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MODELING OF ENGINE AND VEHICLE FOR A COMPACT CAR WITH A FLYWHEEL BASED KINETIC ENERGY RECOVERY SYSTEMS AND A HIGH EFFICIENCY SMALL DIESEL ENGINE

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ABSTRACT

Recovery of kinetic energy during driving cycles is the most effective option to improve fuel economy and reduce green house gas (GHG) emissions. Flywheel kinetic energy recovery systems (KERS) may boost this efficiency up to values of about 70%. An engine and vehicle model is developed to simulate the fuel economy of a compact car equipped with a TDI Diesel engine and a KERS. Introduction of KERS reduces the fuel used by the 1.6L TDI engine to 3.16 liters per 100 km, corresponding to 82.4 g of CO_2 per km. Downsizing the engine to 1.2 liters as permitted by the torque assistance by KERS, further reduces the fuel consumption to 3.04 liters per 100 km, corresponding to 79.2 g of CO_2 per km. These CO_2 values are 11% better than those of today's most fuel efficient hybrid electric vehicle.

INTRODUCTION

Regenerative braking is probably the best option to improve the fuel economy of passenger cars, light and heavy duty trucks and busses covering driving cycles characterized by frequent accelerations and decelerations [16-27]. Recovering the kinetic energy otherwise lost during braking may indeed significantly reduce the amount of energy to be supplied by the engine to reaccelerate the vehicle. Recovery of kinetic energy during driving cycles is the most effective option to improve fuel economy and reduce green house gas (GHG) emissions.

The latest generation of hybrid electric vehicles (HEV) makes use of many fuel savings technologies to increase fuel efficiency. The power-train system comprises a gasoline engine, an electric motor, a generator, a hybrid battery pack, drive wheels and brakes. The series-parallel power-train system provides drive power independently from the gasoline engine or the electric motor or from both of them simultaneously. Starting is powered by the battery feed electric motor. Normal running with light acceleration is achieved by using a combination of both the battery feed electric motor and the gasoline engine. Full, heavy acceleration is obtained by using all the power of the engine and the battery feed electric motor. During deceleration and braking, the gasoline engine is shut-off and the electric motor convert the kinetic energy into electricity stored in the battery. Finally, stopping, the gasoline engine is also shut-off. The most fuel efficient compact car hybrid electric now available has a CO_2 production of 89 g/km over the new European driving cycle, corresponding to a hydrocarbon fuel economy 10% better than the most fuel efficient vehicle with a traditional power train [1].

Analyzing the vehicle in a minimum ecological footprint perspective over the full life time, such a hybrid vehicle clearly has a largest cost to produce, maintain and dispose than a purely thermal-mechanical power-train due to the increased number of parts and the increased complexity of the assembly. However, the hybrid vehicle could still be a more environmentally friendly alternative than a conventional thermal-mechanical power-train if it could deliver a significantly better fuel economy. This is the case right now, but recent advances in flywheel kinetic energy recovery systems (KERS), already a technology mature for production [2-14] may change this statement.

An engine and vehicle model is developed to simulate the fuel economy of a compact car equipped with a TDI Diesel engine and a KERS. A validated engine model is applied to compute the brake specific fuel consumption map versus engine speed and load. A validated vehicle model is finally applied to compute the instantaneous fuel flow rate to the engine over a driving cycle interpolating these maps with the computed instantaneous speed and load.

DRAWBACK OF HYBRID ELECTRIC VEHICLES

The most part of the fuel saving of HEV comes from recharging the battery during braking and using the electric motor to replace the thermal engine power supply, with the latter being shut-off at idle and during braking and portions of the accelerations. Savings also comes in minor part from the thermal engine downsizing permitted by the torque assistance in heavy accelerations. Recovery of kinetic energy in HEV is not very efficient due to a very well known fundamental of physics, that transforming energy from one form to another inevitably introduces significant losses.

When a battery is involved, there are four efficiency reducing transformations in each regenerative braking cycle. (1) Kinetic energy is transformed into electrical energy in a motor/generator, (2) the electrical energy is transformed into chemical energy as the battery charges up, (3) the battery discharges transforming chemical into electrical energy, (4) the electrical energy passes into the motor/generator acting as a motor and is transformed once more into kinetic energy. The four energy transformations reduce the overall level of efficiency. If the motor/generator operates at 80% efficiency under peak load, in and out, and the battery charges and discharges at 75% efficiency at high power, the overall efficiency over a full regenerative cycle is only 36% [6-8, 10]. Efficiencies considerably smaller than 36% may also be estimated analyzing the hybrid vehicle data proposed in [28]. This means that hybrid vehicles waste near 64% of the braking energy that could possibly be recovered to improve the fuel economy.

