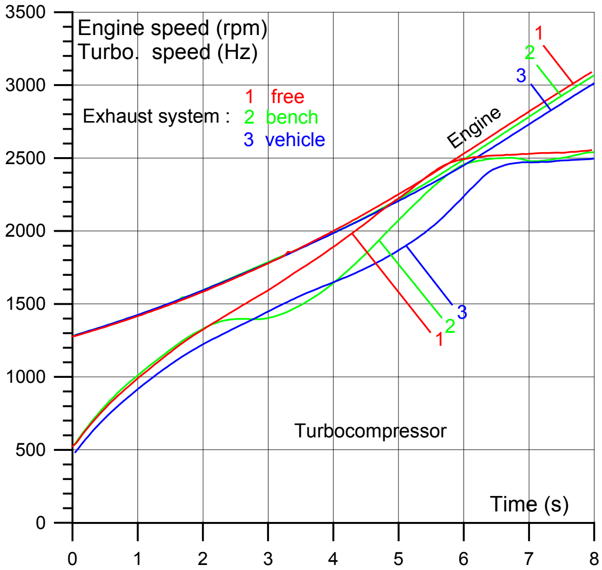

Fig. 12 - Engine and turbocharger acceleration with different exhaust system.

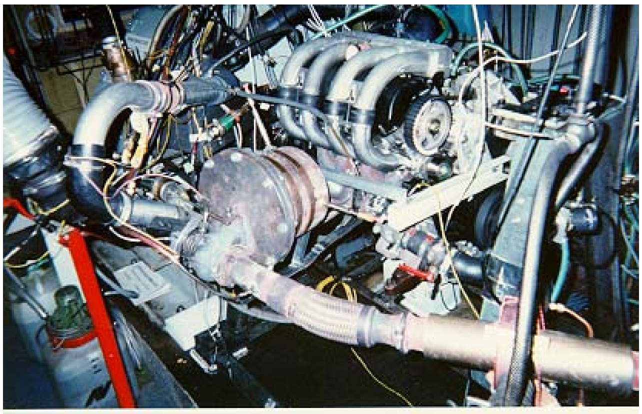

Fig. 13 - Engine equipped with a 4 liter capacity.

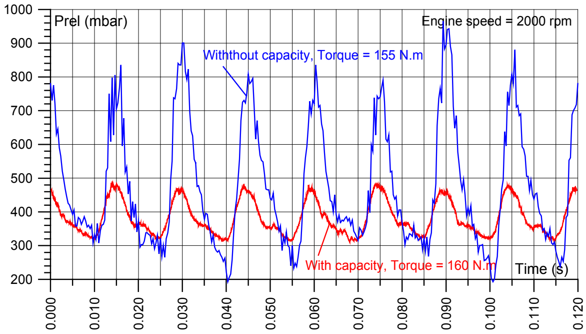

Fig. 14 - Pressure attenuation

5.2 Influence of Pressure pulsation at turbine inlet

In our laboratory, characteristics of turbines are established with a cold test bench. Then we have to correct these values for hot working and then for engine functioning with an unsteady gas flow. Working on this subject has lead us to set a capacity just before the turbine. So we have taken advantage of this opportunity to make some engine performance tests, the effect of pressure being a recurring subject in automotive industry (Capobianco et al 1990, Podevin, 1996).

In figure 13, we can see the engine equipped with a 4 liter capacity. In the next figure, n° 14, the pressure attenuation can be estimated.

Tests at full load, figure 15, show a lack of torque with the capacity, when compared with the original setting. However when the capacity is isolated we get closer performances and we can attribute this difference in energy losses to brutal sectional area variations between capacity and exhaust manifold.

On the contrary acceleration performances are strongly affected by the presence of the capacity, even with an insulation coat. In 3rd gear there is a one second delay before reaching the engine speed of 2500 rpm (see figure 16).

So, we can conclude that engine steady performances are not affected if the turbine is filled correctly with constant pressure or pulse pressure, but these arrangements have a very deep effect on acceleration performances. That is why short and small section exhaust manifolds are needed for car engines.

