Volume 38, Number 4, 2012.

Mobility & Vehicle Mechanics

International Journal for Vehicle Mechanics, Engines and Transportation Systems

ISSN 1450 - 5304

UDC 621 + 629(05)=802.0

UNIVERSITY OF KRAGUJEVAC, FACULTY OF ENGINEERING

SERBIAN SOCIETY OF AUTOMOTIVE ENGINEERS

M V M Mobility Vehicle Mechanics

*Editors: Prof. dr **Jovanka Lukić**; Prof. dr **Čedomir Duboka***

MVM *Editorial Board*
University of Kragujevac
Faculty of Engineering
Sestre Janjić 6, 34000 Kragujevac, Serbia
Tel.: +381/34/335990; Fax: + 381/34/333192

For Publisher: Prof. dr Miroslav Babić, dean, University of Kragujevac, Faculty of Engineering

Publishing of this Journal is financially supported from:
Ministry of Education, Science and Technological Development, Republic Serbia

NOTIFICATION TO AUTHORS

The Journal MVM publishes original papers which have not been previously published in other journals. This is responsibility of the author. The authors agree that the copyright for their article is transferred to the publisher when the article is accepted for publication.

The language of the Journal is English.

Journal ***Mobility & Vehicles Mechanics*** is at the SSCI list.

All submitted manuscripts will be reviewed. Entire correspondence will be performed with the first-named author.

Authors will be notified of acceptance of their manuscripts, if their manuscripts are adopted.

INSTRUCTIONS TO AUTHORS AS REGARDS THE TECHNICAL ARRANGEMENTS OF MANUSCRIPTS:

Abstract is a separate Word document, "*First author family name_ABSTRACT.doc*". Native authors should write the abstract in both languages (Serbian and English). The abstracts of foreign authors will be translated in Serbian.

This document should include the following: 1) author's name, affiliation and title, the first named author's address and e-mail – for correspondence, 2) working title of the paper, 3) abstract containing no more then 100 words, 4) abstract containing no more than 5 key words.

The manuscript is the separate file, „*First author family name_Paper.doc*" which includes appendices and figures involved within the text. At the end of the paper, a reference list and eventual acknowledgements should be given. References to published literature should be quoted in the text brackets and grouped together at the end of the paper in numerical order.

Paper size: Max 16 pages of B5 format, excluding abstract
Text processor: Microsoft Word
Margins: left/right: mirror margin, inside: 2.5 cm, outside: 2 cm, top: 2.5 cm, bottom: 2 cm
Font: Times New Roman, 10 pt
Paper title: Uppercase, bold, 11 pt
Chapter title: Uppercase, bold, 10 pt
Subchapter title: Lowercase, bold, 10 pt
Table and chart width: max 125 mm
Figure and table title: Figure _ (Table _): Times New Roman, italic 10 pt

Manuscript submission: application should be sent to the following e-mail:

mvm@kg.ac.rs ; lukicj@kg.ac.rs
or posted to address of the Journal:
University of Kragujevac – Faculty of Engineering
International Journal M V M
Sestre Janjić 6, 34000 Kragujevac, Serbia

The Journal editorial board will send to the first-named author a copy of the Journal offprint.

OBAVEŠTENJE AUTORIMA

Časopis MVM objavljuje orginalne radove koji nisu prethodno objavljivani u drugim časopisima, što je odgovornost autora. Za rad koji je prihvaćen za štampu, prava umnožavanja pripadaju izdavaču.

Časopis se izdaje na engleskom jeziku.

Časopis ***Mobility & Vehicles Mechanics*** se nalazi na SSCI listi.

Svi prispeli radovi se recenziraju. Sva komunikacija se obavlja sa prvim autorom.

UPUTSTVO AUTORIMA ZA TEHNIČKU PRIPREMU RADOVA

Rezime je poseban Word dokument, "*First author family name_ABSTRACT.doc*". Za domaće autore je dvojezičan (srpski i engleski). Inostranim autorima rezime se prevodi na srpski jezik. Ovaj dokument treba da sadrži: 1) ime autora, zanimanje i zvanje, adresu prvog autora preko koje se obavlja sva potrebna korespondencija; 2) naslov rada; 3) kratak sažetak, do 100 reči, 4) do 5 ključnih reči.

Rad je poseban fajl, „*First author family name_Paper.doc*" koji sadrži priloge i slike uključene u tekst. Na kraju rada nalazi se spisak literature i eventualno zahvalnost. Numeraciju korišćenih referenci treba navesti u srednjim zagradama i grupisati ih na kraju rada po rastućem redosledu.

Dužina rada: Najviše 16 stranica B5 formata, ne uključujući rezime
Tekst procesor: Microsoft Word
Margine: levo/desno: mirror margine; unurašnja: 2.5 cm; spoljna: 2 cm, gore: 2.5 cm, dole: 2 cm
Font: Times New Roman, 10 pt
Naslov rada: Velika slova, bold, 11 pt
Naslov poglavlja: Velika slova, bold, 10 pt
Naslov potpoglavlja: Mala slova, bold, 10 pt
Širina tabela,dijagrama: max 125 mm
Nazivi slika, tabela: Figure __ (Table _): Times New Roman, italic 10 pt

Dostavljanje rada elektronski na E-mail: **mvm@kg.ac.rs ; lukicj@kg.ac.rs**

ili poštom na adresu Časopisa
Redakcija časopisa M V M
Fakultet inženjerskih nauka
Sestre Janjić 6, 34000 Kragujevac, Srbija

Po objavljivanju rada, Redakcija časopisa šalje prvom autoru jedan primerak časopisa.

Mobility & **V**ehicle **M**echanics

Motorna **V**ozila i **M**otori

Volume 38
Number 4
2012.

Mobility & **V**ehicle **M**echanics

Volume 38
Number 4
2012.

Motorna **V**ozila i **M**otori

[1]RECENT DEVELOPMENT IN CAR BODY LIGHTWEIGHT DESIGN - A CONTRIBUTION TOWARD GREENER ENVIRONMENT

Giovanni Belingardi, PhD, Professor, *Jovan Obradović*, PhD

UDC: 629.02

Summary

After a period of progressive increase of the vehicle mass, car manufacturer are asked to change the trend and make sound efforts toward lightweight. This is due to the need of decrease the fuel consumption (that is nearly proportional to the vehicle mass) but also to the decrease the CO2 production (that is considered as one of the main responsible of the dramatic climate change). One of the considered strategy toward lightweight is the substitution of the material used for manufacturing the different parts of the car body. Together with the use of new developed steels, generally known as HSS, that have been recently developed with very high strength and good performance in formability and weldability, some other metallic materials have been considered such as aluminium and magnesium. Recently composite material solutions have gained a lot of attention due to the very interesting characteristic of this class of materials. The paper points out all the aspects that have to be taken in evidence when developing a new material solution from the material production to the recycling at the end-of-life.

If all these aspects are not dealt with and satisfactory answers are obtained (compatible with production plant technologies and costs) then the adoption of the new developed material will not be possible, even if in this way one has to loose some advantages.

Key words: lightweight design, car body, climate change, HS steel, light alloys, composite materials

NAJNOVIJA DOSTIGNUĆA U RAZVOJU LAKE ŠKOLJKE AUTOMOBILA - DOPRINOS ZELENIJEM OKRUŽENJU

UDC: 629.02

Rezime

Posle perioda naglog porasta mase vozila, proizvođači vozila su suočeni sa potrebom da menjaju trend i da načine značajan pomak u smanjenju mase vozila. Ovo je nastalo kao potreba za smanjenjem potrošnje goriva (skoro poroporcionalna masi vozila) al i smanjenju emisije CO_2 (smatra se najodogovornijim za dramatične klimatske promene). Jedna od razmotrenih strategija u cilju smanjenja težine je zamena materijala koji se koriste za proizvodnju različitih delova car body. Zajedno sa korišćenjem novo razvijenih čelika i dobrih karakteristika u pogledu deformabilnosti i zavarljivosti razmetreni su neki metalni materijali kao što su aluminijum i magnezijum. Novija rešenja kao što su kompozitni materijali privukla su veliku pažnju zbog veoma interesantnih karakteristika ove klase

[1] *Received August, 2012, accepted October 2012.*

materijala. Ovaj rad ističe sve aspekte koje treba uzeti u obzir kada se razvija novo rešenje materijala is sa aspekta proizvodnje i sa aspekta reciklaže na kraju životnog veka.

Ako svi askekti sa kojima smo se suočili ne daju zadovoljavajuće rezultate (compatible with production plant technologies and costs) tada usvajanje novorazvijenih metrijala neće biti moguće, čak i da se na ovaj način izgube neke prednosti.

Ključne reči: projektovanje lakih konstrukcija, školjka, klimatske promene, čelici povišene jačine, lake legure, kompozitni materijali

RECENT DEVELOPMENT IN CAR BODY LIGHTWEIGHT DESIGN - A CONTRIBUTION TOWARD GREENER ENVIRONMENT

Giovanni Belingardi[1]*, PhD professor,* ***Jovan Obradović****, PhD*

UDC:629.02

1. INTRODUCTION

The design of modern cars must meet many requirements in terms of transport performance, comfort, active and passive safety, costs, reliability, environmental impact and end-f-life destination. To satisfy these goals and match legislation prescriptions and costumer expectations multidisciplinary approach to the design is required. These many aspects of car performance intersect each other when performing the various tasks of design.

Nowadays, automotive industry needs to face continuous demands concerning the reduction of fuel consumption and exhaust emissions. In the last years, vehicle weight has increased in order to guarantee much higher vehicle performance, passenger comfort, safety and emission standards but, on the other hand, this has penalised the fuel consumption and, as a consequence, the CO_2 emissions. Since new generation cars need to ensure lower emission levels, particularly for what concern the Greenhouse Gas (GHG) production that are the main responsible of the climate changes and the progressive world heating, according to EU and government legislations, lightweight design can be an important contribution to achieve this target.

Vehicles are one of the most important sources of pollution for the planet and are one of the important source in the production of carbon dioxide. In perfect combustion, the chemical reaction between the hydrocarbons and the air only produces carbon dioxide (CO_2), and water steam (H_2O). Unfortunately, a perfect combustion does not occur, so in addition to carbon dioxide and water steam, some other chemical products are created. In particular, carbon monoxide (CO), nitrogen oxides (NO_X) and unburned hydrocarbons (HC) are produced. The additives and the impurities in the fuel also create some minute quantities of other pollutants such as lead oxides, lead halogenides and sulphur dioxide. Moreover, in the exhaust gases made by diesel engines, there is also particulate matter (PM) and an appreciable quantity of soot. The production of these gases strictly depends from the air fuel mixture ratio used for the combustion [1].