The ideal solution is to avoid all four of the efficiency reducing transformations from one form of energy to another by keeping the vehicle's energy in the same form as when the vehicle starts braking when the vehicle is back up to speed. This can be done using high-speed flywheels, popular in space and uninterruptible power supplies for computer systems [29], but novel in ground vehicles [6-13]. For the space and computer applications, high-speed motor or generators are used to add and remove energy from the flywheels, while in ground vehicles; more efficient mechanical, geared systems are preferred [6-13, 29].

FLYWHEEL BASED KERS

Over the short periods required in cut-and-thrust traffic, a mechanically driven flywheel is much more effective than a battery-based hybrid, providing an overall efficiency over a full regenerative cycle of more than 70%, almost twice the value of battery-based hybrids [8]. However, a mechanically driven flywheel system has losses, due to friction in bearings and windage effects, which make it less efficient than a battery-based system in storing energy for long times.

Almost every vehicle with a manual transmission is already fitted with a flywheel to smooth the flow of power from the engine and to provide a small store of energy to help prevent stalling on launch. Toy cars use a small flywheel geared up to spin fast enough to provide spectacular scale performance. The geared high-speed flywheel concept is now being applied to full-sized cars with a resulting dramatic improvement in fuel economy, at low cost, without sacrificing acceleration.

Considering the theoretical advantages of storing braking mechanical energy with a much more efficient, simple and lighter mechanical device, and the recent improvements in kinetic energy recovery systems (KERS) for F1 applications [2 to 13], conventional power-trains with high efficiency Diesel engines may be coupled with KERS to deliver better than hybrids fuel economies.

For a traditional power train, the driveline equation balances vehicle side output torque from clutch or torque converter with inertia torque of the entire driveline and vehicle and the effective torque of the retarding forces on the vehicle, namely aerodynamic, rolling resistance and grade forces:

$$\tau_{drv,v} = \left[I_{trans1} + \frac{I_{trans2}}{R_t^2} + \frac{I_{dsh}}{R_t^2} + \frac{I_{axl}}{R_d^2 R_t^2} + \frac{M_{veh} r_{whl}^2}{R_d^2 R_t^2} \right] \frac{d\omega_{drv}}{dt}$$
$$- \left[\frac{I_{trans2}}{R_t^3} + \frac{I_{dsh}}{R_t^3} + \frac{I_{axl}}{R_d^2 R_t^3} + \frac{M_{veh} r_{whl}^2}{R_d^2 R_t^3} \right] \omega_{drv} \frac{dR_t}{dt}$$
$$+ \left[\frac{F_{aer} + F_{rol} + F_{grd}}{R_d R_t} \right] r_{whl}$$

Where $\tau_{drv,e}$ is the engine side torque of clutch or torque converter, $\tau_{drv,v}$ the vehicle side torque of clutch or torque converter. ω_{drv} the driveline speed on vehicle side of clutch or torque converter, I_{axl} the axle moment of inertia, $\mathbf{I}_{dsh}$ the driveshaft inertia, $\mathbf{I}_{trans1}$ the input side transmission moment of inertia, $\mathbf{I}_{trans2}$ the output side transmission moment of inertia, $\mathbf{M}_{veh}$ the vehicle mass, $\mathbf{r}_{whl}$ the wheel radius, $\mathbf{F}_{aer}$ the aerodynamic force on vehicle, $\mathbf{F}_{rol}$ the rolling resistance force on vehicle, $\mathbf{F}_{grd}$ the grade force on vehicle, $\mathbf{R}_t$ the transmission ratio, $\mathbf{R}_d$ the final drive ratio, **t** the time. This equation and the engine equation of motion, this latter balancing engine brake torque with engine inertia torque and engine side load torque from the clutch or torque converter, determine the operating points (torque and speed) of the engine. Braking at the wheels may be assimilated to a torque component, or even better to a slipping clutch component. Either way, braking at the wheels dissipates the kinetic energy of the vehicle that is therefore lost.

