

# A fun-to-drive, economical and environmentally-friendly mobility solution

Alberto Boretti\*

*RMIT University*

*Po Box 71, Bundoora, 3383 VIC, Australia*

## Abstract

A kinetic energy recovery system (KERS) placed on the rear non-motored axle of a small, lightweight, forward drive passenger car with a turbocharged direct injection (TDI) internal combustion engine is possibly the best solution presently available to dramatically improve the fuel economy of passenger cars within today's constraints of budget, weight, packaging, simple construction, easy operation and best life cycle environmental friendliness. The vehicle may be built using various KERS designs, from the purely mechanical M-KERS based on a continuously variable transmission and a flywheel permitting round trip regenerative braking efficiencies above 80% but requiring additional research and development, to purely electric E-KERS systems based on an electric motor/generator and a battery with off-the-shelf components permitting round trip regenerative braking efficiencies above 70% but having a traction battery as the weak part of the design, to mixed mechanical-electric systems EM-KERS adopting an electromechanical flywheel replacing the traction battery for intermediate advantages and downsides. The engine is small displacement, small number of cylinders, high power density, turbocharged and direct injection. The TDI internal combustion engine may be gasoline or diesel, with higher power density but lower fuel conversion efficiency or vice-versa, with or without start-stop capability, to deliver high part load efficiencies over the reduced off idle operating points of a driving cycle. Downsizing, down speeding and KERS assistance makes it possible to reduce the operation of the thermal engine (internal combustion engine) over non-efficient BMEP x speed map points and regenerative braking reduces the thermal engine energy supply. The front wheel drive vehicle behaves like a four wheel drive during driving characterized by accelerations and decelerations, with the thermal engine torque boosted by KERS. The proposed vehicles may have fuel economy figures well below 2.5 litres/100 km covering a modified NEDC where the unrealistic sharp deceleration from 120 km/h to resting at the end of the extra urban sector is followed by another urban sector like the first four ones.

**Keywords:** Environmentally friendly vehicles, Internal combustion engines, Turbocharging, Direct injection, Kinetic energy recovery system

## 1. Introduction

The electric car is a fine idea which despite its environmentally friendly reputation is not actually that

good in practice. If we were to move from combustion fuel based transport to a purely electric system today, it would be a disaster under all relevant criteria, economic and environmental. Electricity production in the OECD countries in 2011 and H1 2012 [1] is 62.21% and 61.81% combustible fuels (including biomass), 18.04% and 19.90% nuclear, 14.63% and

\*Corresponding author

Email address: a\_boretti@yahoo.com (Alberto Boretti\*)

14.05% hydro-electric, and only 5.12% and 4.23% geothermal plus wind plus solar plus other. Taking Australia as a case study, the electricity production of 2011 and H1 2012 [1] is 89.29% and 90.37% combustible fuels, 7.43% and 6.66% hydro-electric, 3.28% and 2.98% geothermal plus wind plus solar plus other. Consequently, the move to electric transport would require additional power stations to be built, novel infrastructure to be constructed to distribute the additional electric energy and recharge the batteries of electric vehicles, and the generation of more electricity mostly—if not entirely—by burning fossil fuels. This would translate in quite a negative big picture in both the economy and the environment, despite the zero tailpipe emission claims of electric vehicles.

As a result, even before considering: (i) the battery issue translating into weight, load and especially limited range and long recharging times and (ii) the significantly larger economic and environmental costs to produce and dispose of the vehicle, the electric mass transport is not presently competitive with fossil fuel mass transport based on internal combustion engines.

Internal combustion engines (hereinafter: “thermal engines”) are easily the most successful energy conversion device developed to date. Low speed engines for power generation or large marine applications have brake fuel conversion efficiencies  $\eta_b$  approaching 55% [2, 3]. In these engines,  $\eta_b$  also slightly increases, reducing the load from 100% to 75%, and is about the same at full load as at 50% load [2, 3].

