A Hybrid-Propulsion Powertrain with Planetary Gear Set: Simulation Results and a Design Approach

Marco Santoro
Dresden University of Technology - Germany

Leone Martellucci
University of Rome I "La Sapienza" - Italy

ABSTRACT

A power-split hybrid powertrain adopting a planetary gear set is proposed in this work as alternative to the traditional hybrid-propulsion schemes.
The main advantages of this drivetrain are:

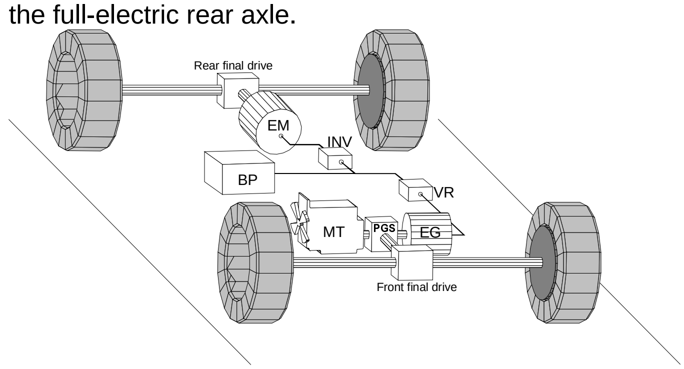
- *Sluggish* dynamic behaviour of the internal combustion engine, like in series powertrains;
- Traction torque provided directly by the Internal Combustion Engine (ICE) and by the electrical drive at the same time, like in parallel powertrains;
- 2 or 4-wheels-drive layout;
- Pure electric operation when driving into restricted zones.

The Simulink® model which allows ADVISOR© to generate energy flows and emissions of the vehicle is presented. Moreover, the paper explains the control strategy and proposes a design approach of a sports-car adopting this powertrain.

INTRODUCTION

The Department of Nuclear Engineering and Energy Conversions at University of Rome I “La Sapienza” has studied in the last years a “family” of power-split drivetrains provided with a planetary gear system: the **SIPRE** - an acronym in the Italian language: **S**istema **I**brido di **P**ropulsione con **R**uotismo **E**picicloidale (Hybrid-Propulsion System with Planetary Gear Set) - family. The third member of this family, the **SIPRE 3** [1], is proposed in this paper.

The planetary gear set is the heart of the SIPRE 3 system. Due to the planetary-gear-set (PGS) unit it is possible to share the thermal-energy driving torque between the electrical generator and the front axle; this is the main original characteristic that distinguishes the SIPRE 3 system from a traditional series-hybrid powertrain. In fact, such a behaviour, warranted by the presence of a PGS, allows the mechanical transmission of part of the ICE torque to the front-driving wheels in order to contribute to the vehicle traction together with the full-electric rear axle.

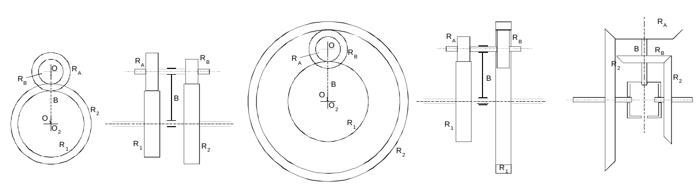


BP: battery pack; EM: electric motor; INV: inverter; MT: internal combustion engine; PGS: planetary gear set; EG: electrical generator; VR: voltage regulator

Figure 1: SIPRE 3 in the 4WD layout

POWERTRAIN DESCRIPTION

In order to explain the PGS kinetic and dynamic behaviour and its influence over the entire system operation in detail, it is necessary to illustrate the layout of the various mechanical linkages. The planetary gear train used can be chosen between three different configurations: the Rolls Royce, the Pickering and the differential one. The choice depends on the desired transmission ratio, with reversal or upward conversion.



Pickering (τ positive) | Rolls-Royce (τ negative) | Differential (τ negative)

Figure 2: PGS layouts

The main parameter that defines the PGS behaviour is its conversion ratio τ, which depends on the number of teeth in the sun and ring gear, and the principal relationship among the speeds of the axes is the *Willis* [2] one:

$$\tau = \frac{\omega_2 - \Omega}{\omega_1 - \Omega} \quad (1)$$

where ω_2, Ω and ω_1 are the rotation speeds, respectively, of the internal ring gear (the transmission shaft $\omega_{driving\_shaft}$), of the planetary carrier (the electrical generator $\omega_{generator}$) and of the sun gear (the internal combustion engine ω_{engine}). In the Eq.1 when $\Omega=0$ is

$$\tau_{|\Omega=0} = \frac{\omega_2}{\omega_1} \quad (2)$$

and τ is positive if the first and last gear rotate in the same direction (upward conversion) and is negative otherwise (reversal conversion).

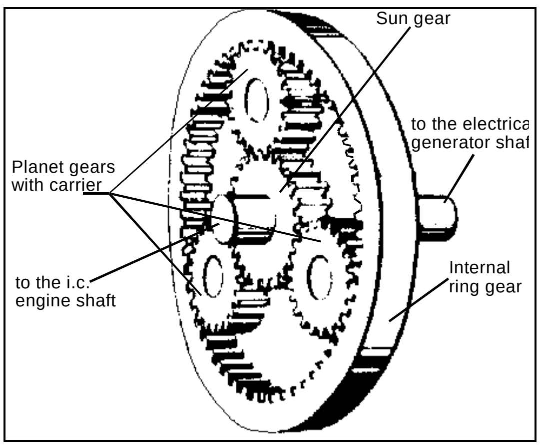


Figure 3: PGS links in the SIPRE 3

From the *Willis formula* the relationship among the various speeds can be conveniently derived as follows

$$\omega_{engine} = \frac{1}{\tau} \cdot \omega_{driving\_shaft} + \frac{\tau - 1}{\tau} \cdot \omega_{generator}$$

$$\omega_{driving\_shaft} = \tau \cdot \omega_{engine} + (1 - \tau) \cdot \omega_{generator} \quad (3)$$

$$\omega_{generator} = \frac{\tau}{\tau - 1} \cdot \omega_{engine} - \frac{1}{\tau - 1} \cdot \omega_{driving\_shaft}$$

From these relations is clear that, unlike a traditional generator set used in series hybrid systems, the electrical generator of SIPRE 3 works at variable speed with a range of speed that is a function of τ. The *kinematics of the PGS thus supports two degrees of freedom*, so it is possible to freely select two different speeds (e.g. the ICE speed and the transmission shaft speed).