KERS store energy under vehicle braking and return it under vehicle acceleration. The system utilises a flywheel as the energy storage device and a Continuously Variable Transmission (CVT) to transfer energy to and from the driveline. Transfer of vehicle kinetic energy to flywheel kinetic energy reduces the speed of the vehicle and increases the speed of the flywheel. Transfer of flywheel kinetic energy to vehicle kinetic energy reduces the speed of the flywheel and increases the speed of the vehicle. The CVT is used because ratios of vehicle and flywheel speed are different during a braking or acceleration event. A clutch allows disengagement of the flywheel when not used.

The kinetic energy of the flywheel is $\mathbf{E}=½\cdot\mathbf{J}\cdot\boldsymbol{\omega}^2$ where **J** is the moment of inertia of the flywheel and $\boldsymbol{\omega}$ the angular velocity. The flywheel has a moment of inertia $\mathbf{J}=½\cdot\mathbf{m}\cdot(\mathbf{r}_1^2 - \mathbf{r}_2^2)$, where **m** is the mass, $\mathbf{r}_1$ the outer radius and $\mathbf{r}_2$ the inner radius. It is possible to use low speed high inertia flywheels, or high speed low inertia flywheels, to store same energy. F1 systems use a very light weight composite flywheel, made up of a carbon fiber filament wound rim surrounding a steel hub, rotating at very high speed in a vacuum [9]. This design has proved to be quite effective but also quite expensive to produce, with other solutions being considered for mass production [14].

Recovery of the braking energy reduces the amount of thermal energy requested to power the vehicle and reduce the time the thermal engine is on. Efficiency of KERS energy storage and release, maximum amount of energy being stored, energy loss in start/stop of engine and timing of deceleration and acceleration processes and therefore efficiency of the control play a dominant role in determining the best configuration of a KERS assisted power train. Using optimized strategies, CO_2 and fuel consumption reductions of over 20% are possible on test cycles and more than 30% is possible in real world conditions with gasoline powered vehicles [3].

FUEL ECONOMY DATA

Fuel economy is measured over test cycles. The ECE+EUDC cycle is a test cycle performed on a chassis dynamometer used for emission certification of light duty vehicles in Europe [EEC Directive 90/C81/01]. The entire cycle includes four ECE segments, repeated without interruption, followed by one EUDC segment. Before the test, the vehicle is allowed to soak for at least 6 hours at a test temperature of 20-30°C. It is then started and the emission sampling begins at the same time. This cold-start procedure is also referred to as the New European Driving Cycle or NEDC. The ECE cycle is an urban driving cycle, also known as UDC. It was devised to represent city driving conditions, e.g. in Paris or Rome. It is characterized by low vehicle speed, low engine load, and low exhaust gas temperature. The EUDC (Extra Urban Driving Cycle) segment has been added after the fourth ECE cycle to account for more aggressive, high speed driving modes. The maximum speed of the EUDC cycle is 120 km/h.

The most fuel efficient compact car vehicle available today [1] couples thermal engine, electric motor, generator, battery pack, drive wheels and brakes to power the vehicle with modulated thermal and electric motors and recovery of braking energy. However, the increase in vehicle weight and dimensions per load volume and the inefficiency of the multiple mechanical to electric energy conversions make their effectiveness much less than what is expected by a car much more environmentally expensive to produce, maintain and dispose.

Characteristics	**ECE**	**EUDC**
Distance [km]	4×1.013=4.052	6.955
Duration [s]	4×195=780	400
Average Speed [km/h]	18.7 (with idling)	62.6
Maximum Speed [km/h]	50	120

Table 1 – Main characteristics of ECE and EUDC cycles.

	Most fuel efficient compact car hybrid electric (H1 in Table A1 of Appendix)	Most fuel efficient compact car with a traditional power train (T1 in Table A1 of Appendix)
Fuel	gasoline	Diesel
Urban (cold) Fuel [l/100km]	4	4.7
Extra Urban Fuel [l/100km]	3.8	3.4
Combined Fuel [l/100km]	4	3.8
Combined CO_2 [g/km]	89	99
Combined Energy [MJ/km]	1.26	1.38

Table 2 – Fuel economy of compact car with hybrid and traditional power trains (measured values [1]).