These low speed engines are not exactly the same as passenger car engines, where power density and speed have to be much greater, and the load excursion also has to cover lighter loads. However, diesel engines for passenger car applications are already approaching 45% peak efficiencies and have efficiencies of almost 40% from one third of the load.

The use of KERS to replace thermal engine energy supply may avoid the use of the thermal engine at poor efficiency points in addition to globally producing less mechanical energy [4–6].

Vehicles powered by thermal engines may certainly have their fuel economy drastically improved by adopting simple kinetic energy recovery systems

such as those embedded in electric vehicles, but enjoying a lower target cost and greater environmental friendliness than full hybrids where the thermal engine is completely integrated with the electric motor.

The use of a small, turbocharged, directly injected thermal engine of the diesel or gasoline type plus mechanical, electrical or mechanical-electrical KERS (M-KERS, E-KERS and EM-KERS hereafter) is considered in the rest of the paper, coupled with a lightweight and environmentally friendly design of the vehicle.

## 2. Kinetic energy recovery systems

Driveline kinetic energy recovery systems have become popular since their introduction into F1 racing in 2009, both in fully mechanical and fully electrical flavors [4]. The mechanical system is made up of a clutch and a continuously variable transmission plus a flywheel. The electric system consists of a clutch, an electric motor/generator and a traction battery, whereas the electro-mechanical system has a clutch, an electric motor/generator and an electro-mechanical flywheel energy storage device.

Non-driveline KERS may have the advantage of being potentially a much cheaper product, also permitting four wheel drive performance with a two wheel drive thermal power train.

Different KERS may be built purely electric, purely mechanic, hybrid mechanic/electric differing for round trip efficiency, packaging, weight, costs and environmental friendliness.

The Audi R18 e-tron Quattro Le Mans [7] is possibly the most successful example of non-driveline KERS.

Audi’s R18 e-tron Quattro marks the successful return of four driven wheels to the race track coupled with the novelty of hybridization of the power train with a mixed mechanical/electric system.

The hybrid system is made of an electric flywheel accumulator with maximum 500 KJ energy storage and a Motor Generator Unit (MGU) on the front axle, water cooled with integrated power electronics, of  $2 \times 75$  kW power. Kinetic energy is recovered on the front axle during the braking phase. This energy is fed into an electric flywheel accumulator before being released during acceleration. The thermal engine

transfers its power to the rear wheels. The two systems complement one another. The selection of a flywheel accumulator system is due to the high power density which is crucial during regenerative braking and re-acceleration. The system is comprised of two drive shafts, the MGU including planetary gears, an electronic flywheel accumulator alongside the driver, plus the monitoring and control systems. The planetary gears adapt the transmission ratio during acceleration and braking. During braking the wheels drive the MGU.