When controlling combustion parameters and using refined fuels and particular filters, the limitation of pollution emissions is possible. On the contrary, the carbon dioxide production is directly connected to the fuel consumption of the vehicle because it is a product of combustion chemical reaction. Therefore, the only way to limit the CO_2 production is to decrease the fuel consumption. Carbon dioxide is considered responsible for the climatic change and the global warming problems of the planet because it is a green house gas. Even little reductions of the fuel consumption of each car would result in an overall big reduction of CO_2 emissions.

A weight reduction of 100 kg including secondary effects, leads to a reduction in fuel consumption of approximately from 0.3 to 0.5 litres per 100 km. This goes along with a reduction of CO_2 emission of from 8 to 11 grams per kilometre [2]. If all cars in Europe

[1] Giovanni Belingardi, Dept. of Mechanical and Aerospace Engineering, Politecnico di Torino, Italy, giovanni.belingardi@polito.it; Visiting Professor of the University of Kragujevac, Faculty of Engineering

(210 million vehicles) would save a quarter litres per 100 kilometres, the CO_2 emissions would be reduced by 17,344 million tons each year [3].

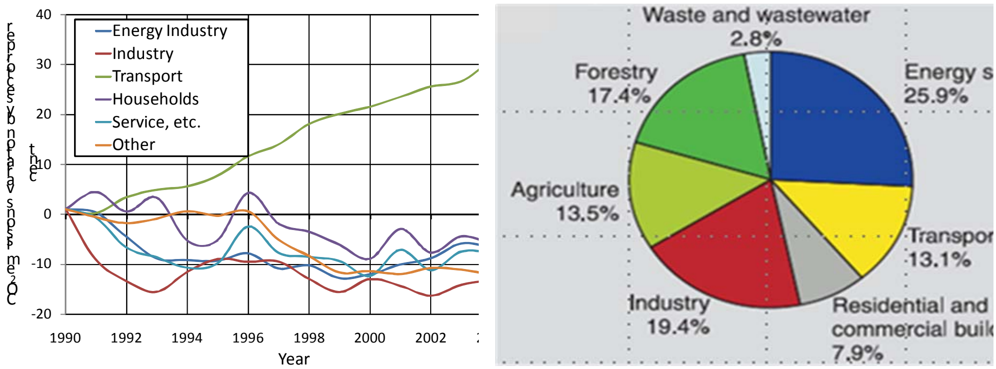


***Figure 1**: Recent historical trend in the CO_2 emission for different emission sources (left), percentage weight of the different CO_2 emission sources (right).*

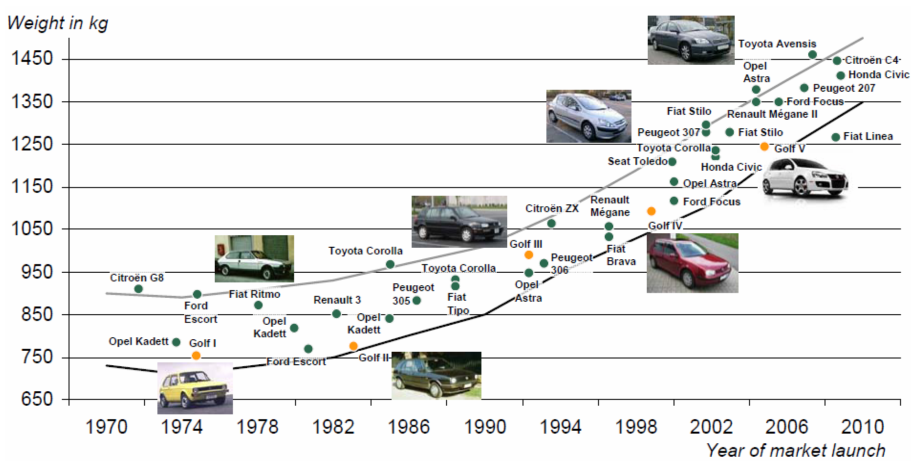


***Figure 2**: Comparison of curb weights of common B-segment vehicles over the model years [4]*

In the last decades of the previous century, the rate of weight increase was steeper. The motivations of this high gradient needs to be searched on larger vehicle and engine dimensions as well as on stronger performance requirements. At the same time, even enhanced vehicle features are responsible for the weight increase. In particular, safety and pollution control subsystems as well as comfort-related subsystems and equipment provide an important contribution. Also, the rate of weight increase has reached the maximum value. This aspect is consequence of concerns about environmental pollution and, at the same time, it is due to the introduction in the automotive industry of more efficient materials and technologies as well as innovative design concepts.

The Figure 2 shows the tendency of weight increase for B-segment vehicles over the model years. In 40 years, weight increase from the Golf I to the Toyota Avensis is about 700 kg.

The vehicle mass (m_F) is the dominant driving-resistance since it is represented in three of four parts of the power demand equation (Eq. 1.1) and thus has direct influence on the fuel consumption. The benefits of weight reduction in this regard are made clear by the power demand of a vehicle:

$$\begin{aligned} P &= P_{ac} + P_{cl} + P_{roll} + P_{aer} = \\ &(e_i + m_F + m_{Zu}) \cdot a \cdot v + (m_F + m_{Zu}) \cdot g \cdot \sin(\alpha_{St}) \cdot v + \\ &(m_F + m_{Zu}) \cdot g \cdot \cos(\alpha_{St}) \cdot f_R \cdot v + 0,5 \cdot \rho_L \cdot c_w \cdot A \cdot (v - v_w)^2 \cdot v \end{aligned} \quad (1)$$

where:
P_{ac} - acceleration-resistance
P_{cl} - climbing-resistance
P_{roll} - roll-resistance
P_{aer} - aerodynamic-resistance
m_F - empty vehicle weight
m_{Zu} - payload
g - gravitational acceleration
α_{St} - angle of ascent
f_R - rolling-resistance coefficient
v - vehicle speed
e_i - inertia coefficient of the *i*-th gear
a - longitudinal vehicle acceleration
ρ_L - density of the ambient air
c_w - drag coefficient
A - cross-sectional area of the vehicle
v_w - wind speed in driving direction

Except for the drag resistance, which can only be reduced by decreasing the drag coefficient or by the reduction of the cross sectional area of the vehicle, every addend of the formula above contains the mass of the full vehicle. In city traffic, the drag resistance is almost insignificant and the acceleration phases cause up to 40 % of the total fuel consumption.

The reduction of fuel consumption and the consequent reduction of CO_2 emissions can be achieved through driver training and vehicle technologies. Within the vehicle technologies lightweight design plays an important role. This is just one approach to lower fuel consumption. Improvements achieved by lightening of the structures should be constantly compared with those achieved through other engineering approaches, such as developments in aerodynamics or in engine thermodynamics.

Furthermore, strategies in automotive vehicle design for the reduction of fuel consumption are particularly focused on body structures rather than power train efficiency or electrical power consumption. On the other hand, specific studies demonstrated that improvements on power train efficiency can significantly limit the fuel consumption. Therefore, gains in terms of CO_2 emissions can be achieved acting in particular on lightweight design and power train efficiency, in order to pursue the objective value of about 4,7 l/100km in fuel consumption before 2012 [5].

Generally, a decrease in vehicle weights can be obtained basically by constructive measures and by the use of alternative materials with better weight-specific properties than conventional mild steel. These two forms of lightweight design cannot be strictly separated.

Change to the component material usually requires changes to the design of the component, too.

2. TRENDS OF LIGHTWEIGHT MATERIALS FOR CAR BODY CONSTRUCTIONS

Material selection

The use of unconventional materials offers a vast number of alternatives and in the same time proposes big challenge to designers, which, to meet the various, sometimes contradictory, requirements and goals, must face puzzling problems: new manufacturing technologies for parts production, different assembly methodologies, mounting techniques, compatibility issues, recycling deeds, always paying the attention to a problem of paramount importance: cost. Material costs, production costs, time-to-market costs and whatever operation costs affect the design and production of every single vehicle.

Furthermore, material selection has to deal with many different considerations both technical (including structural behaviour, manufacturing process and environmental sustainability) and non technical, mainly related to costs. A simple evaluation of the advantages of substituting the universally adopted deep drawing mild steel with other materials can be performed by using simple engineering formulas for structural parts behaviour.

There are many criteria with which it is possible to rank the material for a specific application. In fact, the selection process of candidate materials asks for the in depth knowledge of their chemical, physical and mechanical characteristics. The simplest method is to look at tables (from the technical literature, internal reports, and specific test results) summarizing the material properties (for example: specific weight, elastic modulus, strength, etc.).

This task is very distressing and awkward. The same material properties can be put together in bar charts, eventually with their scattering. This method can result unsatisfactory, since the designer would observe only to a few properties at a time. A more efficient practice is to plot one property versus another competing one (for instance young modulus versus density, as on the left image of Figure 3 [6]). Many materials of a single class or from several different classes can be put together to compare each other. This technique, although not yet completely satisfactory, because we are dealing with a multidimensional domain but we are obliged to restrict its representation to only two dimensions, will at least put into evidence the relative influence of most important parameters. Moreover, it will make clear which materials are most suitable to get a specific objective.

The most appropriate technique for material selection is the use of three-dimensional diagrams which are allowing the multi-property domain evaluation, as it is presented on the right image of Figure 3. We can see properties relevant in the perspective of lightweight design: density, E-modulus and tensile strength of different reinforcing fibres compared to steel, aluminium and titanium [7].

The selection of an appropriate material in the multi material design structure is overall the outcome of the best possible environment and legislation conditions, not forgetting the costs. Multi material design can be seen as a driver for affordable lightweight design in body construction. This problem has been widely treated in a number of the EU-Projects, we would like to mention one of these projects: Super Light Car (SLC) with the example of a vehicle of the A-class segment.

The aim of the SLC-Project was the development of lightweight body structures in multi material design, which are 30% lighter than the actual reference vehicle that is based on a extensive steel construction. This aim was only achieved with the exact evaluation of different material combinations, the development of new designs, simulations methods and joining techniques. In order to forecast reliability, the evaluation of costs and the sustainability of innovative multi material design, appropriate methods for lightweight vehicles have been used.

The analysis within the multi disciplinary SLC-project deals with the manufacturing of new solutions based on hybrid, multi-material compounds. The design of these innovative solutions asks also for innovative joining technologies (particularly in the case of multi material design) and innovative manufacturing process. Within the multi material design concepts, functionality has the highest priority. The material choice is assessed discretely for several components and implied the overall function [5].