Table 1 summarizes the parameters for both the ECE and EUDC cycles. Table 2 presents fuel economy and CO_2 production data of the most fuel efficient compact car hybrid electric and traditional power train now available [1]. Combustion of one liter of gasoline fuel is conventionally supposed to produce 2330 g of CO_2, while combustion of one liter of Diesel fuel is supposed to produce 2630 g of CO_2 following their conventional approximation as purely hydrocarbon fuels. The first has a 1.8L gasoline engine, while the second a 1.6L TDI Diesel engine. Considered lower heating values (LHV) are 42MJ/Kg and 43.5MJ/Kg for gasoline and Diesel fuels, while densities are 0.75 and 0.835 kg/liter respectively. The hybrid electric vehicle is more environmentally friendly during operation, and in particular covering the urban (cold) sector where accelerations are followed by decelerations and stop thanks to the recovery of braking energy completely dissipated with the traditional power train configuration. Table A1 in appendix presents dimension, weight and performance of most fuel efficient compact car hybrid electric and traditional (H1 and T1 cars respectively).

KERS MODELING

KERS have been coupled so far to gasoline powered engines in large sedans to provide improvements of fuel economy of about 25% [30]. Figure 1 presents the fuel flow rate for a full size car equipped with a large 4L gasoline engine, during two accelerations with an intermediate deceleration. The KERS permits to shut off the engine when the car is braking spinning the flywheel to increase its energy. The engine is then restarted when the stored kinetic energy is used to partially reaccelerate the vehicle. The engine stop/start is integrated with the KERS.

A KERS reduces the amount of fuel energy needed to accelerate the vehicle. Therefore, the engine warm up slowly with a KERS. During the cold start New European Driving Cycle, oil, water and metal temperatures are often below the fully warmed up values even at the end of the cycle, 1180 s after start. However, effects on fuel economy are particularly significant only during the first city sector. Figure 2 presents the measured temperatures of oil and cylinder head close to the water entry over the four city sectors in a 4L gasoline engine powering a full size car, as well as the measure fuel flow rate.

The 4L gasoline engine uses 0.149 kg of fuel to cover the first ECE sector, 0.103 Kg of fuel to cover the second ECE sector, 0.096 Kg of fuel to cover the third ECE sector, 0.090 Kg of fuel to cover the fourth ECE sector and finally 0.850 Kg of fuel to cover all the cycle. The total cold start penalty is less than 10%. The slow down of engine warm up produced by KERS is therefore expected to introduce a fuel efficiency penalty of less than 5% in the worst scenario of a very large 4L gasoline engine.

Smaller improvements in fuel consumption than with gasoline engines, but better then hybrids fuel economies, may be obtained by coupling KERS to small, turbocharged Diesel engine. The small 1.6L TDI Diesel engine considered here is expected to have a much smaller penalty due to the cold start than the large gasoline engine considered above. In the followings sections, the different warming up profile with KERS is neglected.

The 60 kW maximum power and 400 kJ energy storage F1 KERS by Flybrid [4-12] has a very light and compact design. It weighs 25 kg and has a volume of 13 liters. The 240 mm diameter flywheel weighs 5 kg and revolves at up to 64,500 rpm. A passenger car KERS is designed for an energy capacity of 400 kJ and a maximum power of 30 kW. Weight and dimension are slightly increased to reduce the speed of rotation and account for adoption of a vacuum pump. However, KERS remain light and compact for easy installation in passenger cars. The efficiency of a round trip regenerative braking is assumed to be 70% [4-12]. This is a minimum value often exceeded during operation [4-12]. Charging and discharging rates are very fast, 50 ms zero to full charge and vice versa. Control of the coupled regenerative and friction braking is very simple. KERS are charged during a deceleration and then immediately discharged during the subsequent acceleration. The engine is shut-off during decelerations, and it is restarted during the following acceleration when the kinetic energy recovered during the braking is fully consumed. Reference values are assumed for energy penalties for start/stop. Results of vehicle simulations are presented in the following section.