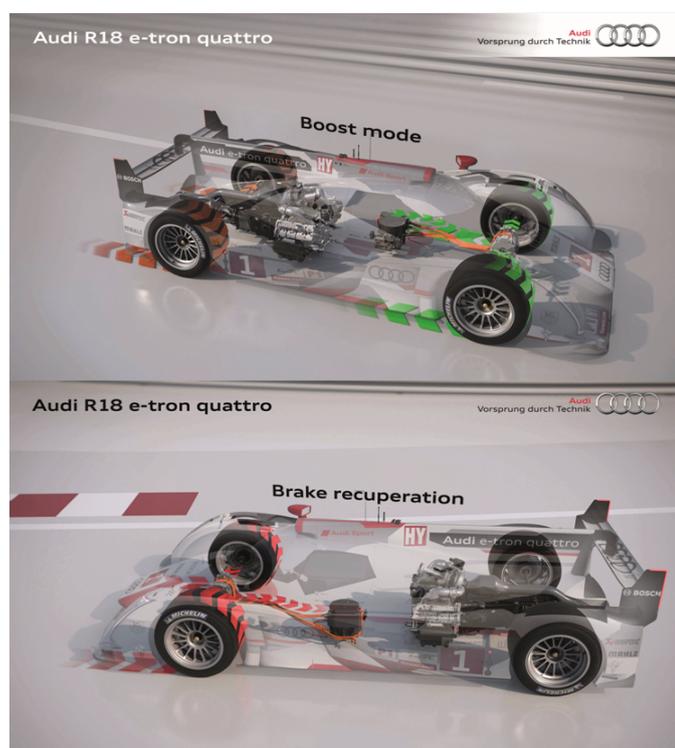


Figure 1: Audi R18 e-tron Quattro KERS (from [7]). Recuperation and boost mode of operation

The MGU accelerates electrically a carbon-fiber flywheel running in a high-vacuum. When the driver re-accelerates, the system delivers the energy to the front axle. The energy to be transferred to the front wheels between two braking phases is set by the regulations to the previously mentioned 500 kJ. The two independently powered axles on the e-tron quattro are synchronized by the electronic control unit (ECU) without driver intervention. The charging process is controlled by the deceleration of the car subject to the accumulator's state of charge. The discharging process is defined by the minimum speed

of 120 km/h set by the regulations, the race strategy, the throttle pedal movement and the acceleration of the car. The type of drive is rear wheel drive, traction control (ASR), with the option of four-wheel drive e-tron quattro from 120 km/h.

The core component of the Audi KERS is the Williams Hybrid Power (WHP)'s electric flywheel energy storage [8] working as an electro-mechanical battery or, equally, as an ultra-high-speed electric motor/generator having a high inertia, composite rotor. The unit connects using only electrical cables to transmit the energy back and forth, allowing the same vehicle packaging freedom as a traction battery.

This system has been proposed for prestige cars, but the use in small, low cost but environmentally friendly passenger cars could certainly be challenging.

A fully mechanical non-driveline KERS has been proposed in [5, 6], delivering theoretical round trip efficiencies above 80%.

### 3. Small, high power density, directly injected turbocharged engines

Small, high power density, directly injected turbocharged engines are receiving more and more attention as the preferred thermal engine powering vehicles with kinetic energy recovery systems [9–12]. Engines with a small displacement and a small number of cylinders permit reduced weight and packaging. Their warm-up is much quicker than large displacement multi-cylinder engines. The high power density translates into high top BMEP values. The small displacement and the KERS support permit operation over driving cycles at relatively high BMEP values of good fuel conversion efficiency. The full load output and the KERS boost permit similar performances to large displacement multi-cylinder engines. This section reports on the latest trends in the design of the fuel delivery, combustion, gas exchange and turbocharge systems for these engines. The compression ignition diesel versions permit lower power densities, but much higher full and part load fuel conversion efficiencies. The spark ignition gasoline versions permit much higher power densities for the higher BMEP and the higher revolutions per minute,

but at the expense of lower full and part load fuel conversion efficiencies.

#### 4. Thermal engine plus KERS vehicle theory

From basic vehicle dynamic courses [13], we know that force  $F$  is equal to the product of mass by acceleration of the vehicle  $m \cdot a$  plus the aerodynamic resistance force  $R_a$ , the rolling resistance force  $R_{rl}$  and the grade resistance force  $R_g$ . Force  $F$  is propulsive if accelerating the vehicle, or braking if decelerating the vehicle. We may indicate these forces as  $F_p$  and  $-F_b$  respectively. The propulsive force  $F_p$  for a vehicle equipped with an internal combustion engine (ICE) and KERS can then be split into the ICE and the KERS components, i.e.  $F_p = F_{p,ICE} + F_{p,KERS}$ . Similarly, the braking force  $F_b$  is split into the friction brakes and the KERS, i.e.  $F_b = F_{b,FRI} + F_{b,KERS}$ . With these assumptions, Newton's equation reads as follow:

$$F_{p,ICE} + F_{p,KERS} - F_{b,FRI} - F_{b,KERS} - R_a - R_{rl} - R_d = m \cdot a \quad (1)$$

The forces in equation (1) multiplied by the vehicle speed  $v$  provide the propulsive, braking and resistance powers. The propulsive and braking energies are obtained by integrating in time the propulsive and braking powers.