Other power-split powertrains with planetary gear systems have been proposed in the technical literature. In the Toyota Prius [3] the ICE is linked to the planetary carrier, the generator to the sun gear and the driving shaft to the ring gear. In the drivetrain proposed by researchers at Warsaw University of Technology [4] the ICE is connected to the sun gear, the generator to the ring gear and the driving shaft to the planetary carrier. The aim is always to select the engine's operating point independently from the vehicle's speed, exploiting the two degrees of freedom the PGS allows.

In order to understand the system behaviour completely, it is important to report the torque distribution over the three PGS axes. In fact in the dynamic field the PGS behaviour is quite different; the main relationship that describes the PGS operation is:

$$T_{driving\_shaft} + T_{generator} + T_{engine} = 0 \quad (4)$$

where the torque notation has the same meaning as the speed notation previously described.

From the Willis formula and the balance of powers in the device

$$T_{driving\_shaft} \cdot \omega_{driving\_shaft} + T_{generator} \cdot \omega_{generator} + T_{engine} \cdot \omega_{engine} = 0 \quad (5)$$

it is possible to come to the following expressions:

$$T_{engine} = \frac{\tau}{1 - \tau} \cdot T_{generator}$$

$$\frac{T_{driving\_shaft}}{T_{engine}} = -\frac{1}{\tau} \quad (6)$$

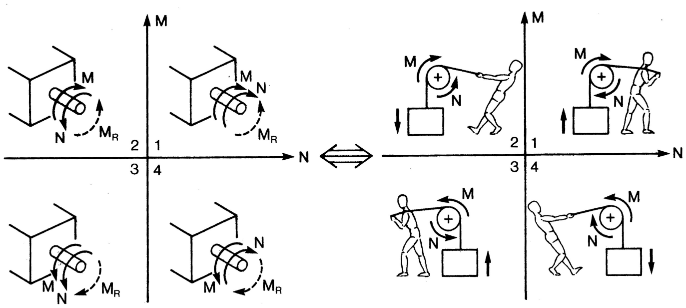
The dynamic problem is *completely settled* when just one of the three axis torques is fixed. For an automotive power unit the main condition can be the *driving torque* $T_{driving\_shaft}$ needed for the traction, so $T_{generator}$ and T_{engine} have to exactly match the Equations 6 and the choice of the value of the transmission ratio τ affects the kinematic and dynamic behaviour of this hybrid traction system.

It is important to note that the vehicle's dynamic behaviour is controlled via the brake and accelerator pedals, acting exclusively on the electrical traction equipment arranged on the rear axle. From this point of view *this vehicle is managed just like a full electric vehicle*. This is possible considering that the hybrid equipment acting on the front wheels, which supplies an additional traction torque to the vehicle and cooperates with the rear electrical traction, is characterised by a fully automatic operation without the need of an external management. Furthermore, the engine needs no starter because the generator can act to crank it. Because there is no reverse gear, vehicle reversing is a motor-only drive mode.

Looking at the relations among the speeds in the PGS, it is interesting to observe that the speed of the generator is zero when

$$\omega_{driving\_shaft}\big|_{\omega_{generator}=0} = \tau \cdot \omega_{engine} \qquad (7)$$

and the two degrees of freedom supported by the kinematics of the PGS allow the generator to operate in two different quadrants, depending on the engine's and vehicle's speeds, in generating (2nd and 4th quadrants) or motoring (1st and 3rd quadrants) mode (Figure 4). The generator/controller allows thus a bi-directional flow of power from the batteries to the PGS unit.



M: traction torque; M_R: resistance torque; N: rotation speed

Figure 4: The four operating quadrants of a motor/generator

The electric motor driving the rear wheels operates in the 1st (traction motor) or 4th (regenerative braking) quadrant. The electrical generator connected to the PGS planetary carrier operates in the 1st/2nd or 3rd/4th quadrants, depending on the sign of τ.

From the previous kinetic and dynamic equations it is easy to calculate the expressions for the power distributions over the PGS axes (Eq. 8):

$$\begin{aligned}
P_{DS} &= T_{driving_shaft} \cdot \omega_{driving_shaft} = \\
&T_{engine} \cdot \omega_{engine} \cdot \frac{T_{driving_shaft}}{T_{engine}} \cdot \frac{\omega_{driving_shaft}}{\omega_{engine}} = \\
&P_0 \cdot \left(-\frac{1}{\tau}\right) \cdot \left(\frac{\omega_{driving_shaft}}{\omega_{engine}}\right) \\
P_{EG} &= T_{generator} \cdot \omega_{generator} = \\
&T_{engine} \cdot \omega_{engine} \cdot \frac{T_{generator}}{T_{engine}} \cdot \frac{\omega_{generator}}{\omega_{engine}} = \\
&P_0 \cdot \left(\frac{1-\tau}{\tau}\right) \cdot \left(\frac{\omega_{generator}}{\omega_{engine}}\right)
\end{aligned} \qquad (8)$$

where P_{DS} is the power that reaches the driving shaft, P_0 is the power supplied by the ICE and P_{EG} is the power absorbed by the electrical generator.