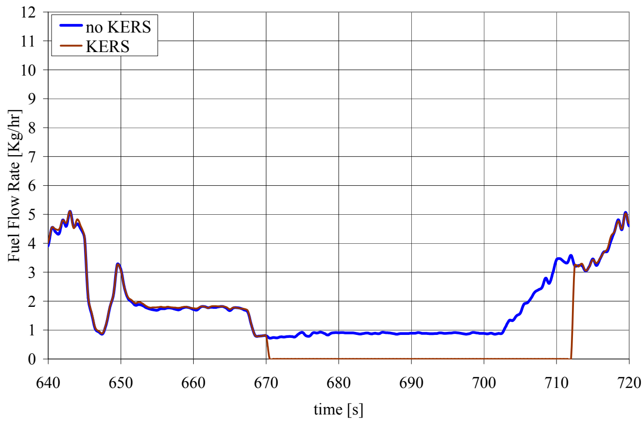

Figure 1 – Fuel flow rates with and without KERS.

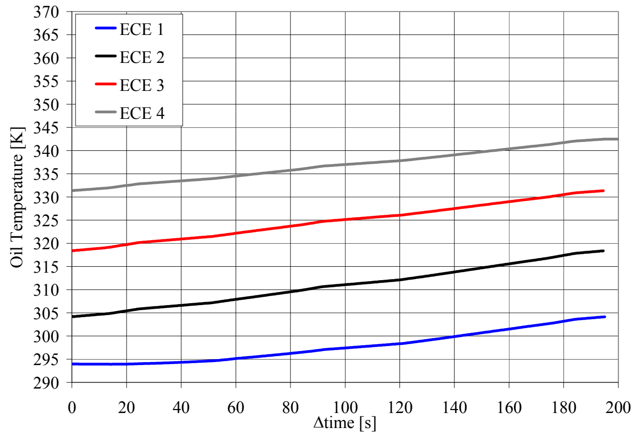

Figure 2a – Measured cylinder head temperature over the four ECE sectors of the NEDC for a full size car powered by a 4L gasoline engine.

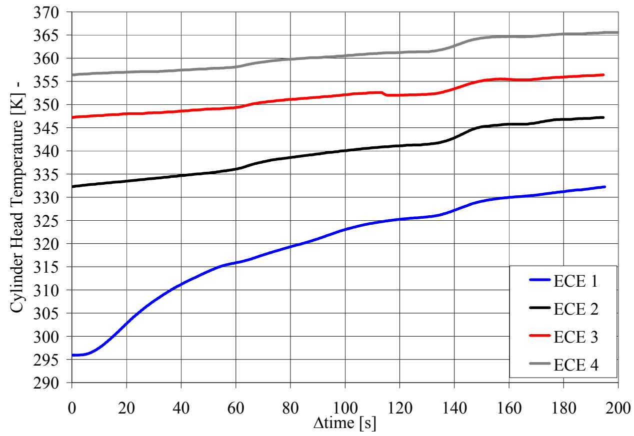

Figure 2b – Measured oil temperature over the four ECE sectors of the NEDC for a full size car powered by a 4L gasoline engine.

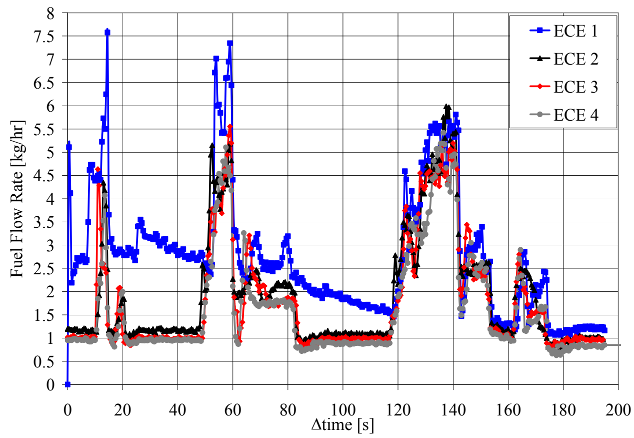

Figure 2c – Measured fuel flow rate over the four ECE sectors of the NEDC for a full size car powered by a 4L gasoline engine.

SIMULATION RESULTS

A model for the engine and a model for the car have been defined using the WAVE and the Lotus vehicle software [14 and 15 respectively]. An engine model is applied first to compute the brake specific fuel consumption map versus engine speed and load of the engine. Results of simulations are validated versus available experimental data. Then, a vehicle model is applied to compute the instantaneous fuel flow rate to the engine of the vehicle with traditional power train running the New European Driving Cycle (NEDC). The fuel flow rates are obtained interpolating the steady state brake specific fuel consumption map with the computed instantaneous speeds and loads with corrections for the cold start. With reference to a standard simulation without KERS, the engine is shut off when the car starts to decelerate and the braking energy starts to flow to the flywheel where it is stored with a first efficiency. When the car is then requested to reaccelerate, the stored braking energy in the flywheels starts to flow to the wheels powering the vehicle with a second efficiency. The product of charging and discharging efficiencies is supposed to be a conservative 70%. The engine is finally restarted when the flywheel energy reaches the minimum value necessary to perform the restart.