In Figure 4, it is possible to see paths for car body concepts, defined by Audi [8]. The steel unibody is the reference design solution, which serves as the base for later body-in-white development. Firstly, the traditional steel construction includes some production technologies as roll forming and thin casting technology, which lead to steel spaceframe and stainless steel spaceframe. The aluminium construction is the second path which was used for the production of aluminium shell construction and aluminium spaceframe (the typical example is Audi R8, completely made of aluminium with small use of carbon fibre reinforcements). The third path for car body concept is the plastic material construction, mainly described by use of fibre reinforced plastics which leads to the so-called body-in-black. The mixed construction is considering the multi-material design. First structures were focused on combination of steel and aluminium. At first, it was produced the lightweight metal front end with the use of other lightweight materials as magnesium die-casting parts and adhesives. Finally, current mixed construction is defined as hybrid structure which includes mostly steel, aluminium, magnesium and fibre reinforced plastics.

Lightweight materials

The basic prerequisite for all materials in the production of car bodies is of course their availability in the first place. Aspects such as globalisation and the production of one and the same car model on several continents calls for worldwide availability of materials [9]. After the fulfilment of this fundamental prerequisite the most important criteria for the application of any particular material are strength, stiffness and the material costs.

Material-related lightweight construction involves replacing the original material by a different material with better weight-specific properties. Lightweight construction can be achieved with many different materials, such as high strength steels, aluminium, magnesium of reinforced polymers. High-performance fibre-reinforced polymers offer the biggest potential for saving weight but are also very expensive, both as a material and in terms of manufacturing.

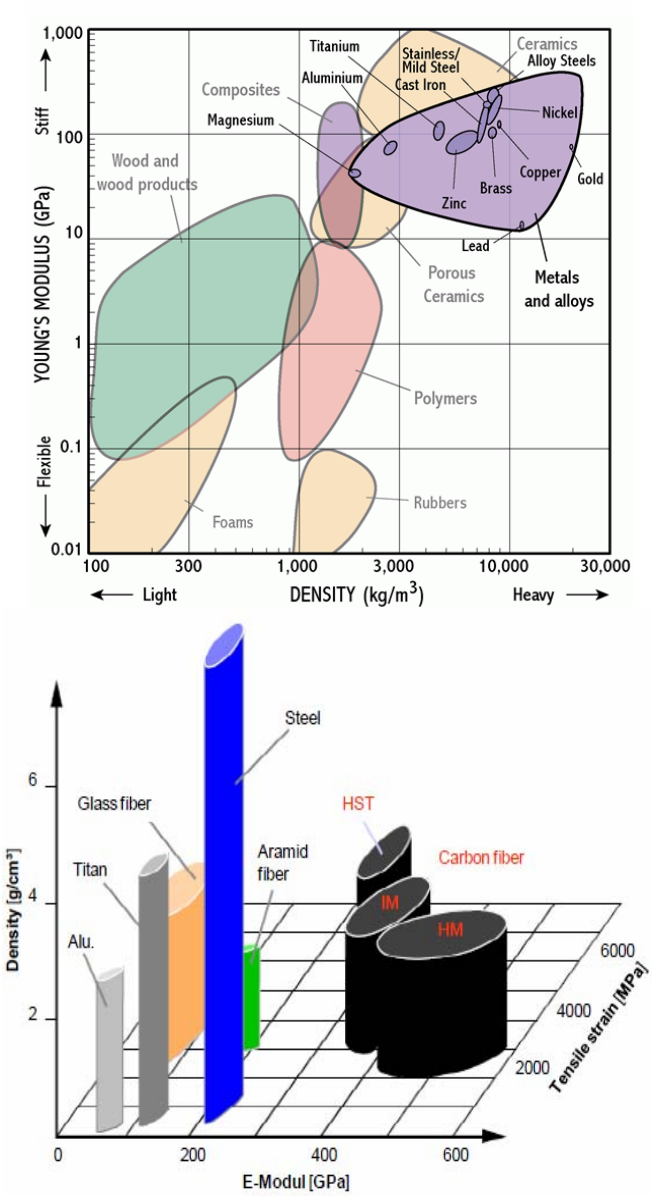


Figure 3: *Lightweight material characteristics*

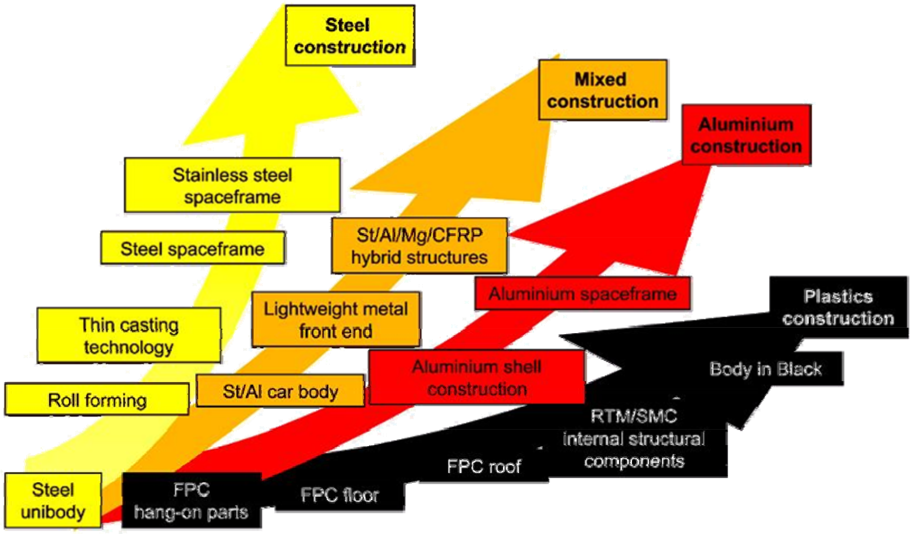


Figure 4: *Paths for car body concepts [8]*

a) High strength steels

For the most car body, steel continues to play main role. However, there is a clear trend in the utilization on a larger basis of high strength steels, especially of the type of dual-phase bake-hardening steels for the structural parts and of ultra high strength steels for safety components, such as anti-intrusion bar for side impacts.

High-strength steels (above 180 MPa yield strength and up to 400-500 MPa) will get ever increasing importance in all structural parts (frame, pillars, etc.) whereas ultra high-strength steels are used for passive safety components (especially side impact bars). The problem with high-strength steels is that higher loads and energy is required for manufacturing, with important consequences on costs. Dual-phase bake hardening steels are a very interesting solution since these steels have yield strength comparable to most common deep-drawing mild steels (for example DC04 and DC06) at their bought, therefore their use does not affect the part workability. But their strength can be dramatically increased by means of a thermal cycle (at about 200^{o}C) so they can reach, according to the different grades, 600-800 MPa yield strength. Usually, the required thermal cycle is performed in the oven after painting, at no additional cost.

Although the steels have become more specialized in their application, the material cost has remained competitive when compared to other materials such as aluminium and magnesium. Recent studies by ThyssenKrupp have indicated that it is possible to save approximately 24% of BIW mass by using high strength steels and also by redesigning the body structure to take advantage of material and mechanical properties [10].

Recently developed steels (Figure 5) have made possible an increase in both tensile strength and failure strain, so that even higher requirements regarding the combination of high strength and good formability can be met.

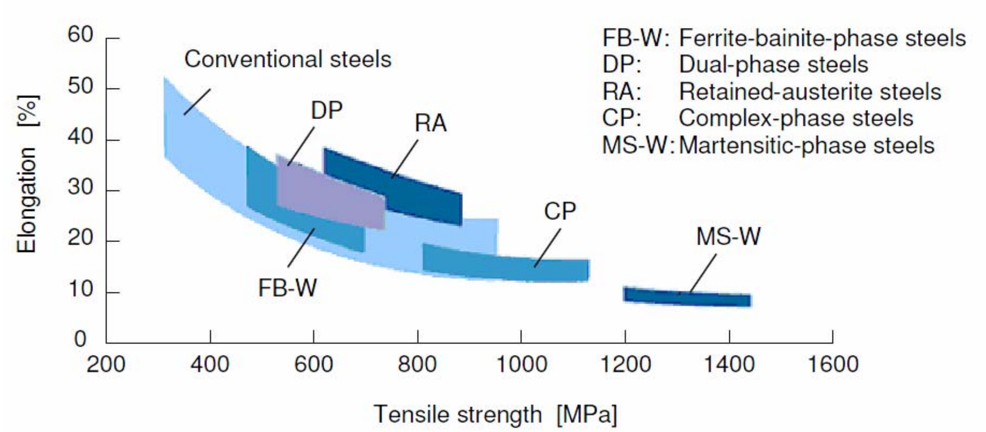


***Figure 5**: Application of new steels [11]*

High-strength steels have been also used for the fabrication of chassis and interior equipment components. Such is the case of the front axle wishbone of vehicle as VW Polo, Seat Ibiza and Skoda Fabia. ThyssenKrupp Umformtechnik a company from ThyssenKrupp Steel manufactures annually 1.2 million pieces of this component for the McPherson front axle suspension in hot-rolled strip CP-W 800, a high-strength steel with a tensile strength of 800 MPa and a yielding point of 680 MPa. This one-piece unit does not only save weight, but also consists of fewer individual parts and integrate operations, which contribute leads to a cost saving of approximately 20%.

b) Aluminium

Aluminium has been used in vehicle construction for the past two decades. However, its use has been rather limited in vehicles. Aluminium, like other lightweight materials, has certain disadvantages in comparison with steel. Besides cost, joining and forming technologies make the application of aluminium somewhat difficult. Furthermore, the energy input for the material supply is definitely higher than in case of steel.

Aluminium stampings have been used for weight saving on such items as hoods, deck lids and door skin panels for a number of years. The Jaguar XJ series used an aluminium body structure to reduce the BIW weight by approximately 200kg.

Aluminium castings have also been used for areas that sustain high forces such as shock towers and nodal points in structures that use extruded sections such as the Audi A8.

Car manufacturers have developed two design concepts of all-aluminium bodies: conventional unibody and the spaceframe. Since aluminium is difficult to process by deep drawing (risk of crack formation), but very well suited for the production of extruded and casting sections, it is almost predestined for the construction of spaceframe body structures. However, some manufacturers like Audi, have used aluminium in extensive form for BIW construction

In regards to the chassis area, aluminium has be used mainly for the fabrication of forged suspension parts, which are 30–35% lighter than steel parts. That is the case of the Audi Q5, where the five-link front suspension and the trapezoidal-link rear suspension are made substantially from aluminium.