The advantages of the PGS operation, governed by the previous equations, are manifest when one analyses the ratio between the power mechanically transmitted to the front driving wheels and the total power supplied by the ICE; in fact, this parameter provides the exact amount of purely mechanical traction power available to the front vehicle wheels cooperating with the rear electric motor for the vehicle motion. In other words, thanks to the presence of a PGS, the electric motor has to supply a lower power than that necessary in a series hybrid drive train. Moreover, the load on the electrical generator is lower too, with evident benefits for the overall equipment cost.

A power ratio parameter can be mathematically expressed as a function of the PGS conversion ratio τ:

$$\rho = \left|\frac{P_{DS}}{P_0}\right| = \left|-\frac{1}{\tau}\right| \cdot \frac{\omega_{driving\_shaft}}{\omega_{engine}} \qquad (9)$$

Assuming the speed ω_{engine} of the ICE fixed, the ICE power transmitted directly to the driving shaft increases linearly with the vehicle speed, related to $\omega_{driving\_shaft}$. At low speed the traction power is thus mostly supplied by the electrical drive. The PGS acts like a power-split device and a CVT (Continuously Variable Transmission) at the same time.

Another power ratio parameter is

$$\sigma = \left|\frac{P_{EG}}{P_0}\right| = 1 - \left|-\frac{1}{\tau}\right| \cdot \frac{\omega_{driving\_shaft}}{\omega_{engine}} \qquad (10)$$

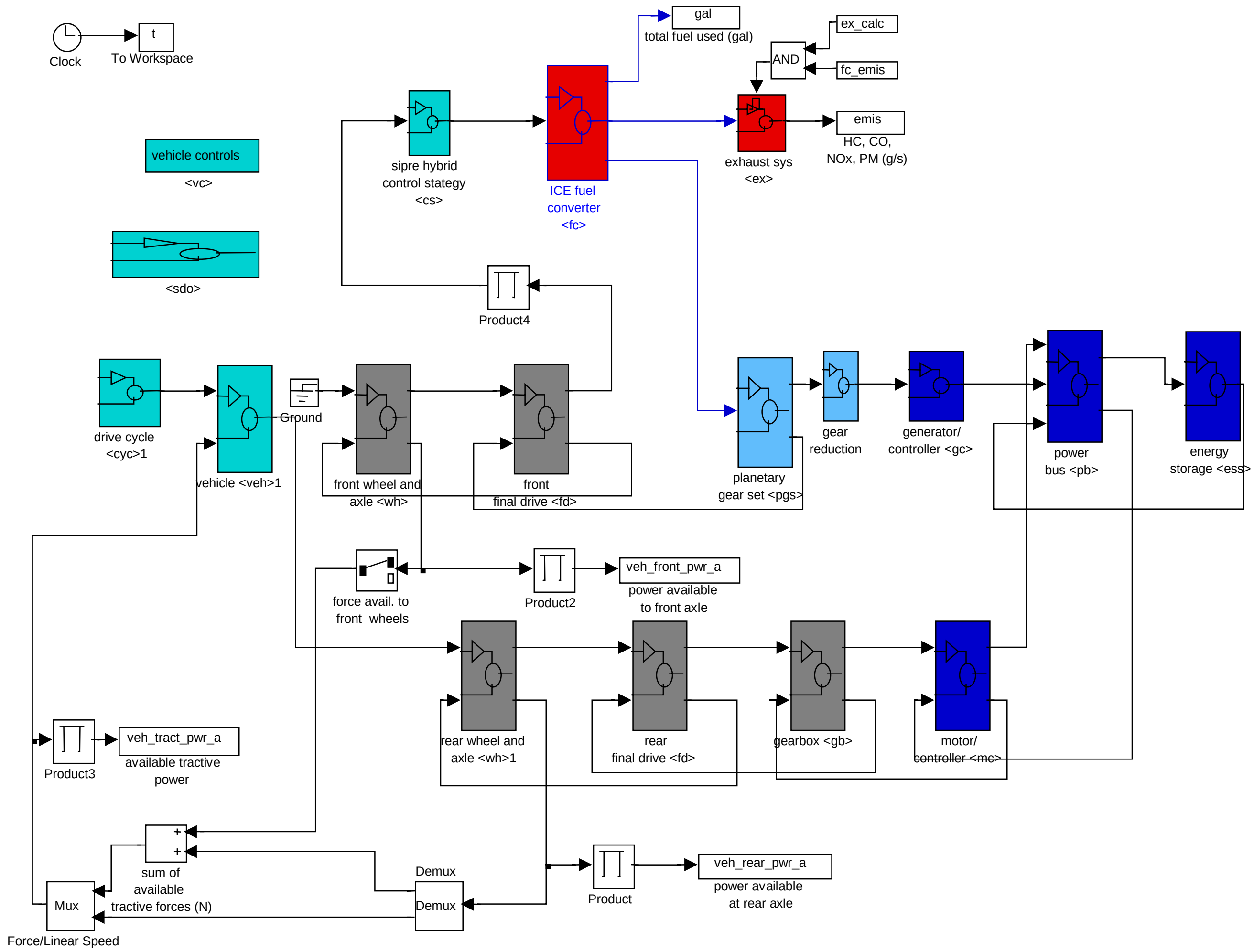


Figure 5: Simulink SIPRE 3 HEV block diagram's top level.

When the vehicle is at rest ($\omega_{driving\_shaft}=0$), σ = 1 in Eq. 10 and the vehicle is a series hybrid because the whole power generated by the ICE flows uniquely to the generator. At higher speeds the powertrain tends to behave like a parallel hybrid and increases the power flowing to the front wheels.