Results of simulations are validated versus the fuel consumption data measured. Table 3 presents the main data of the vehicle, while Table 4 presents the main data of the 1.6L TDI engine. Figure 3 presents the brake specific fuel consumption map computed with WAVE. Brake specific fuel consumptions in g/kWh and presented vs. engine speed in rpm and brake mean effective pressure in bar. Figure 3 also presents the maximum load brake mean effective pressure vs. engine speed.

Load variations are obtained by reducing the amount of fuel injected, i.e. changing the air-to-fuel equivalence ratio. This produces the typical high efficiency map of Diesel over the most part of engine loads. At idle, efficiency theoretically goes to zero, or the brake specific fuel consumption goes theoretically to infinity, because a certain amount of fuel is used to produce an indicated mean effective pressure equal to the friction mean effective pressure with no brake mean effective pressure output. The brake specific fuel consumption map is completed by using finite values at idle.

First, baseline computations have been performed. Results of simulations agree with measured data. Figure 4 presents the engine brake mean effective pressure - speed operating points of the baseline configuration. One operating point is considered every 0.5 s.

Computations have then been performed modeling a modified version with KERS. No weight penalty is considered for the KERS, as no weight reduction is then considered following downsizing. Results show the engine may be stopped more than 50% of the time with KERS, with the engine being run to deliver only the amount of energy needed by the vehicle during part of accelerations and cruising, and to cover the start-stop penalties. Figure 5 presents the engine brake mean effective pressure - speed operating points of the configuration with a 1.6L TDI engine and the KERS. One operating point is considered every 0.5 s. The shut off of the engine reduces the number of points in figure.

Computations have finally been performed considering the option to downsize the engine to 1.2 liters thanks to the boost provided by KERS. Just for sake of simplicity, the same brake specific fuel consumption map and maximum load brake mean effective pressure curve are supposed to apply for a downsized version of the engine to 1.2 liters. Therefore maximum power and maximum torque speeds are the same for both engines, while maximum power and maximum torque outputs reduce with downsizing by the displacement ratio. The 1.2L engine is not supposed to be derived from the 1.6L through a reduction of stroke, and the turbocharger is not supposed to be the one of the 1.6L engine. Actual brake specific fuel consumption map and maximum load brake mean effective pressure curve of a 1.2L TDI Diesel engine are expected to overlap with those proposed but with remarkable positive and negative differences.

Figure 6 presents the engine brake mean effective pressure - speed operating points of the configuration with a 1.2L TDI engine and the KERS. One operating point is considered every 0.5 s. The shut off of the engine reduces the number of points in figure. The downsizing of the engine increases the operating BMEP towards points of better fuel economy. Torque assistance by KERS permits same maximum accelerations of the larger engine following a deceleration.

Parameter	Most fuel efficient compact car with a traditional power train (T1 in Table A1 of Appendix)
Weight [kg]	1336
Frontal Area [m^2]	2.2
Drag Coefficient	0.298
Tyre Rolling Radius [m]	0.3080
Final Drive Ratio	3.389
Gearbox	Manual
Number of ratios	5
Gear. 1 Ratio	3.7780
Gear. 2 Ratio	1.9440
Gear. 3 Ratio	1.1850
Gear. 4 Ratio	0.8160
Gear. 5 Ratio	0.6250

Table 3 – Basic vehicle data.

Parameter	1.6L TDI Diesel engine
Number of Cylinders	4
Bore [mm]	79.50
Stroke [mm]	80.50
Compression ratio	16.5
Swept Volume [l]	1.5984

Table 4 – Basic engine data.