Finally, aluminium has been also used for the manufacture of other automotive components such as heat exchangers, engine blocks, wheels (up to 35% lighter than steel wheels), and interior equipment for decoration.

Aluminium types for car body are in 5xxx and 6xxx range. Main joining and forming characteristics of these aluminium types are shown in Figure 6.

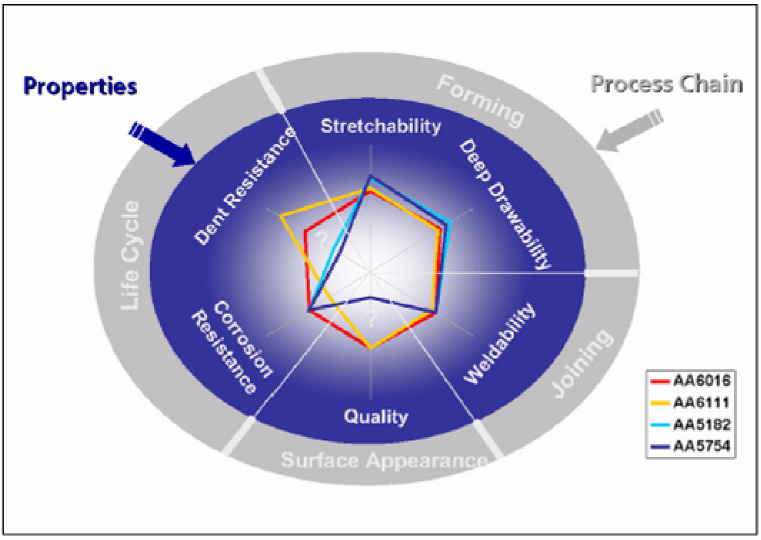


Illustration 5: EN-AW 5xxx and 6xxx alloys competing for car body sheets

Figure 6: 5xxx and 6xxx alloys competing for car body sheets [12]

c) Magnesium

Magnesium is interesting because of its very low density (compared with aluminium still 30 % less) but its applications are a few up to now. Magnesium alloy castings are being used on a limited number of production vehicles. These castings provide a significant mass saving and are currently being used to achieve shapes that are not feasible using stamping techniques and to integrate numerous small parts that would otherwise require fixturing and welding. Large scale castings can eliminate a significant number of stamping tools for individual parts.

Applications of magnesium castings include the roof frame for the Chevrolet Corvette ZO6, the dash panel for the Dodge Viper, the liftgate inner for the Lincoln MKT and the front end module for the Land Rover LR3. Meridian Lightweight Technologies Inc., the supplier of these castings, estimates that a magnesium casting similar to that used on the Lincoln liftgate combined with an aluminium outer panel is approximately 40% lighter than the same Toyota Venza components made from equivalent steel stampings.

The 2003 Dodge Viper SRT10 dash panel, shown below in Figure 7, had a mass of 9.5 kg vs. 30 kg for the original steel panel. This was a savings of 20.5kg or 68% compared with the steel panel. Figures supplied by Meridian Lightweight Technologies, the manufacturer of the Viper magnesium casting [10].

***Figure** 7: Dodge Viper dash panel [10]*

Magnesium gearbox housing is the other example of vehicle efficiency improvement by magnesium die casting. In Figure 8, it is possible to see the advantage of magnesium over aluminium gearbox housing in terms of torque capacity. In this case, the advantages of magnesium use are weight reduction and tool durability, but the main restrictions are stiffness, deformation and costs [13].

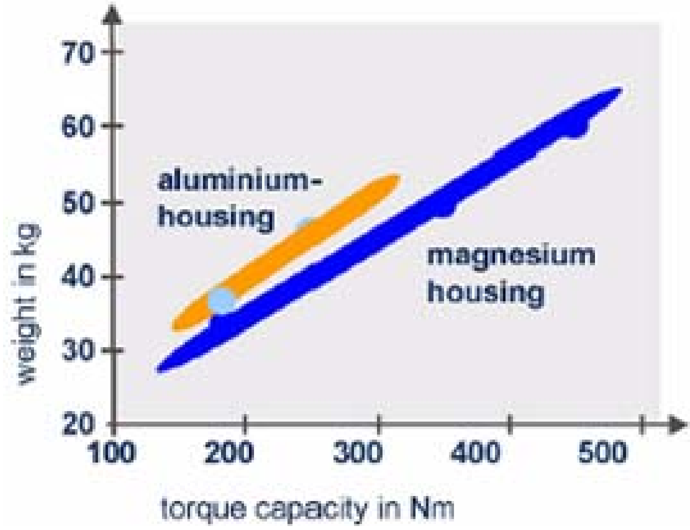


***Figure 8**: The advantage of magnesium over aluminium housing [13]*

d) Plastics and composites

Plastic materials, such as polyamide, are primarily used for non-supporting components of the interior and exterior trim due to their low material stiffness. Plastics are used extensively in front and rear ends of passenger cars, because of their high specific energy absorption. Nowadays, bumper fascias are made of polymers almost without exception. The technological properties of plastics make them economical and highly effective to produce these kinds of components. Plastics provide extensive freedom for shaping while ensuring dimensional, shape stability, as well as high function integration [14]. This trend has been followed by using plastics side panels (front and rear fenders).

Thermoplastic foams, another kind of polymer, are also used in vehicle design with very high success. Besides their high stiffness-to-weight ratio and high energy absorption, thermoplastic foams possess high noise absorption capabilities. Instrument panels and heating and air-conditioning system, which are not subject to high load are typical application areas for thermoplastic foams. Engine covers, front-end modules, door modules and bumpers can be made also using this polymer.

In order for plastics to fulfil structural tasks, they must be compulsory reinforced with fibres to increase their strength and stiffness properties. This combination is typically known as fibre reinforced plastics (FRP). Fibre-reinforced plastics offer great weight saving potential in the construction of automotive components.

There are two main problems that limit the use of plastics in cars, even if we neglect the fact that there is scarce knowledge of plastics in general and of their properties in particular. The first problem is degradation of the mechanical and physical characteristics with temperature and age. The second problem relates to recycling: recent legislation requirements impose that recycle procedures to be designed by car manufacturer itself and a certain percentage of vehicle mass should be recovered to be use again after life time.

Although composites have been used on high volume production vehicles such as the Saturn and early GM mini vans which were fundamentally space frame architecture, the applications are now being expanded into structural areas on niche and specialty vehicles where materials such as:

- Sheet composite materials,
- Multi layer composites using sheet materials such as aluminium or glass fiber on either side of a foam, or cellular core
- Carbon fibers are being used or proposed in structural applications.

The Aston Martin Vanquish front crush structure shown in Figure 9, on the left, is predominantly carbon Fiber as well as the Mercedes front bumper and crash boxes shown in the same figure on the right.

Figure 9: *Aston Martin Vanquish Front Crush Structure (left) and Mercedes front bumper and crash boxes (right)*

Other potential applications include:

- Using long fiber reinforced polypropylene for the trunk floor area as proposed by the European study headed by Volkswagen [15]

- The use of long fiber reinforced polyurethane8 for load floors which has been investigated with Bayer Material Science and shows promise in reducing part count and assembly time while maintaining structural stiffness [10]

3. MATERIAL LIFE CYCLE

Figure 10 show a schematic diagram of the material cycle in the life of a vehicle. Each of these steps must be considered carefully when choosing an innovative solution. New material formulation is the result of the research activity of specialised Institutes, Universities and Research Centers. The peculiar properties of the these innovative materials influence the design of the vehicle, while specific demands of material performance are posed by the designers. The material is one of the main input in the manufacturing process both for the OEM and for the component and subassembly suppliers.

Very often the change of the material ask for a different manufacturing technology, this means that new processes have to be developed with relevant impact on the tooling costs, production pace, new product tests along the production lines. Then there is the time period (some years) intended for the vehicle use by the costumer; during this period, obviously, the materials are submitted to a progressive degradation of their performance due to the applied loads (in particular fatigue but also small impacts), to the environmental effects (temperature, ageing, corrosion, etc.). In spite of the effort of the manufacturer to protect as longer as possible the vehicle against these effects, the vehicle at the end of its life is quite different from what it was when it was new.

At the end of life a challenging problem is posed: what is possible to do with the old car, is it possible to recover some of the used material? The common answer in the past was to put the old car into the landfill because to recover components or material has a cost and the production of new material and component is cheaper.

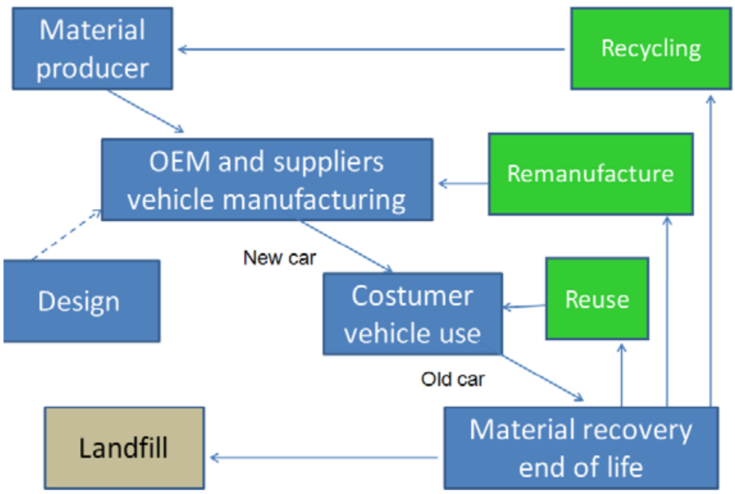


Figure 10: *Material life cycle in automotive industry*

This is no more an acceptable answer for two main reasons: the progressive increment of the amount of material put into the landfills that leads to an environmentally unsustainable situation, and the realisation that the materials at the vehicle end-of-life have still some value (even if their properties are degradated) and the landfill is not the best final solution.

Nowadays, as it is shown in figure 10, it is possible to recover the material by dismounting the vehicle components and to reuse the component itself (sometime as a spare component), or to remanufacture the component in order to use the transformed one as a new component, or at least to recycle the materials. Material recycling has two main possibilities: to use the recovered material in order to produce new material with approximately the same characteristics of the previous one (this is for example typical for the metallic materials that are put into the oven mixed with new rough material and used to cast new ingots of parts; the second way is the get materials of lower value to use for example as filler (this is the main destination of composite materials in particular when thermoset matrix are used, but we have to notice that there are interesting research results that show that fibers can be recovered and reused). It is clear that in the first way the material is fully recycled in the sense that is fully reusable while in the second way the material, although is not waste into the landfill, is degradated.