THE SIMULINK MODEL

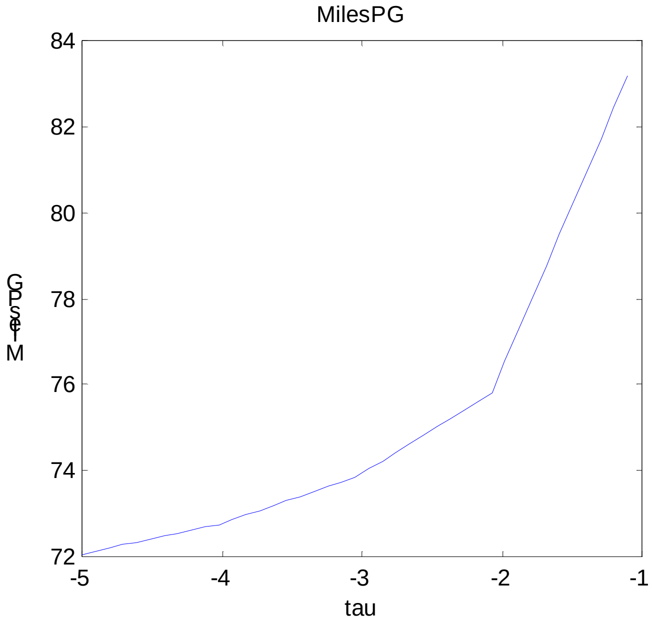
Figure 5 shows the Simulink model which allows ADVISOR to generate energy flows, emissions and consumption of the vehicle. The model describes the front and rear axles of a vehicle provided with a SIPRE 3 drivetrain in the 4WD layout and has been built modifying ADVISOR at the block diagram level, by programming in Simulink. Although ADVISOR relies heavily on a backward-facing approach for its operation [5], it is possible to reconnect ADVISOR block diagrams to model new vehicle types and add new component block diagrams, like the PGS one, which are related to a forward-facing approach. The generator/controller block diagram allows bi-directional power flow, depending on the sign of power and following the convention in Figure 4: negative power (the electrical machine operates as generator) flows from the PGS unit to the batteries; positive power (the electrical machine operates as motor) flows from the batteries to the PGS unit.

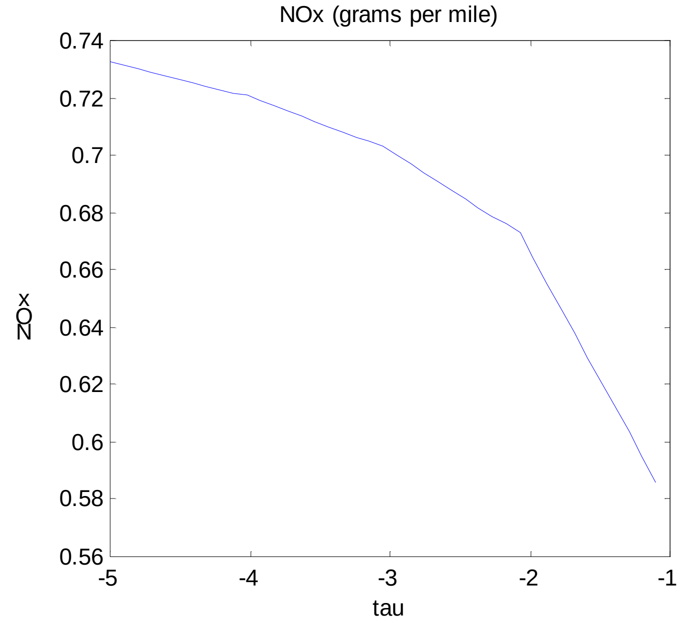
SIMULATION RESULTS

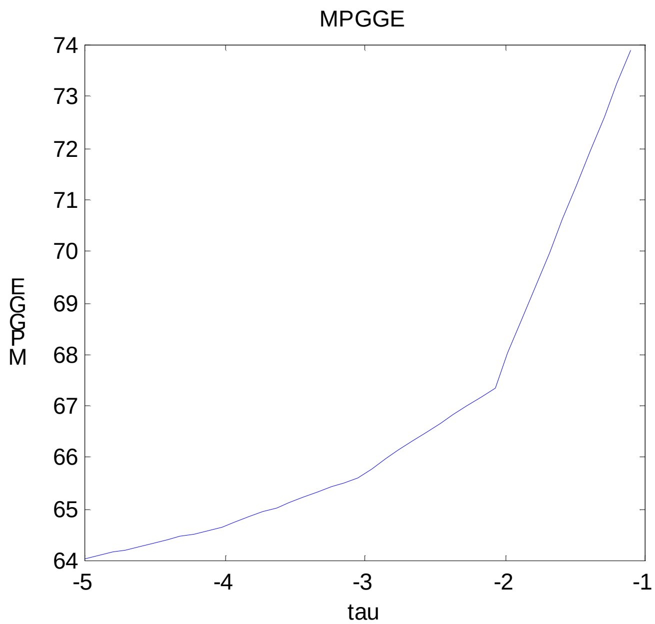
The vehicle used in the simulations was a PNGV-type vehicle. Its components and characteristics included:

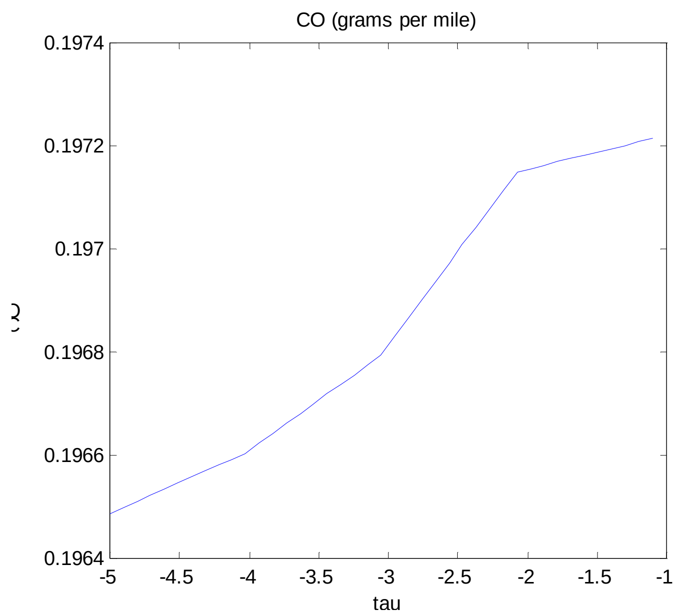
- 28 kW CIDI engine (scaled from Fiat 100 kW 2.4 L Turbo Diesel Common Rail Direct Injection engine)
- Auxilec Thomson 32 kW PM traction drive [6]
- 22 kW generator/controller (scaled from Mannesmann Sachs 63 kW permanent magnet generator/controller [7])
- Twenty 18 Ah lead acid batteries (Optima spiral-wound VRLA, data from NREL tests)
- Mass of 1010 kg.
- Coefficient of drag (C_d) of 0.3

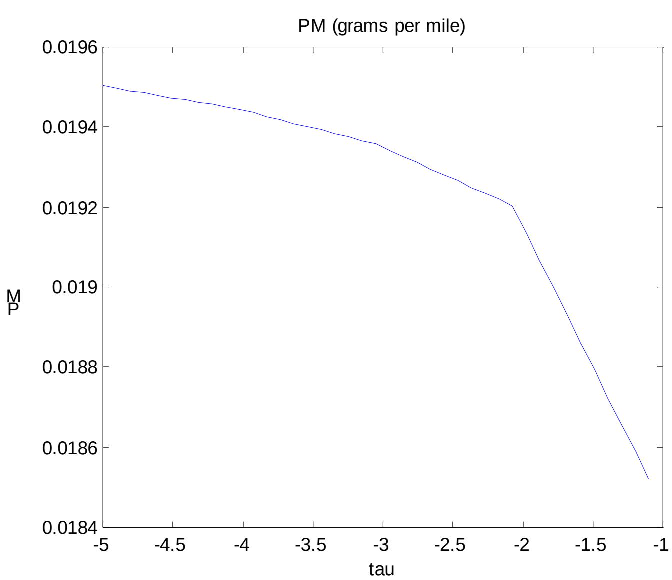
- Frontal area of 2 m^2.