We neglect the grading resistance, while we assume the rolling resistance a linear function of  $v$  and the aerodynamic resistance a function of  $v$  squared.

The ICE power is then proportional to the engine braking mean effective pressure  $BMEP$ , the engine displacement  $V_d$  and the engine rotational speed  $\omega$ :

$$P_{p,ICE} \equiv BMEP \cdot V_d \cdot \omega \quad (2)$$

The speed of rotation of the engine  $\omega$  is proportional to  $v$  through the gear ratio, the final drive ratio and the circumference of the tires.

The brake mean effective pressure is the difference between the indicated and the friction mean effective pressures:

$$BMEP = IMEP - FMEP \quad (3)$$

The friction mean effective pressure  $FMEP$  is roughly a quadratic function of  $\omega$ , while the in-

dicated mean effective pressure  $IMEP$  is the in-cylinder pressure work per unit displaced volume.

If LHV is the lower heating value of the fuel,  $m_f$  the mass of fuel trapped within the cylinder per cycle,  $p$  the pressure,  $V$  the volume,  $\eta_i$  and  $\eta_b$  the indicated and brake fuel energy conversion efficiencies, then

$$\begin{aligned} IMEP &= \frac{\oint p \cdot dV}{V_d} = \frac{\eta_i \cdot m_f \cdot LHV}{V_d} \\ BMEP &= \frac{\eta_b \cdot m_f \cdot LHV}{V_d} \end{aligned} \quad (4)$$

HSDI Diesel passenger cars have top  $\eta_b$  approaching 45% and reduced penalties changing the load. High values of  $\eta_b$  are possible from roughly one third of the maximum load. The maximum engine speed is less than 4500 rpm because the diffusion and kinetically controlled diesel combustion requires an almost constant time to develop. The engine is run lean of stoichiometry at full load, and the load is reduced by reducing the quantity of fuel injected.

Gasoline engines have top  $\eta_b$  below 40% and usually more significant penalties reducing the load because of throttling and the homogeneous operation. Maximum speed is 5,000–7,500 rpm, but the gasoline combustion mostly controlled by the turbulent mixing may permit almost any speed, as the combustion duration is almost constant in terms of crank angle degrees and therefore time duration is almost inversely proportional to the engine speed. Racing engines have been revving above 20,000 rpm without major combustion issues. The engine is run about stoichiometric at all loads and the load is controlled by throttling the intake. Throttling losses are mitigated by a fully variable valve actuation replacing the throttle.

In these engines, most of the fuel energy is still lost. More than 50% of the fuel energy is lost in the best operating points of the best thermal engine. The amount of lost fuel changes drastically by changing the load and speed vs. these optimum points.

IMEP largely reduces by reducing the load in gasoline engines, while it does not change too much in Diesel engines; actually it improves with leaner mixtures in Diesel engines. However, in general, low BMEP operating points have poor efficiencies ( $\eta_b$  is zero when  $IMEP = FMEP$ ).

The ICE power required by the vehicle may be provided more efficiently by working higher

BMEP through downsizing ( $V_d$  reduced) and down-speeding (reduced  $\omega$ ).

The opportunity to achieve large BMEP (exceeding 25 bar in the latest passenger cars TC GDI) and high maximum speed enable nearly optimum cycle operation while permitting the top end torque and power required by marketing purposes more than actual use of the car.