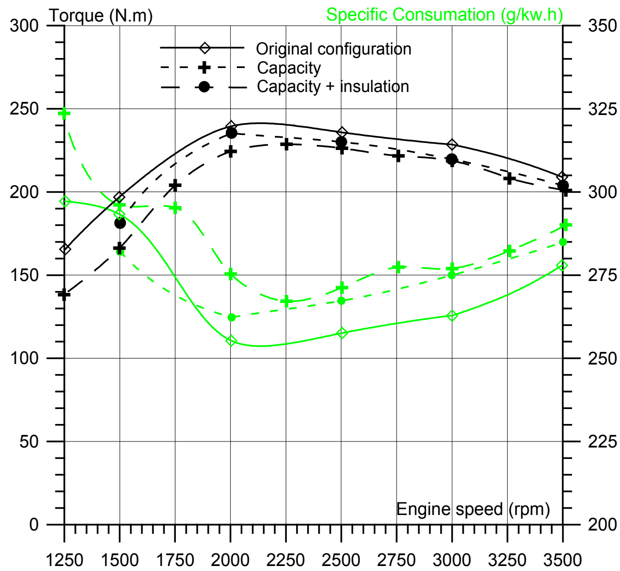

Fig. 15 - Influence of capacity on engine performances at full load

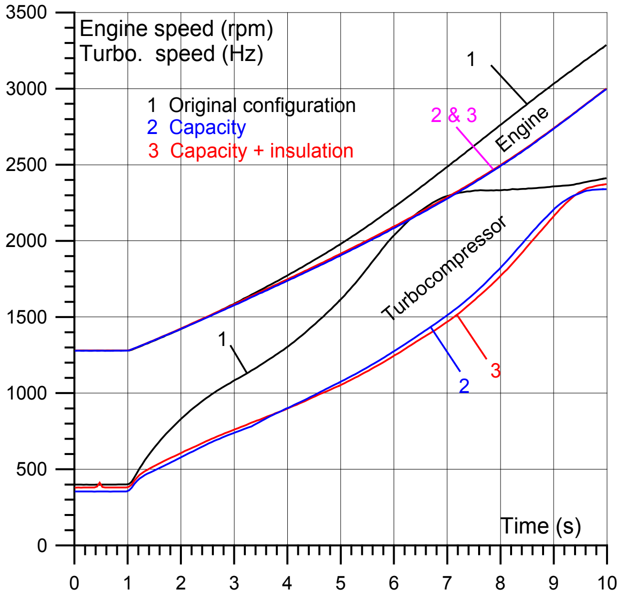

Fig. 16 - Influence of capacity on engine acceleration in 3rd gear

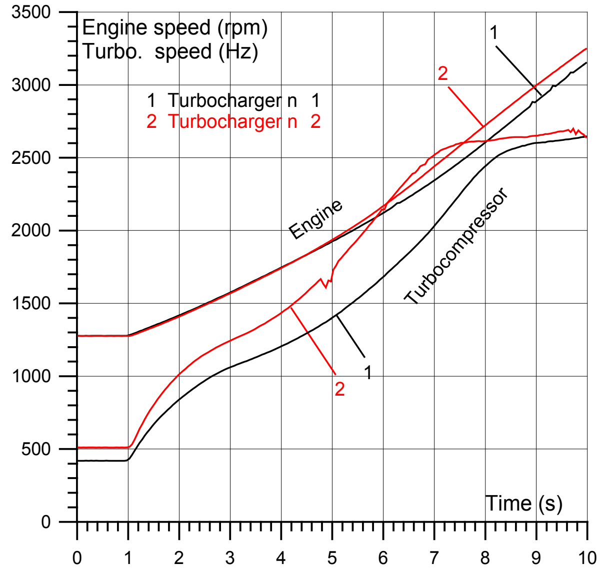

Fig. 18 - Comparison of vehicle acceleration in 3rd gear for two kinds of turbochargers

5.3 Influence of turbocharger

This last example presents the acceleration benefit we can get using a small turbocharger instead of the original one . There is a noticeable increase of the torque at low engine speed (see figure 17)

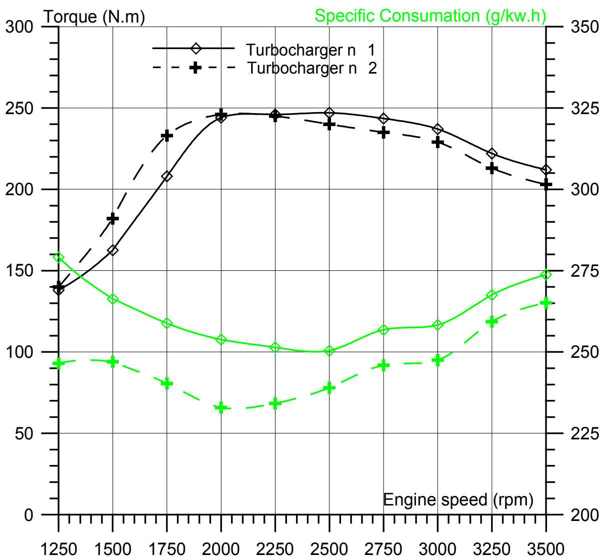

Fig. 17 - Comparison of engine torque at full load for two kinds of turbochargers

This benefit in acceleration is clearly seen in figure 18.

Unfortunately, using a small turbocharger increases counter-pressure at high engine speed and is not acceptable. As always, a compromise must be made between maximum power at full speed and suitable acceleration or other technologies employed, as for example variable area turbines.

CONCLUSION

Simulation of acceleration of a vehicle has been obtained by placing a flywheel directly between the engine and the dynamometer of a classical test bench, without using a gear box.

Test results show that a constant resistant torque induced by the dynamometer allows one to get a good simulation, especially if short accelerations are studied.

The measurements made enable us to record most of the parameters which influence the working of the turbocharger and the engine during acceleration.

Functioning since 1992 without mechanical failure this bench has proved an effective device to study and understand the physical events involved during engine acceleration.

REFERENCES

CAPOBIANCO, M., GAMBAROTTA, A., CIPOLLA, G., 1990, "Effect of inlet pulsating pressure characteristics on turbine performance of an automotive wastegated turbocharger," SAE (Society of automotive Engineers) ref: 900359.

DEGOBERT, P., 1994, "Pollution atmosphérique. Origine et réduction des émissions au niveau du moteur," Techniques de l'Ingénieur B2710 5

HIERETH, H., 1986, "Testing methods for the transient behaviour of charged vehicle engines," SAE (Society of automotive Engineers) ref: 860451.

PODEVIN,P., 1996, "Contribution à l'étude de la réponse transitoire d'un moteur à combustion interne soumis à une accélération," Ph.D. Thesis, Conservatoire National des Arts et Métiers - Paris.

PODEVIN, P., HAMMOUD, J. A., MAREZ, P., DUBOIS, F., 1997, "Simulation des accélérations d'un véhicule sur un banc à volant d'inertie," SIA (Société des Ingénieurs de l'Automobile), N° 716, P.62-67.