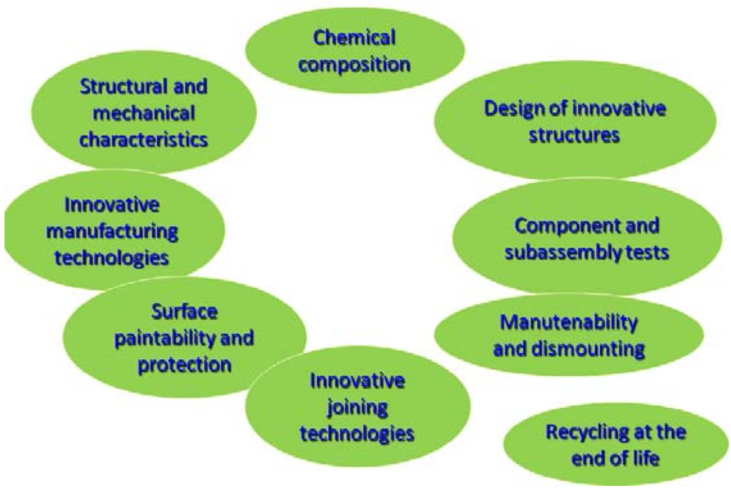


Figure 11: *Different concurrent aspects in the material selection in the automotive industry*

Figure 11 shows another schematic diagram that is intended to put in evidence the multiple aspects that should taken into account when developing an innovative solution that makes use of a new material. .The chemical and physical development of that material is an important point, we can even think that it is the starting point of this development, but it is not enough. In order to evaluate the possibility of application of this new developed material one has to characterise to get all the structural and mechanical characteristics that use needed for its application in the design of some parts. In most of the case the use of a new material ask for a redesign of the part in order to take advantage from its peculiar characteristic, while a simple substitution of the old material with the new developed one leads to a poorer solution. Very often also the testing and validation procedure should be adapted in order to take into consideration the strength and weakness of the new solution . Very often the new material needs for specific manufacturing technologies and specific tooling (we can think the big change of technology when passing from a part in steel sheet that is manufactured by deep drawing to a part made of composite material and manufactured through a RTM – resin transfer moulding – technology). If the new structural solution puts together parts made of different material (for example a steel part and a composite part) the traditional spot welding joining procedure is no more usable and another one (for example adhesive joining or riveting) should be used. Fundamental steps in the manufacturing flow of the parts are the protective coating and the painting. These are generally made by means of an oven. When adopting a new material solution one has to think about this important point: is the new material able to sustain the oven temperature without distortion or degradation ? If this is not the case and a separate painting cycle should be adopted, how can one assure the appropriate match of the colours?

Finally, come the questions related to the possibility of recycling at the end-of-life.

If all these points are not dealt with and satisfactory answers are obtained (compatible with production plant technologies and costs) then the adoption of the new developed material will not be possible, even if in this way one has to loose some advantages.

4. CONCLUSIONS

The lightweight design is becoming rapidly one of the main target in the development of a new car. This is countertendency with the trend of the last decades, when the mass of the vehicle has increased progressively.

The reduction of the mass of the vehicle is of great importance from two linked points of view: the first is the reduction of the fuel consumption, the second one it the reduction of the CO_2 production, as far as CO_2 is considered the main green-house gas.

The reduction of the mass of the vehicle can be obtained by decreasing the number of apparatus that are on-board but costumers do not like this, by optimise the structure of the vehicle, in particular the body, as it is shown in one paper presented in this same conference, by substituting the commonly use deep drawing steel with other materials of more interesting performance.

One possibility is to use the new HS steels that have been recently further developed, they have also the advantage of not disturbing so much the manufacturing process that has been optimised during the years.

Another possibility is the use of light weight alloys such as aluminium or magnesium. This alternative is asking for relevant changes in the manufacturing process and there are also some questions related to the technologies to be adopted for the joining of parts made of different materials.

Another possibility is the use of composite materials. This is the clear trend in the aeronautical industry and this can be the near future also for the automotive industry, although a number of problems are still open and ask for practicable answers.

The questions that arise when the usual material is replaced by a new one have been discussed in some extent and it has been put in evidence that answers are needed to all the questions. For what concern the use of the composite material the end-of-life problem is still an open question. Although some recycling is proposed, generally this is not satisfactory as the performance of the material is fully degradated from noble structural use to the use as filler. Some new results in this perspective have already been published and ask for verification of their practicability.

ACKNOWLEDGMENTS

Authors would like to acknowledge very useful discussion with colleagues form the FIAT Research Center (CRF) and in particular with Dr. Brunetto Martorana. Valuable contribution to the main research activity came also from Dr. Ermias Koricho and Mr. Alem Tekalign who are working as Research Fellow with the authors at the Mechanical and Aerospace Engineering Department of the Politecnico di Torino.

5. REFERENCES

[1] Ferrari G. – "Motori a Combustion interna", Torino, Italy, 2001

[2] Wallentowitz H. – "Structural design of vehicles", Instutut fur Kraftfahrzeuge, Aachen, Germany, 2004

[3] Eurostat, 2004

[4] Klose P. – "Survival of the fittest – Evolution and perspectives in automotive lightweight design", Materials in car body engineering 2009, Bad Nauheim, Germany

[5] Goede M. – "Strategies for vehicle lightweight design", Aachen body engineering days 2008, Aachen, Germany

[6] Belingardi G., Avalle M. – "Advanced materials for automotive applications", International journal for vehicle mechanics, engines and transportation systems, Vol. 30, N. 2&3, June-September 2004

[7] Gries T. – "Bionik II: Bionik in der Textiltechnik", Institut fur Textiltechnik (ITA) Aachen, Germany, 2008

[8] Koglin K. – "Car body concepts of the future", Innovative developments for lightweight vehicle structures, Wolfsburg, Germany, May 2009

[9] Staeves J. – "Requirements for new car body materials from the perspective of an automobile manufacturer", Aachener Kolloquim Fahrzeug und Motorentechnik, Aachen, Germany, 2007

[10] An assessment of mass reduction opportunities for a 2017-2020 model year vehicle program, Lotus engineering, March 2010

[11] High-performance and environment-friendly – advanced high-strength stainless steels in automotive applications, Inside ThyssenKrupp techforum, Februar 2007

[12] Hirsch J., Bassan D., Lahaye C., Goede M. – "Aluminium in innovative light-weight car design", Innovative developments for lightweight vehicle structures, Wolfsburg, Germany, May 2009

[13] Leohold J. – "Pathways for a sustainable automotive future in Europe", Innovative developments for lightweight vehicle structures, Wolfsburg, Germany, May 2009

[14] Rosa J. - "Assesment of the lightweight potential for structural components in hybrid construction", MSc thesis, Aachen, Gemany, April 2009

[15] NSB – New Steel Body Report, ThuseenKrupp Steel

[1]PROCESS ERGONOMICS OF MOTOR VEHICLES

Maria Pia Cavatorta , Lidia Ghibaudo, Fabrizio Sessa, Stefania Spada

UDC: 614.8

Summary
In Europe, protection of health and safety at work is regarded as a public responsibility. Traditionally, national authorities and researchers have been the main promoters of ergonomics in industry. However, starting from the 1990s the interest for ergonomic issues has grown within enterprise, as a result of an increasing awareness of the importance of these matters for corporate core values. At the start, ergonomic programs were usually limited to reactive measures, but more and more programs are now established as a continuous process, with activities expanded to involve proactive efforts that address workstation as well as product design. Cooperation between industries, universities and research institutions is often crucial for programs to be most effective. Education is indeed essential to promote the ergonomic culture at the workplace.

Key words: process ergonomics, early risk assessment, work design, virtual manufacturing

ERGONOMSKI PROCESI U MOTORNIM VOZILIMA

UDC:614.8

Rezime
U Evropi, zaštita zdravlja i sigurnost na radu se smatraju društvenom odgovornošću. Tradicionalno, nacionalni autoriteti I istraživači su vodeći promoteri ergonomije u industriji. Međutim, počev od 1990. godine interes za ergonomske aspekte unutar organizacija se povećao, kao rezultat sve većeg shvatanja značaja ovih stvari kao glavnih vrednosti firmi.

Na početku ergonomski programi su bili ograničeni samo na reaktivne mere, ali sve više i više programa se definiše kao neprekidan proces, sa proaktivnim delovanjem u radnim stanicama kao i kod razvoja proizvoda. Saradnja između industrije, univerziteta I istraživačkih institucija je krucijalna za programe koji treba da budu najefektivniji. Obrazovanje je esencijalno kako bi se promovisala ergonomska kultura na radnom mestu.

Ključne reči: Ergonomski proces, rana procena rizika, projektovanje rada, virtuelna proizvodnja

[1] *Received: August 2012, Accepted: September 2012.*

Intentionally blank

PROCESS ERGONOMICS OF MOTOR VEHICLES

Maria Pia Cavatorta*[1]*, Lidia Ghibaudo, Fabrizio Sessa, Stefania Spada

UDC:614.8

1. INTRODUCTION

Sustainability can be defined as "the development that meets the needs of the present without compromising the ability of future generations to meet their own needs". Therefore, it includes attention to natural resources as well as to human and social resources, in combination with economic sustainability [1,2].

It is often deemed [3] that ergonomics can contribute to developing actions and programmes aimed at combining the human and economic dimension of sustainability and social responsibility by optimizing both system performance and human well-being.

Ergonomics focuses on systems in which humans interact with their environment. The environment is complex and consists of the physical environment, the organizational environment and the social environment.

Ergonomics takes a system (holistic) approach, that is a broad perspective of the human within the environment. A system approach is fundamental, and the object of analysis, assessment and design, simple as it may be, must always be represented with due consideration of all foreseeable inter-correlations. In real work systems, conceptually different issues do overlap and interact, sometimes in complex ways, and investigations that are restricted to one core science and one level of analysis are almost always unsatisfactory [3].

Ergonomics also typically takes a hierarchical approach, where environmental design to fit the human is seen as a priority, and training people to fit the system is only considered when the former is not possible. With a better fit environment, humans are better able to contribute to performance. End target of ergonomics is not only that of preventing accidents and illness, but mainly that of promoting good health as psycho-physical well-being.

In Europe, protection of workers' good health is regarded as a public responsibility. European directives on safety and health at work have their legal foundation in Article 153 of the Treaty on the Functioning of the European Union, which gives EU the authority to adopt directives in this field. A wide variety of directives, setting out minimum health and safety requirements for the protection of workers, have since been adopted. Member States are free to adopt stricter rules for the protection of workers when transposing European directives into national law, and so legislative requirements in the field of safety and health at work may vary across Member States.