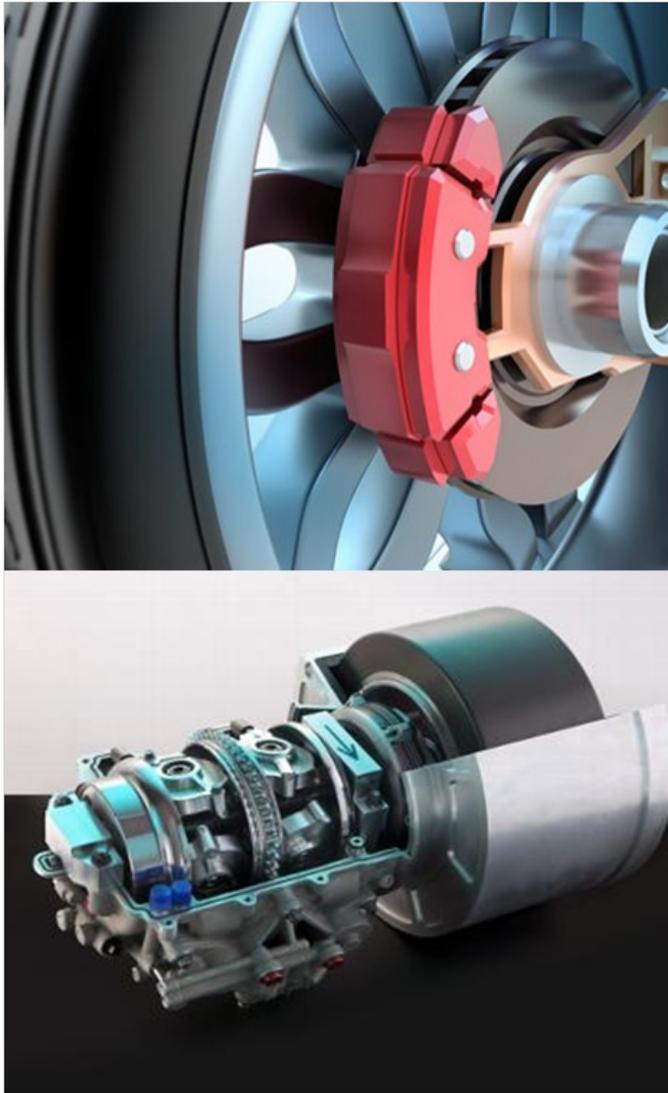


Figure 2: Friction brakes vs. M-KERS

We must certainly increase fuel energy conversion,  $\eta_b$ , by increasing  $\eta_i$  or reducing FMEP, but also avoid using the engine in extremely low efficiency operating points and recovering the vehicle kinetic energy. Figure 2 presents the friction brakes and M-KERS. With friction brakes, all the kinetic energy is dissipated in heat. With M-KERS, the braking energy is

used to spin the flywheel, and this energy is reused in the acceleration immediately following a deceleration by slowing down the flywheel.

An optimum mobility solution may be obtained by using a small ICE on the front wheels, plus M-KERS on the rear wheels. This way, by using the torque and power boost of KERS, an otherwise 2 wheel drive car may have performances similar to a four wheel drive.

Reduction of the thermal engine energy supply depends on the driving cycle and the KERS round trip regenerative braking efficiency [4]. With E or M-KERS more than 70 or 80% of the braking energy may be recovered. The braking energy may be 20% of the propulsive energy on mild cycles as the NEDC, but it may be much larger in aggressive cycles like the USDD. Benefits are larger in terms of fuel energy because the engine will not operate over low efficiency BMEP & speed points.

The benefits of small, few cylinders, turbocharged, direct injection diesel or gasoline engines are also clear. They permit operation with high efficiency BMEP & speeds, faster warm-up, and reduced weight and packaging. Naturally aspirated gasoline and supercharged two stroke gasoline engines are also options of interest, not considered here only for lack of space.