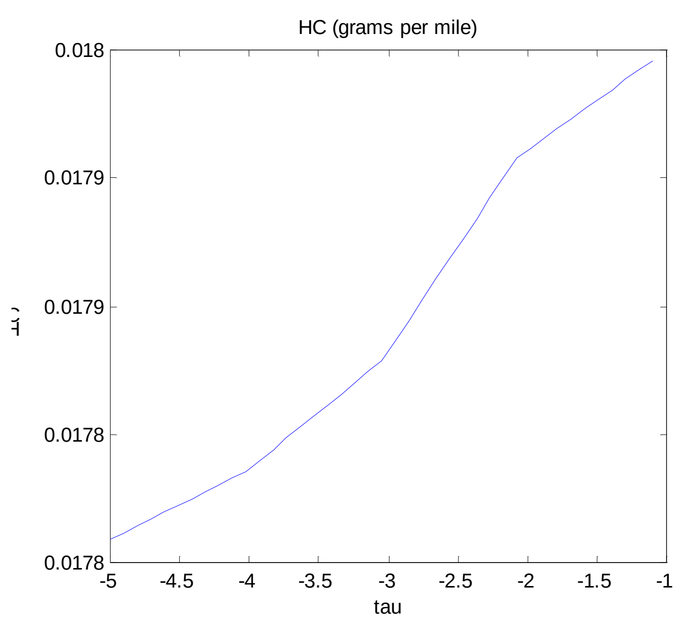


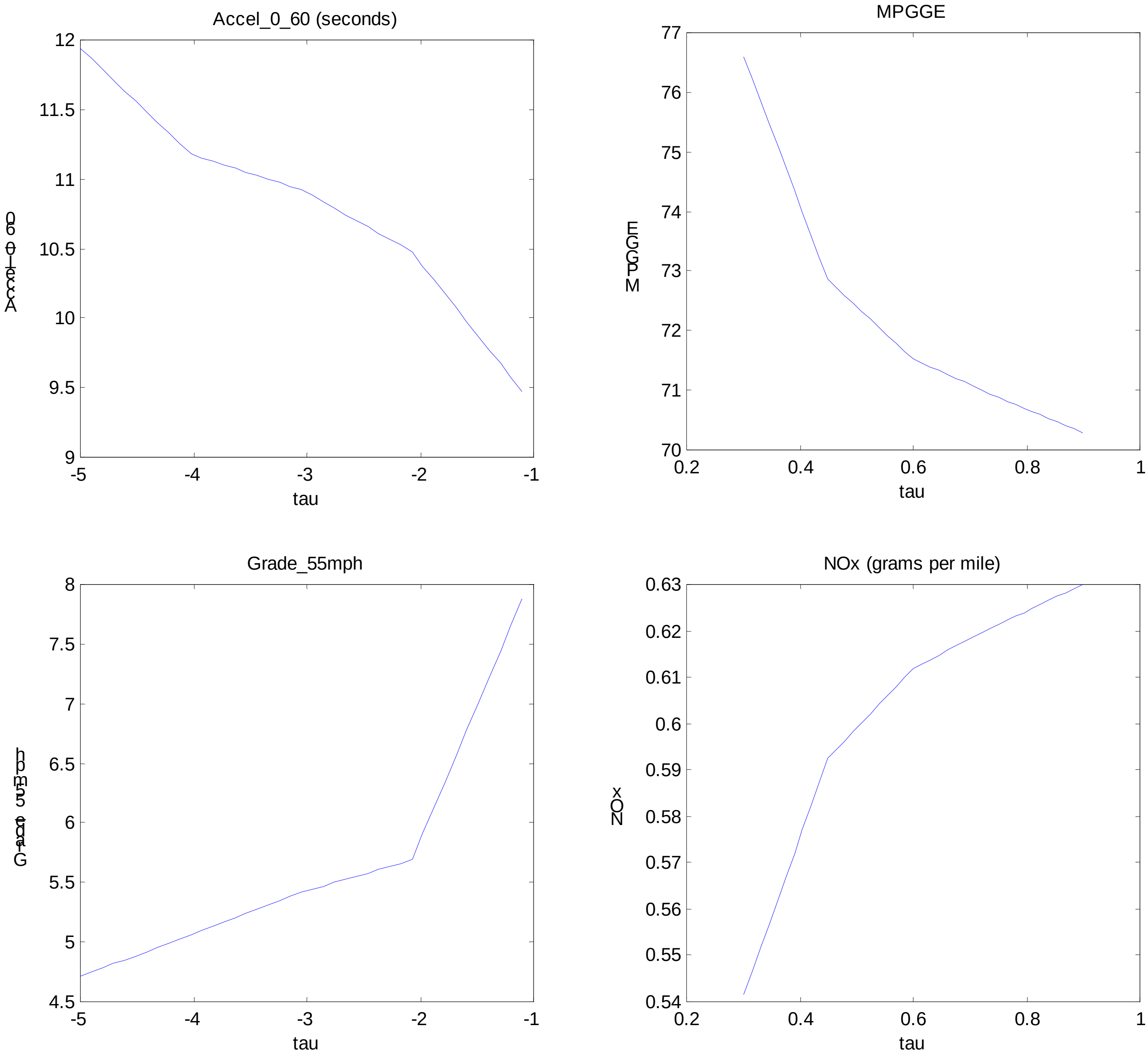


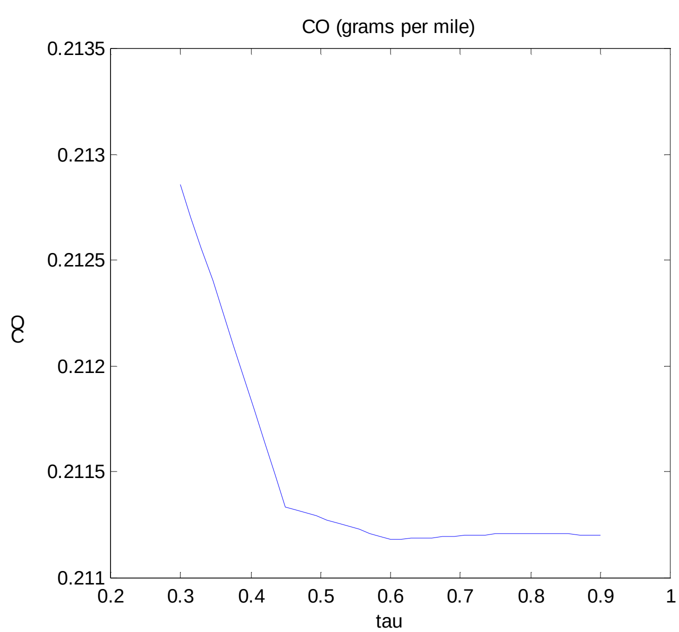






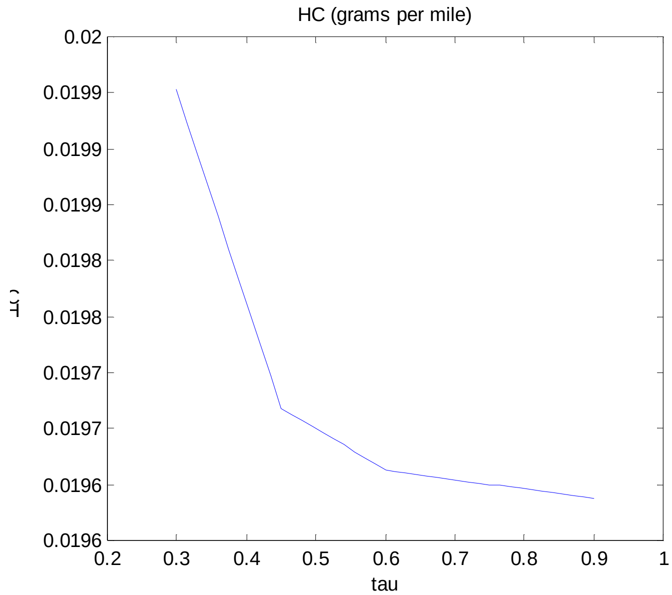


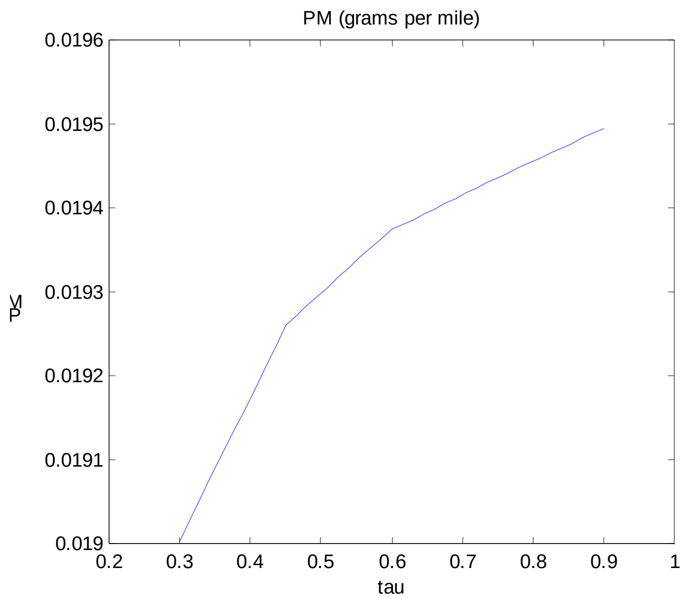




Figg. 6-13: Parametric study. Performances over the US FTP cycle when τ changes between (-5) and (-1.1).

We are testing for the time being a real-time control strategy inspired to a "dynamic" approach recently proposed [8]. In Figg. 6-18 we show the performance results obtained varying the PGS conversion ratio τ in a PNGV-type vehicle controlled with a very simple "static" power follower strategy: the optimum operational design curve in the ICE torque/speed map is calculated by equally weighting the importance of fuel economy and each emission component.





Figg. 14-18: Parametric study. Performances over the US FTP cycle when τ changes between 0.3 and 0.9.

DESIGN APPROACH