Generally, a directive fixes the agreed objectives to be pursued by the European Member States, but leaves freedom of choice in how to achieve them. These directives are supplemented by a series of European EN standards, which fill out the details and enable implementation.

[1] Maria Pia Cavatorta, Department of Mechanical and Aeronautical Engineering, Politecnico di Torino. Corso Duca degli Abruzzi 24, 10129 Torino, Italy. maria.cavatorta@polito.it

The International Organization of Standardization (ISO) has published international standards which deal with ergonomic requirements for workstations, methods of risk assessment and other aspects related to muskolo-skeletal disorders (MSDs).

Basic requirements of physical ergonomics are also contained in a chapter of Machinery Directive (98/37/EU). When designing manufacturing systems and machines, ergonomic principles have to applied to improve safety and efficiency for workers and to enhance the working conditions. A good ergonomic design positively affects manufacturing systems and worker reliability. Whenever a machinery and workplace are being designed or re-designed, designers have to take into account the ergonomic basic requirements reported in CEN Standards to evaluate and minimize all related risks.

2. METHODS FOR RISK ASSESSMENT

According to Italian and international legislation, industries are required to perform a risk assessment of the workplace and create a document with evidence of it. All potential risks present at the workplace must be taken into account, including the ergonomics risk. Each workstation is to be analysed with the aim of improving workers' working quality life and allowing for a proper allocation worker-workstation.

For Italian industries, the ergonomics mapping of workstations is based on the Legislative Decree 81/2008, with reference to ISO 11228 standards and EN 1005 standards. Standards suggest a step approach to hazard identification and subsequent risk assessment and evaluation. Acceptability of risks is to be ensured in time through monitoring and reviewing, else the workplace needs to be redesign and re-evaluated.

Main hazards for musculoskeletal injuries in the workplace can be tackled in: (awkward) posture, high and prolonged levels of exerted force, repetition rate and fatigue. Their external counterparts, related to the task, are therefore accountable to workplace layout, loads to be handled, cycle time and work organization (shifts and rest periods). If hazards are present, the level of risk needs to be assessed. A step approach to risk assessment and evaluation is usually advisable. First level methods are risk assessment methods that utilize checklists. They are often called ergonomic screening tools as they allow for a rapid risk estimation. If the risk estimation signals that some risks may be present, a more detailed risk assessment is recommended. Second level methods are risk assessment methods that allow a detailed analysis through computation of indexes. Second level methods are generally utilized after the pre-screening phase.

Complying with the Machinery Directive (98/37/EU), a street light indication is usually given as a result of the risk assessment analysis. Green means that the task entails negligible risks for muskolo-skeletal problems and should be manageable for all healthy employees. Yellow means that some risk may be present and that action should be planned in terms of risk monitoring (medical screening and surveillance) and/or implementation of solutions. Finally, red means that the task implies a high risk and improvement actions are required as soon as possible.

Table 1 summarizes main risk assessment methods reported in the standards and usually taken as reference methods for control of ergonomic risks at manual workplaces. A brief overview of the methods is presented in the following subparagraphs. A fourth subparagraph introduces two methods developed by the Ergonomics Institute of Darmstadt University of Technology (Germany) with specific reference to the automotive industry.

Table 1 *Main risk assessment methods reported in the standards*

TYPE OF WORKING ACTIVITY		METHOD FOR RISK ASSESSMENT	REFERENCE STANDARD	TARGET BODY SEGMENT
Manual Material Handling (loads above 3 kg)	Lifting Tasks	Lifting Index NIOSH	ISO 11228-1 EN 1005-2	back
	Push/Pull & Carry	Tables of Snook & Ciriello	ISO 11228-2	back and shoulders
Handling of low loads at high frequency		OCRA Checklist OCRA Index	prEN 1005-5 ISO 11228-3	upper limb - wrist, elbow and shoulder joints

Lifting tasks: Lifting Index NIOSH

For risk evaluation of lifting tasks, the reference method is the NIOSH lifting equation [4] which is reported in both ISO 11228-1 [5] and EN 1005-2 [6] standards. The NIOSH lifting equation introduces the use of the Lifting Index (LI), a scalar number that provides a relative estimate of the level of physical stress associated with the manual lifting task. The estimate of the level of physical stress is defined by the relationship of the weight to be lifted and the Recommended Weight Limit (RWL).

$$LI = \frac{Actual\ Load\ to\ be\ lifted}{\mathrm{Re}commended\ Weight\ Limit(RWL)}$$

According to NIOSH indication, lifting tasks characterized by LI greater than 1.0 pose an increased risk for lifting-related low back pain. If the magnitude of the LI increases, the level of the risk for the worker performing the job would be increased, and a greater percentage of the workforce is likely to be at risk for developing lifting-related low back pain.

RWL, denominator of the LI ratio, is defined for a specific set of task conditions (Figure 1) as the weight of the load that nearly all healthy workers could deal with over a substantial period of time without an increased risk of developing lifting-related low back pain.

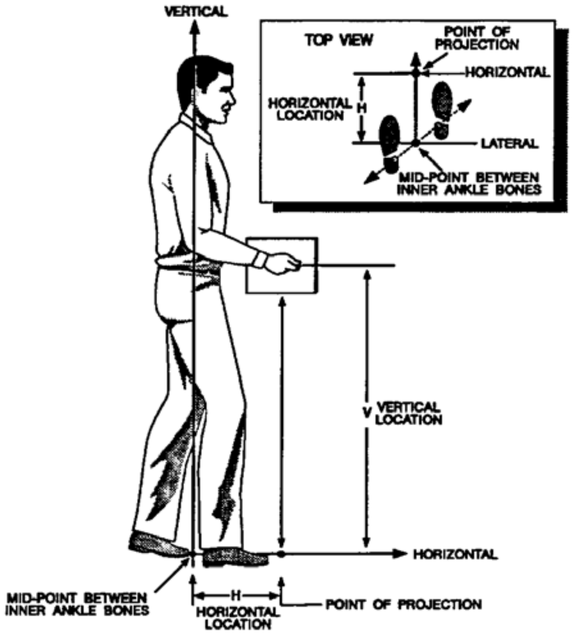


Figure 1 *Task descriptors of NIOSH multipliers [4]*

Calculation of RWL is based on a multiplicative model that provides a weighting for each of six task variables. The weightings are expressed as coefficients that serve to decrease the Load Constant (LC), which represents the maximum recommended load weight to be lifted under ideal conditions (standard lifting location, sagittal plane, occasional lift, good couplings and vertical lift <25 cm):

$$RWL = LC \times HM \times VM \times DM \times AM \times FM \times CM$$

where:

- HM, the horizontal multiplier, depends on the horizontal distance between the worker's ankles and the worker's hands, therefore considering the entity of the bending moment on the worker's spine;
- VM, the vertical multiplier, depends on the vertical distance of the worker's hands from ground, therefore taking into account whether the worker needs to stoop or bend or, on the contrary, raises his/her arms at or above shoulders' level;
- DM, the distance multiplier, depends on the vertical distance between the point of origin and the point of destination of the lift, therefore considering the metabolic effort in the lift;
- AM, the asymmetry multiplier, depends on the extent of trunk rotation required during the lifting task;
- FM, the frequency multiplier, depends on the number of lifts per minute as well as on lifting duration. The latter is specified by distribution of work-time and recovery-time and classified as either short, moderate or long;
- CM, the coupling multiplier, depends on the quality of the gripping offered by the object to be lifted and is classified as either good, fair or poor.

Each multiplier should be computed from the appropriate formula or extracted from a table.

Geometrical parameters are to be evaluated at the origin of the lift, unless significant control of the load is required at destination. Significant condition is defined as a condition requiring precision placement of the load at destination of the lift. This is usually the case when:

– the worker has to re-grasp the load near the destination of the lift;
– the worker has to momentarily hold the object at destination;
– the worker has to carefully position or guide the load at destination.
– For lifting tasks that require significant control at destination, RWL is to computed both at origin and at destination, so to identify the most stressful location of the lift.

With reference to NIOSH indication, LC is set to 23 kg regardless of the operator's gender. The 23 kg weight limit should be protective for 90% of the entire adult healthy population (i.e. 99% of male and 75% of female adult healthy workers). Application in European countries sets different limits of the maximum acceptable load for male and female workers; wishing to be protective for 90% of male and female adult healthy workers, the weight limit is set to 25 kg for adult healthy male workers and to 15-20 kg for adult healthy female workers. Maximum acceptable loads are to be reduced by 5 kg for youth (<18 years old) or older workers (> 45 years old).

For trained healthy adult workers, the weight limits can occasionally be exceeded under particular circumstances (for example maintenance work) but with the guarantee that working conditions remain safe.

Whole-body pushing/pulling and carrying: the Snook & Ciriello Tables

In case the manual material handling involves whole body pushing, pulling and carrying, the commonly employed method for identifying potential hazards and risks refers to the Snook and Ciriello Tables. The Snook & Ciriello psychophysical tables provide limit values of the maximum acceptable initial (static frictional resistance) and sustained (sliding frictional resistance) forces in case of pulling/pushing activities and of maximum weight to be handled in case of carrying.

ISO 11228-2 standard [7] introduces the Risk Index (RI), a scalar number that provides a relative estimate of the level of physical stress associated with a particular pushing-pulling-carrying task.

The estimate of the level of physical stress is defined by the relationship of the effective weight/force value and the recommended limit value obtained from tables. In the case of pushing/pulling activities:

$$RI = \frac{measured\ force}{recommended\ force}$$

RI is the classified according to a traffic light classification system:

- RI < 0,85 green area, the manual handling is acceptable. No need for intervention.
- 0,85 <RI< 1 yellow area, attention zone. A portion of the working population may be at risk. Workers' education and training. Medical surveillance.
- RI > 1 red area, risk zone. Needs for intervention.

Recommended forces and loads are based on the research carried out by Drs. Snook and Ciriello at the Liberty Mutual Research Institute for Safety [8-11]. Their researches used the psychophysical methodology to analyze and to evaluate lifting, lowering, pushing, pulling and carrying tasks. The results of researches provided important pieces of information about capability and limitations of workers and design of manual material handling tasks to reduce low back disability. The psychophysical methodology includes measurements of oxygen consumption, heart rate and anthropometric characteristics. Subjects were given control of either the weight of force variable; all others task variables, such as frequency, size, distance etc., were controlled by the experimenter.