## 5. Modified NEDC results

The new European driving cycle is an unrealistic driving pattern drawn with a ruler by European law makers. In theory, it represents city driving, the first 4 urban sectors then an extra urban driving sector. This last sector has a final sharp deceleration from 120 km/h to park that is very unlikely to occur at any time of day on European roads. The NEDC original is made of 4 Urban and 1 Extra Urban sector. We use the 4 Urban 1 Extra Urban and 1 Urban sector in the modified NEDC.

Vehicle options presently considered are passenger cars: 3 doors/4 seats, 5 doors/5 seats, 5 doors/7 seats, commercial vehicles 4 doors/4 seats plus load.

The front engines are 2–3 cylinder engine TDI Diesel/gasoline, the KERS are E-KERS, M-KERS and EM-KERS rear brakes.

The chassis has a lightweight design, monocoque, with environmentally friendly production. Minimum

maintenance, simplicity of design and operation, and full life cycle economy and environmental friendliness are requisites of the project.

An Excel worksheet was developed to integrate the vehicle equation (1) given a prescribed velocity schedule and basic vehicle parameters. The procedure was tested against proprietary chassis dynamometer data and published data such as the Advanced Powertrain Research Facility Dynamometer Database [14]. Good results are provided for traditional vehicles with traditional, hybrid and electric vehicles.

Figure 3 presents the standard and modified NEDC velocity schedules, the resulting propulsive and braking powers, the thermal engine power supply without KERS, and the thermal engine and KERS power supply with KERS.

The NEDC original cycle is shown in blue. This driving schedule is modified to make the NEDC much closer to a real driving cycle. As parking from highway driving at 120 km/h is practically impossible, another urban sector is added in red, Figure 3.a. The vehicle propulsive and braking powers are obtained from the driving schedule by multiplying the forces in equation (1) by the vehicle speed  $v$ , Figure 3.b. The vehicle propulsive power must be entirely provided by the thermal engine if there is no KERS, Figure 3.c.

With KERS, the braking energy is partially stored, and then re-used in acceleration immediately following the deceleration. Figure 3.d presents the vehicle propulsive power to be provided by the thermal engine in red and the one provided by KERS in blue.

The simulation refers to a vehicle of total mass 1000 kg. KERS is M-KERS of minimum round trip regenerative efficiency 80% [5, 6]. Frontal area is 2.2 m<sup>2</sup> with  $C_d$  of 0.29 (air density 1.29 kg/m<sup>3</sup>). The rolling resistance at 50 km/h is assumed to be 150 N. The vehicle is front wheel drive with rear wheel KERS. The engine is in the front of the car.

The energy stored in KERS during a deceleration is reused immediately in the following acceleration. The energy stored in the last deceleration bringing the vehicle to rest is obviously lost.

Electric vehicles (EV) or hybrid electric vehicles (HEV) may use this last deceleration to recharge the battery up to the start level, but clearly this is not the