In order to give a detailed vision of the hybrid propulsion system here discussed, it is useful to present the design approach for the realization of a working prototype.
The Department of Nuclear Engineering and Energy Conversions of University of Rome “La Sapienza” has recently realized a hybrid sports-car prototype, called Kjara, in collaboration with the National Research Council (CNR); Kjara [9] is a parallel hybrid car and the aim of that project was to develop a laboratory vehicle useful to experiment various hybrid configurations.
The idea is to use the current layout, but adapted to a SIPRE 3 system, maintaining a big part of the system.
Kjara is a roadster and the powertrain characteristics, the arrangement of mechanical components, the architecture of chassis and suspensions are typical of a sports-car (see Figg.19-20).

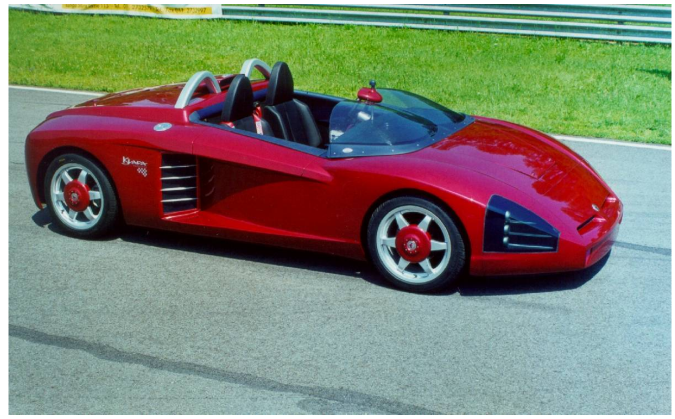
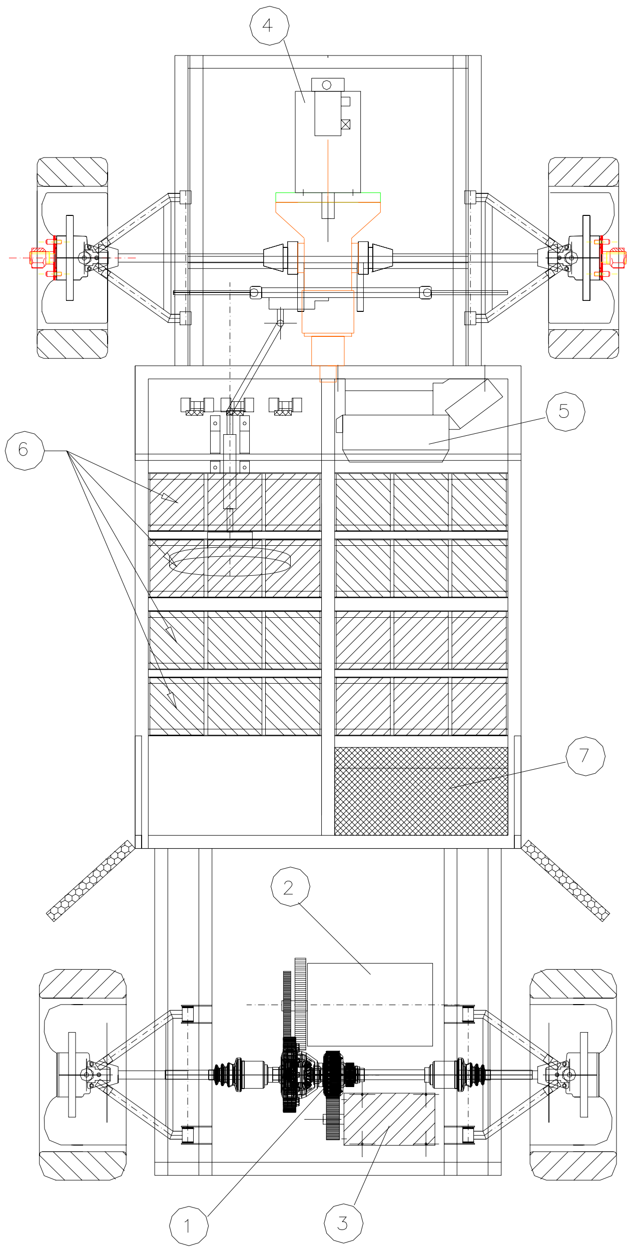


Figure 19: Kjara vehicle prototype.