The tables, published in literature, provide for each type of actions (pushing, pulling and carrying) the maximum acceptable weights and forces depending on the percent protection of male and female adult healthy population (usually taken at 90%). Table values depend on other variables relating to the type of action, such as frequency, height of the handle from floor and covered distance.

Acceptable forces for pushing and pulling are to be compared with the effective measured forces. It is important to note that pulling/pushing forces are not easy to relate to the weight of objects being pushed or pulled because trolley and floor characteristics have to be considered. Indeed pushing and pulling forces have to be measured directly through the use of dynamometers. Moreover, the force required for handling any wheeled device involves several components: starting (initial), stopping, turning and maintaining its motion (i.e., sustained). It is the maximum force generated while completing any of these actions that must be considered in the risk analysis. It is also important to monitor the situation from time to time, to check on the level of maintenance of carts and devices as well as floor conditions.

Whereas lifting, holding and carrying can lead to high compressive loads on the operator’s lumbar spine, the compression forces arising from pushing and pulling are generally much lower. Shear forces on the other hand tend to be higher. To minimise forces on the back, the operator should exert the force with a stable and balanced posture that allow application of his/her own body weight. Load on arms and shoulders is influenced by posture, strongly related to position of the hands. Hands should be at around waist level and should not be too close. Also, the elbows should be kept low.

Handling of low loads at high frequency: the OCRA method

For risk assessment of upper limbs repetitive movements, both ISO 11228-3 [12] and EN 1005-5 [13] refer to the OCRA method. The OCcupational Repetitive Action (OCRA) method was developed in 1996 by two Italian occupational doctors and researchers, Occhipinti and Colombini [14-17]. The method is intended to analyze workers’ exposure to tasks where main upper-limb injury risk factors are present: repetitiveness, force, awkward postures and movements, lack of recovery periods, and others, defined as “additional”. Each identified risk factor is targeted to help identifying possible requirements and preliminary preventive interventions; all factors are then added up to consider overall risk exposure. If job rotation occurs, all repetitive tasks are analyzed and a time-weighted average is calculated for final assessment.

The OCRA method is composed by an index and a checklist. Both methods are mainly observational.

The OCRA index provides a scalar number, representing the ratio between the actual technical actions carried out in the work shift (ATA) and the number of reference technical actions in the shift that can be considered safe under the analyzed working conditions (RTA). It is generally used for the (re)design or in-depth analysis of workstations and tasks [14]. The OCRA checklist, based on the OCRA index, is simpler to apply and is generally recommended for the initial screening of workstations [17].

As in the Lifting Index and in the Risk Index, for the OCRA index the level of risk is measured through a characteristic work task variable: for manual material handling tasks the weight to be handled, for OCRA the frequency of technical actions in the shift:

$$OCRA\,Index = \frac{Actual\,technical\,actions\,in\,the\,shift\,(ATA)}{Number\,of\;reference\,technical\,actions\,in\,the\,shift\,(RTA)}$$

To compute RTA, a reference number of technical actions per unit time is set in ideal conditions. Multipliers are then used to account for working conditions other than optimal.

$$RTA = CF \times FoM \times PoM \times \mathrm{Re}\,M \times AdM \times D \times DuM \times RcM$$

where:

- CF, the constant of frequency of technical actions, is set to 30 actions/min. This would represent a safe number of repetitive operations under ideal working conditions;
- FoM, the force multiplier, which is one under the ideal conditions set in EN 1005-3; else FoM values are given in relation to the force perceived by the worker (Borg scale);
- PoM, the posture multiplier, which is one under the ideal conditions set in EN 1005-4; else PoM values are given depending on the degree of joint deviation from neutral posture and of exposure time;
- ReM, the repetitiveness multiplier, which depends on the level of stereotypy within the cycle, where stereotypy considers two elements to define the risk level: duration of repetitive actions with respect to the work cycle and total cycle time;
- AdM, the additional multiplier, which considers the presence of additional risk factors (examples are the use of inadequate gloves, of vibrating tools or the fact that the work pace is completely set by the machine);
- D is the duration, in minutes, of the analyzed manual repetitive task;
- DuM, the duration multiplier, which considers the overall duration of manual repetitive work. The multiplier allows to take into account working conditions that differ from the standard 8 h work shift (regularly working over-time, part-time work, repetitive manual tasks for only a part of a shift);
- RcM, the recovery periods multiplier, which takes into account the number and distribution of breaks within the work shift.

Whole body risk assessment of work tasks in the car assembly: the AAWS and EAWS Methods

The pieces of information on the ergonomics of the workplace, which may be obtained through the risk assessment methods cited by the legislation, mainly concern manual material handling either of substantial loads, as in lifting and carrying, whole body pushing and pulling activities, or of low loads manipulated at high frequency. However, as frequently suggested in the literature, a multi method risk evaluation should be applied to obtain a more global picture of the risk of the workplace [18,19]. Moreover, overall body risk evaluation should be promoted whenever possible, as in many practical situations the worker attends to tasks that have different components of risk which may involve static postures, action forces, manual material handling as well as repetitive movements.

This is typically the case of work tasks in the car assembly, which are characterized by unfavourable working postures, action forces and material handling. Vehicle geometry is responsible for imposed working postures in the form of (lateral) bending and twisting of the trunk and extension of the arms. The whole body should generally be considered. Other factors can include the need to apply strong forces, potentially heavy stress on the finger-hand-arm system from application of strong action forces and repetitive movements.

In the first years of 2000, the screening tool AAWS (Automotive Assembly Work-Sheet) was specifically developed by the Ergonomics Institute of Darmstadt University of Technology (IAD), for the automotive sector on the basis of several joint research projects with German Automotive Industries. AAWS has been developed to comply with German and international legal requirements for healthy and safety at work with special reference to European Legislation [20].

The ergonomic risk assessment through AAWS is relative to an overall evaluation of the working task. Manual material handling, repetitive actions, awkward postures and level of action forces are considered. Ergonomic load points of AAWS are granted for ergonomic unfavourable conditions.

In following years, IAD developed a second ergonomic screening tool known as EAWS (European Assembly Work-Sheet). Evolved from AAWS to comply with all parts of the EN 1005 standard and the corresponding ISO standards, the structure of EAWS is similar to that of AAWS [21,22]. EAWS has an additional section, section 4, relating to the upper limbs. Authors recommend application primarily to short cyclic work (up to 5 minutes), where long-lasting fatigue-generating load situations as well as peak loads are absent [23].

Risk evaluation through EAWS is extended to repetitive movements and provides two index scores as output: one index relating to the whole body risk exposure as in AAWS and a second index relating to upper limbs risk exposure. For the assessment to be acceptable, both index scores need to lie in the green region, i.e. signalling that the task entails negligible risks for muskolo-skeletal problems and should be manageable for all healthy workers.

A primary value of EAWS is the holistic approach to risk analysis and the attempt made by the method developers to taking into consideration the interconnection among the risk factors of the whole body. A second element of interest is the method applicability for risk estimation in early design phase in the project development process.

3. PROCESS ERGONOMICS IN PROJECT DEVELOPMENT

Anticipating the ergonomic analysis as early as possible in project development is fundamental to reduce ergonomic critical issues in the plants. In this way, problems may be designed out of the product and process before reaching the operation phase. However, for such proactive process to be successful, it is crucial that all parts of product and process development are linked to and communicate with the ergonomics process.

Experience shows that it is not enough to build technically good ergonomic workplaces because of the chain of coordinated factors from design to production. A comprehensive approach is needed if good results are to be achieved [24,25].

Figure 2 clarifies an important aspect that must be considered when running an ergonomic analysis. Each main step of a new project development is characterized by an increasing level of complexity but also of knowledge and definition of the project itself. Not all risk assessment methods are applicable at the different stages of project development. Depending on the phase, different data may constitute the basis of the analysis.

In the early stage of design, the level of knowledge does not allow for a very detailed risk analysis as rough geometric data (digital data mostly) are available. Therefore, at this stage simple tools are advisable to analyze critical ergonomic issues related to posture, action forces and material handling.

It is only in the industrialization phase that more detailed design data, as for geometries, materials and location of parts, become available thus allowing for a detailed ergonomic analysis of postures, action forces and material handling. Some product changes are still possible, even though the cost of changes increases as the project progresses. At the industrialization phase, time information become available. Work organization may be improved taking into consideration the level of biomechanical workload exposure.

At the level of production, planned procedures are already set with limited possibilities to change the process. At this stage, observational methods may be applied at their fullest in compliance to safety laws and technical standards.

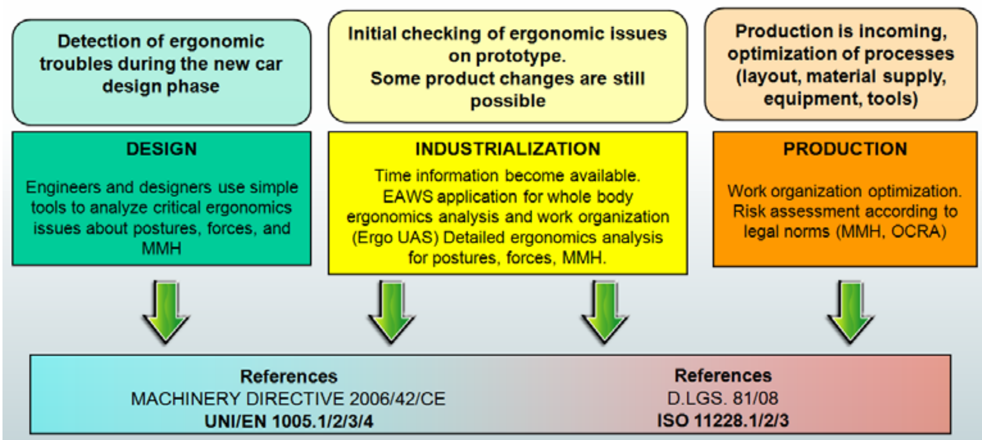


***Figure 2** Ergonomics approach in the main steps of a new project development at FGA*

Table 2 summarizes application of the different risk assessment methods and technical standard, as it pertains to the three stages of a new project development in Fiat Group Automobiles (FGA). Compliance to safety laws is carried out through applicable technical standards in the design phase (EN 1005) and re-evaluated in the production phase at the observational level (ISO 11228); an intermediate and voluntary step of risk evaluation may be added during the industrialization phase through the EAWS method. Assessment of the biomechanical workload exposure at this stage may also provide pieces of information for work organization and line balancing [18].