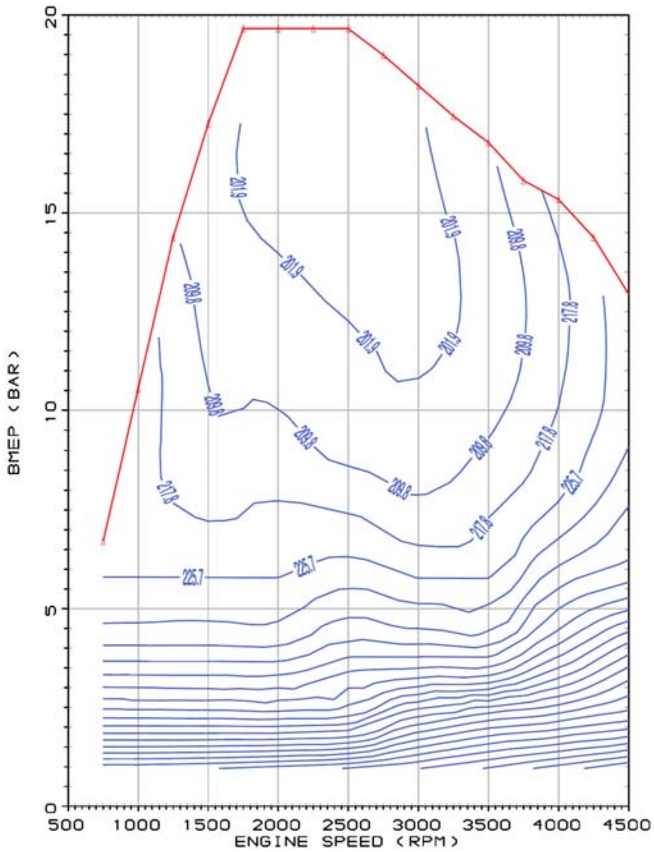

Figure 3 – Computed brake specific fuel consumption (in g/kWh) map for the 1.6 TDI Diesel engine.

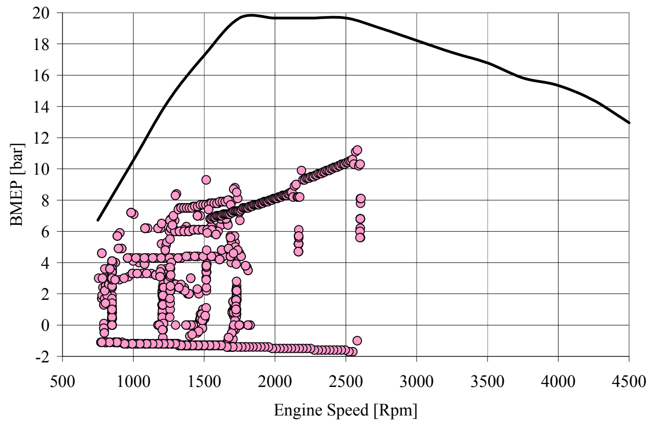

Figure 4 – Computed engine brake mean effective pressure - speed operating points of the baseline configuration with a 1.6L TDI engine.

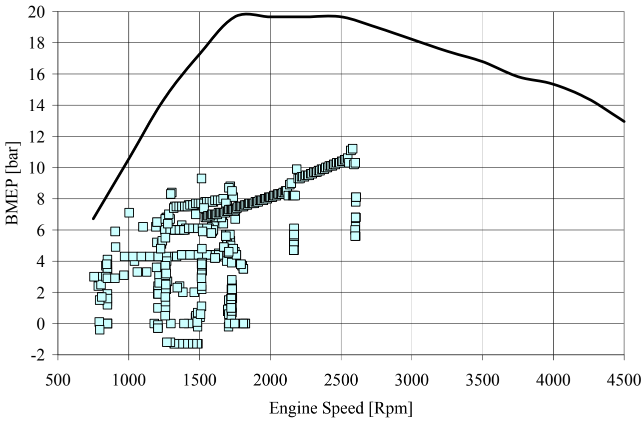

Figure 5 - Computed engine brake mean effective pressure - speed operating points of the configuration with a 1.6L TDI engine and KERS.