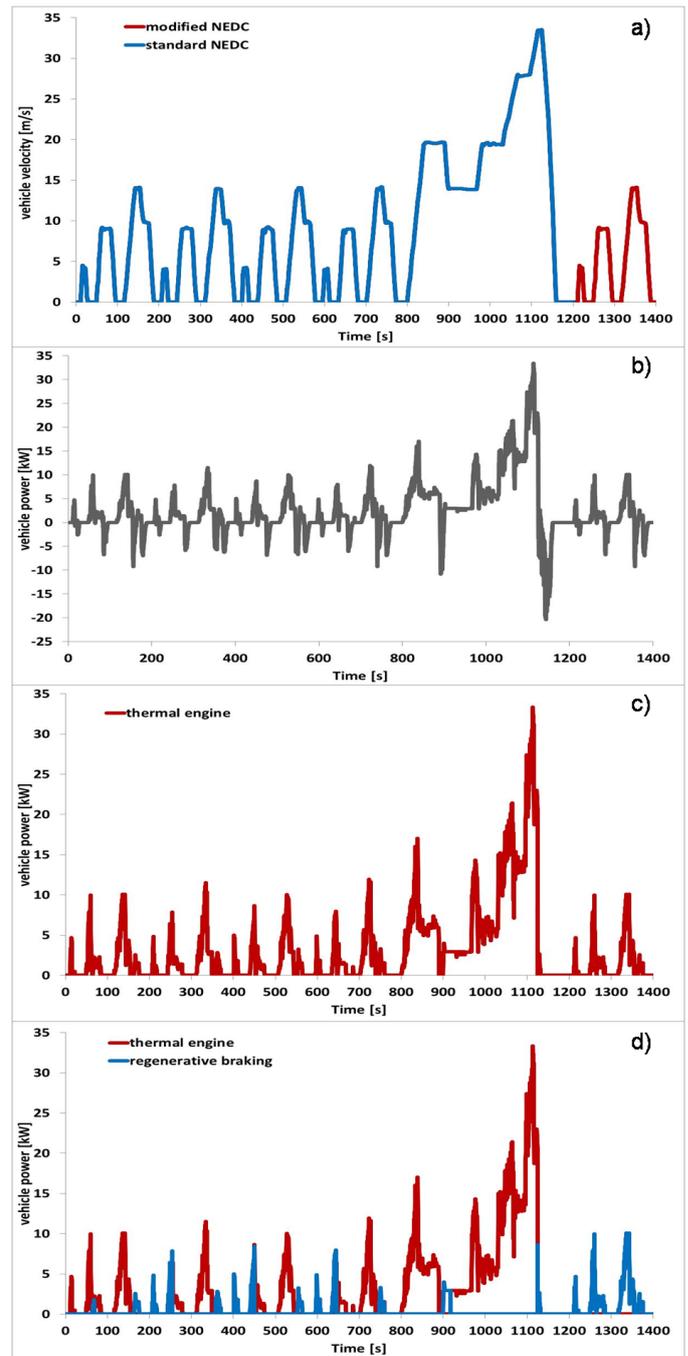


Figure 3: – a) standard and modified NEDC velocity schedules; b) resulting propulsive and braking powers; c) thermal engine power supply without KERS; d) thermal engine and KERS power supplies

way to assess the true energy economy of the vehicle.

START-STOP capabilities may further improve fuel economy. However, there is a trade-off between the increased complexity and cost and the fuel economy benefits in real driving conditions. With KERS the thermal engine is not used during large portions

of the cycle and the thermal engine could possibly be shut down. However, energy is then needed to restart the thermal engine after shutdown. Low speed idling may reduce the fuel wasted during idling and make the engine shut down and restart unnecessary. In the proposed simulations the engine is always operating during the cycle and low load points are simply replaced by low consumption idling points.

The maximum braking power is 20.4 kW. The energy needed to propel the vehicle over the cycle is 4.25 MJ. The braking energy is 0.86 MJ. The 4.25 MJ have to be provided by the thermal engine (if there is no KERS) or by the thermal engine and KERS (when the vehicle is equipped with KERS).

With M-KERS having a minimum regenerative efficiency of 80%, the propulsive energy required from the thermal engine is 3.67 MJ, and the energy recovered by M-KERS is 0.58 MJ.

with KERS. Without KERS, Figure 4.a the thermal engine delivers power 57.05% of the time, with an averaged power supply of 5.64 kW, and it works without load 42.95% of the time. With KERS, Figure 4.b the thermal engine delivers power 40.41% of the time, with an averaged power supply of 6.79 kW, and it works without load 59.59% of the time.

Considering the length of 11.9 km, this translates into thermal engine energy supply of 0.31 MJ/km or 30.82 MJ/100 km.

The analysis of Figures 3 and 4 deals with the power supply required for the thermal engine. A very preliminary estimation of fuel consumption may be obtained by assuming an average efficiency of the engine over the operating points. Better fuel economy figures may only follow a complete definition of the power train, which is presently unavailable.