Figure 20: Kjara vehicle prototype on Lombardore (Turin) track.

The powertrain is composed by a thermal engine and an electric motor: the turbocharged diesel engine is installed in the rear, mid-mounted, transversally. It drives the rear wheels through a conventional 5-speed gearbox. The engine is a 85 kW Fiat 2.5 L turbocharged indirect injection diesel engine. The 18.3 kW electric motor is installed in the front, mid-mounted, longitudinally, and drives the front wheels by means of a transaxle 2-speed gearbox with differential. Its control electronics, manufactured by Celco Profil, is put on the dashboard by the right side of the steering wheel. The lead-acid battery pack is composed of 24 cells, each weighting 9.4 kg (total battery weight is 225.6 kg). Being the cells sealed, they can be put flatwise on one side under the two seats.
With such kind of powertrain, it is easy to design a quick conversion of the system to a SIPRE 3 configuration; in

fact, with the simple and quick substitution of the Diesel engine currently mounted on Kjara prototype with the planetary gear set group (see fig.21: PGS + ICE + EG + final drive, but on rear wheels), it is possible to switch to a SIPRE 3 propulsion system.

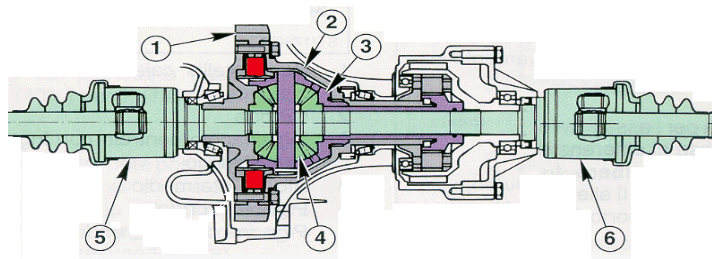


1, Planetary gear set with differential; 2, Diesel engine; 3, Electrical generator; 4, electrical motor; 5, electronics; 6, battery pack; 7, Diesel fuel tank.

Figure 21: Layout solution for the implementation of SIPRE 3 on Kjara vehicle prototype.

In figure 21 it is possible to see the design approach here proposed.
Maintaining the electric motor, its electronics and the battery pack, and mounting the PGS set with a little diesel engine and the electrical generator, it is possible in few hours of mechanical work to pass from the original parallel configuration to the SIPRE 3 system.

The design approach here proposed can be realized in short time and at an affordable cost (for a University it is very important !) using an existent PGS. The drawing in Fig. 22 represents in fact a feasible solution that uses a PGS with incorporated automotive differential, all derived from 1992 4x4 FORD ESCORT. This component, light and with a good transmission ratio, matches well the SIPRE 3 demands, and benefits obviously of a good reliability and quality. The adoption of this component is a very good opportunity for a prototype, cutting consistently the design and construction costs.



1, Sun gear carrier; 2, External case; 3, 4, final drive with differential; 5,6, axle shaft joints.

Figure 22: FORD PGS internal layout.

The FORD PGS internal layout, depicted in Fig.22, is provided with the sun gear jointed to the transmission shaft and to the differential, leaving for ICE and EG the internal ring gear and the planet gears carrier.
Thus, considering that the SIPRE 3 layout can be realized in any different combination of components which can be freely mounted on the three PGS axes, as previously explained, the solution given in Fig.22 is characterized by the Diesel engine joined to the internal ring gear and the electrical generator joined to the planetary gear carrier.
In this way a full SIPRE 3 equipment can be realized, in the four wheel drive configuration, needing only few mechanical modifications and starting from an easy available automotive component acting as PGS. So, using an existing hybrid car prototype it is possible to test on track all the simulation results ADVISOR can generate. The aim is to put on track and test the SIPRE 3 vehicle by the end of 2000.

CONCLUSION

A power-split hybrid drivetrain is analyzed in this paper. Its main characteristics are:

- vehicle reversing is a motor-only drive mode
- the generator cranks the engine
- the vehicle operates electrically when driving into restricted zones

- 2WD and 4WD layouts are available
- the generator can spin backwards

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CONTACT

Marco Santoro holds a "laurea" degree in electronic engineering from University of Rome I "La Sapienza". He is currently doctorate student at University of Rome I "La Sapienza" and guest student at Dresden University of Technology, where he is preparing his thesis about the energy conversion efficiency into hybrid electric vehicles. For further information on this paper, he may be contacted at marco@leonemar.din.uniroma1.it.

Leone Martellucci holds a "laurea" degree in mechanical engineering from University of Rome I "La Sapienza" and a doctorate degree from this same University. He is currently researcher at University of Rome I "La Sapienza", Department of Nuclear Engineering and Energy Conversions. For further information on this paper, he may be contacted at leone@leonemar.din.uniroma1.it.

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DEFINITIONS, ACRONYMS, ABBREVIATIONS

ADVISOR:

ADvanced VehIcle SimulatOR

CIDI:

Compression Ignition Direct Injection

CNR:

Consiglio Nazionale delle Ricerche (Italian National Research Council)

EG:

Electrical Generator

4WD:

Four Wheel Drive

FTP:

US Federal Test Procedure, "city" cycle for city-highway tests

HEV:

Hybrid Electric Vehicle

ICE:

Internal Combustion Engine

MURST:

Ministero dell'Università e della Ricerca Scientifica e Tecnologica (Italian Ministry of Universities and Scientific and Technological Research)

PGS:

Planetary Gear Set

PNGV:

US Partnership for a New Generation of Vehicles

SIPRE:

Sistema Ibrido di Propulsione con Ruotismo Epicicloidale (Hybrid-Propulsion System with Planetary Gear Set

2WD:

Two Wheel Drive

VRLA:

Valve-Regulated Lead Acid