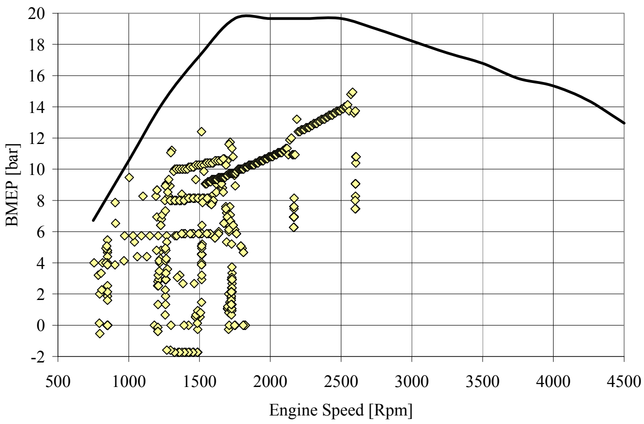

Figure 6 - Engine brake mean effective pressure - speed operating points of the configuration with a 1.2L TDI engine and KERS.

Table 5 resumes the fuel economy results of all the modeled configurations, the baseline 1.6L TDI engine without KERS, this engine and KERS, an intermediate downsized engine 1.2L TDI engine without KERS, and the downsized engine 1.2L TDI and KERS. The baseline configuration with the 1.6L TDI engine and no KERS requires 3.81 liters of Diesel fuel per 100 km. The configuration with the 1.6L engine and the KERS reduces the fuel usage to 3.16 liters per 100 km, with a fuel saving of 17%. The configuration with the downsized 1.2L TDI engine and the KERS reduces the fuel usage to 3.04 liters per 100 km, with a total fuel saving of 20%.

Configuration	**Fuel [l/ 100km]**	**CO_2 [g/km]**	**Energy [MJ/ km]**
1.6L TDI	3.8	99	1.38
1.6L TDI + KERS	3.2	82	1.15
1.2L TDI	3.6	95	1.33
1.2L TDI + KERS	3.0	79	1.10

Table 5 – Computed fuel economies of a compact car with traditional power trains and KERS.

It has to be pointed out that the vehicle stops from high speed at the end of the NEDC with immediate engine turn off. This waste all the energy stored in the KERS following the sharp deceleration. Clearly the end of the NEDC cycle is very far from the real life operation of the car, and therefore real life benefits of KERS may be guessed to be larger, around 25% better fuel economy.

CONCLUSIONS

KERS are light and compact for easy installation in passenger cars. KERS feature very fast charging and discharging rates, and efficiencies of round trip regenerative braking exceeding 70%. KERS permit efficient regenerative braking and torque assistance as a means of dramatically improving efficiency and hence reducing fuel consumption and CO_2 emissions.

Computational results presented here for a conventional compact car equipped with a 1.6L TDI Diesel engine running the new European driving cycle (NEDC) are very promising.

The configuration with the 1.6L TDI Diesel engine and KERS reduces the fuel usage to 3.16 liters per 100 km, corresponding to a production of 82.4 g of CO_2 per km. These CO_2 values are 7% better than those of today's most fuel efficient hybrid electric vehicle.

Downsizing the engine to 1.2 liters, the fuel consumption is reduced to 3.04 liters per 100 km, corresponding to a production of 79.2 g of CO_2 per km. These CO_2 values are 11% better than those of today's most fuel efficient hybrid electric vehicle.

Considering the end of the NEDC cycle with the stop of the vehicle from high speed and immediate engine turn off is very far from the real life operation of the car, real life benefits of KERS may be estimated to be even more fuel saving.

KERS are effective in improving the fuel economy with all the types of internal combustion engines, controlled by changing the air-to-fuel ratio or reducing the amount of charge introduced within the cylinder.

The unaffordable financial cost of innovations in the automotive industry these days is the major issue to be overcome to apply this technique to vehicles.

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NOMENCLATURE

BMEP Brake Mean Effective Pressure
BSFC Brake Specific Fuel Consumption
CVT Continuously Variable Transmission
ECE Economic Commission for Europe
EUDC Extra Urban Driving Cycle
GHG Green House Gases
KERS Kinetic Energy Recovery System
NEDC New European Driving Cycle
TDI Turbo Direct Injection

APPENDIX

Car	H1	T1
Overall length (mm)	4460	4199
Overall width (mm)	1745	1786
Overall height (mm)	1490	1479
Wheel base (mm)	2700	2578
Cargo Volume (liters)	890	350
Curb weight total maximum (kg)	1420	1314
Gross vehicle weight total (kg)	1805	1750
Max speed (km/h)	180	190
Acceleration (0-100 km/h) (s)	10.4	11.3

Table A1 – Weight, dimensions and performance of the production hybrid and conventional passenger cars considered in the paper.