By assuming an average engine efficiency of 38–40% during the cycle (non-zero load points) for a specifically developed Diesel engine, the fuel energy supply is 81.1–77.0 MJ/100 km, translating into 2.25–2.14 litres/100 km of 0.8 Kg/litre density, 43.30 MJ/kg LHV fuel.

By assuming an average engine efficiency of 33–35% during the cycle (non-zero load points), for a specifically developed gasoline engine the fuel energy supply is 93.4–88.0 MJ/100 km, translating into 2.80–2.64 litres/100 km of 0.75 Kg/litre density, 44.40 MJ/kg LHV fuel. These fuel consumption figures are obviously much less accurate than the fuel energy supply figures, provided by the details of the engine, the transmission and the kinetic energy recovery system.

Costing of the proposed mobility solution is presently impossible, dependent as it is on unavailable technical details and production volumes.

The benefits vs. a traditional power train configuration without KERS derive from the saving of energy supplied by KERS and the thermal engine energy supply at higher efficiency. In “sporty” driving made up of sharp accelerations and decelerations, a vehicle with KERS may have the same performance as a 4 wheel drive car with a much larger thermal engine. The proposed vehicle has indeed the power of the thermal engine and KERS available for acceleration following deceleration, and this power is available on the front and rear wheels.

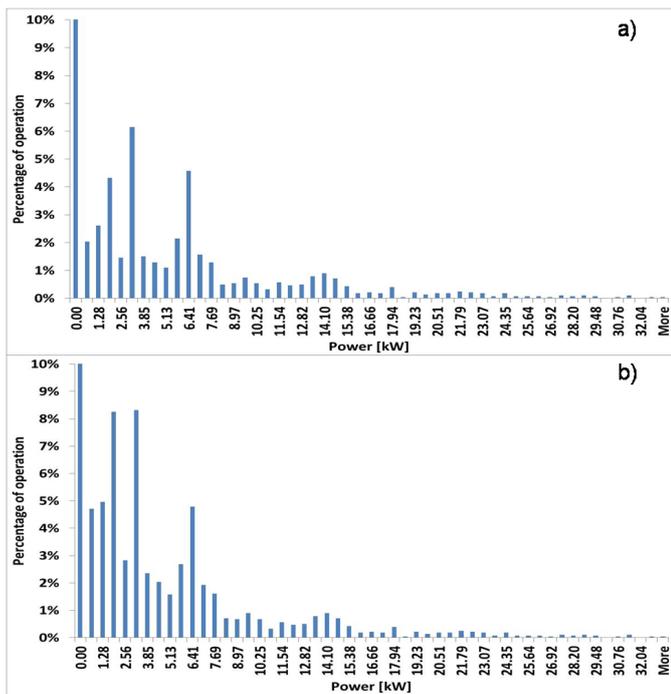


Figure 4: Percentage of the cycle the THERMAL ENGINE spends at a certain power without KERS (a) and with KERS (b)

From figures 3.c (thermal engine power supply without KERS) and 3.d (thermal engine power supply with KERS) it is possible to compute the fraction of time spent by the thermal engine at different powers. Figure 4 presents the percentage of the cycle the thermal engine spends at a certain power without and

## 6. Summary/Conclusions

The best mobility solution in the short term is the use of simple, lightweight vehicles equipped with front small, high power density, internal combustion engines and rear kinetic energy recovery system brakes.

The engines have few cylinders, and are turbocharged and directly injected, gasoline or Diesel depending on the target use. KERS is preferably mechanical, but electric and electro-mechanical solutions are also options.

Thanks to M-KERS on the rear non-motored wheels, the thermal engine powering the front wheels has to supply 0.31 MJ/km or 30.82 MJ/100 km for a 1000 kg vehicle of standard rolling and aerodynamic resistances covering a modified version of the new European driving cycle.

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