Table 2 *Application of risk assessment methods and technical standards at FGA*

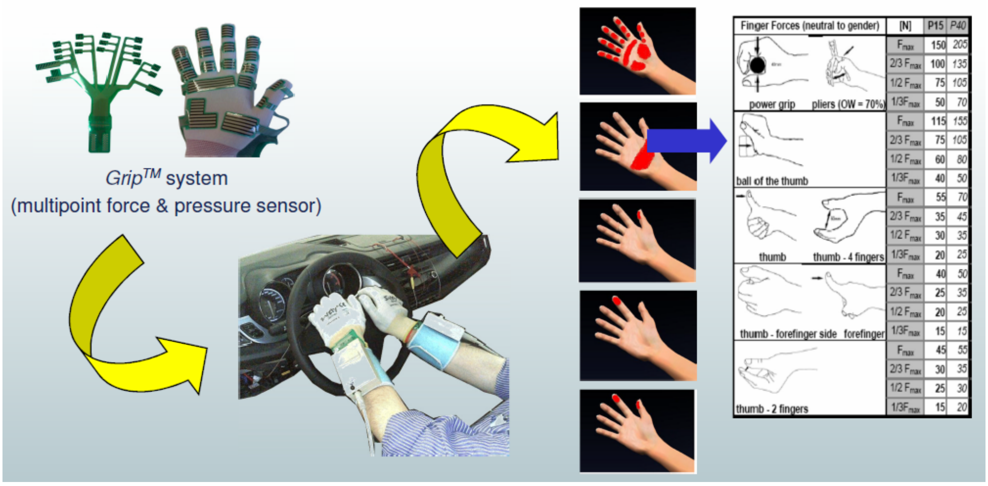
TYPE OF ANALYSIS	APPLICATION	METHODS (STANDARDS)	ITALIAN/EUROPEAN SAFETY LAWS
Postural Analysis	Design phase	(EN 1005-4)	Mandatory
Forces	Design Pahse	(EN 1005-3)	Mandatory
Manual Material Handling	Design Phase	Lifting Index NIOSH, Snook & Ciriello Tables (EN 1005-2))	Mandatory
Whole body	Industrialization phase	EAWS (EN 1005-1,2,3,4,5)	-
Manual Material Handling	Production phase	Lifting Index NIOSH, Snook & Ciriello Tables (ISO 11228-1,2))	Mandatory
Handling of low loads at high frequency	Production phase	OCRA (ISO 11228-3; EN 1005-5)	Mandatory

A pro-active ergonomic approach calls for a preliminary estimation of physical workload in the design phase, and a successive measurement when the workstation is in place. Body postures and forces are fundamental biomechanical parameters for ergonomics assessment and are closely linked together. Awkward postures are known to conduce to pain and should be avoided; non-neutral postures also limit the maximum level of force that can be sustained by a given articulation, and so the maximum level of effort that can be exerted by the related muscles.

The Three-Dimensional Static Strength Predic-tion Program (3DSSPP) designed by researchers at the University of Michigan’s Center for Ergonomics is now a commercial software, available since 1989, that allow designers to manipulate the posture of a three-dimensional human form model with evaluative algorithms derived from static strength of approximately 3000 healthy college students and workers, ranging in age from 17 to 65 years [26]. The algorithms consider the posture, selected anthropometry, gender and forces on the hands to determine spinal compression forces, joint static strength capabilities and balance [27]. NIOSH guidelines are implemented for joint strength capabilities and back compression limits.

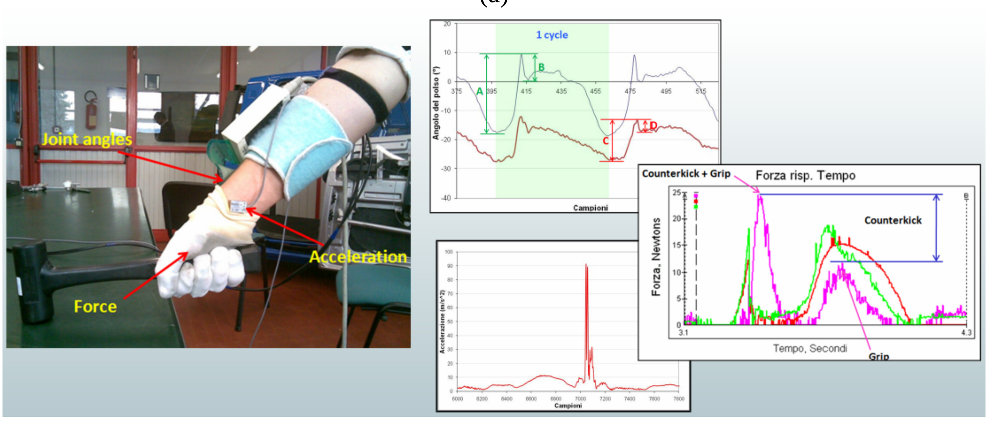
Analysis capabilities have been implemented as part of workplace design; the simulation is not intended for computing the biomechanical workload on a specific worker, but rather to verify task feasibility and assess information on strength capability requirements at the earliest stage of design. Typically, the population used is composed by 5th, 50th and 95th percentile of both genders; for each of the six defined anthropometries, specific postures within each task are simulated and parameters of joint moments and postures can be computed, once forces on hands are introduced as input parameters in the model.

From the engineering point of view, objective measures are a fundamental requirement to perform a robust and repetitive physical workload evaluation. While direct measurement of articular moments is quite impractical, especially during operator work, direct measurement of external hand forces, despite of significant complexity, may be approached.



Finger Forces (neutral to gender)	[N]	P15	P40
power grip / pliers (OW = 70%)	F_{max}	150	205
	2/3 F_{max}	100	135
	1/2 F_{max}	75	105
	1/3 F_{max}	50	70
ball of the thumb	F_{max}	115	155
	2/3 F_{max}	75	105
	1/2 F_{max}	60	80
	1/3 F_{max}	40	50
thumb / thumb - 4 fingers	F_{max}	55	70
	2/3 F_{max}	35	45
	1/2 F_{max}	30	35
	1/3 F_{max}	20	25
thumb - forefinger side / forefinger	F_{max}	40	50
	2/3 F_{max}	25	35
	1/2 F_{max}	20	25
	1/3 F_{max}	15	15
thumb - 2 fingers	F_{max}	45	55
	2/3 F_{max}	30	35
	1/2 F_{max}	25	30
	1/3 F_{max}	15	20

(a)



(b)

Figure 3 *Examples of experimental activities for characterization of finger/hand forces (a) and work tools(b)*

Figure 3 depicts two activities carried out thanks to the cooperation with Fiat Research Center (CRF). Experimental set-ups for direct measurement of hand forces, involving the use of thin, high-resolution, tactile pressure sensors, are being investigated and tested. Calibration methods and experimental procedures are being developed as well as data processing techniques. Twin axes goniometer, that simultaneously measures angles in two planes of movement, are used to get information on wrist joint angles in flexion-extension as well as in radial –ulnar deviation.

Meanwhile, a laboratory facility is being build and equipped next to the Mirafiori Plant in Torino. The lab should become fully operational within the upcoming year. By reproducing a workcell in the lab, it will be possible to perform product and process feasibility analysis, to test compliance of product components to specifications as well as to acquire the experimental data that may be necessary for work task ergonomic characterization.

Virtual workplace optimization through computer-aided simulation techniques may also bring important advantages, allowing for visualization of postures and movement of the human operator at earliest stage of design (Figure 4). In the computer 3D simulation techniques, the human operator is replaced by an anthropometrical articulated representation called “mannequin”. A number of ergonomics simulation tools have been developed using this approach and are used at the different steps of project development [28,29]

At a first step, simulation of manual assembly tasks allows for checking human movements and postures in order to evaluate general feasibility of the task and risks, mainly from the stand point of reach ability, space demands and visual needs for various anthropometries. Implementation of objective ergonomics methods is a following and necessary step for testing the workplace with respect to infringements upon threshold values of applicable standards and guidelines [30].

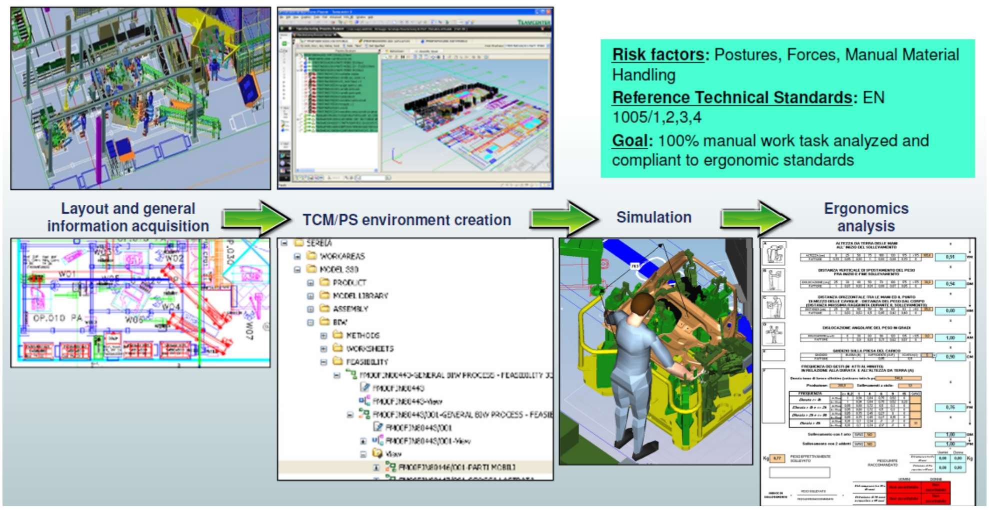


Figure 4 *An example of virtual simulation for ergonomic analysis in FGA*

4. THE NECESSARY ROLE OF EDUCATION

An objection sometimes moved against product designers is that they tend to focus on product performance and design, often overlooking the impact design choices have on the workers that will actually manufacture the product.

In 2008, FGA and Politecnico signed an agreement aimed at enhancing active cooperation in the area of ergonomics between the industrial world and the academia as well as at promoting the introduction of ergonomics workplace design at the curricular level of future production engineers and designers. The aim has being pursued through multiple initiatives: activation of courses on ergonomics, grant of Ph.D. scholarships in ergonomics and participation in joint research projects. In all initiatives, active cooperation with the Department of Occupational Medicine at Università degli Studi di Torino was pursued for a comprehensive view of ergonomic matters [31].

Following the agreement, a 60 hour course “Ergonomics for Manufacturing Systems”, was activated within the Master Degree in Automotive Engineering. The course, soon to be at its fifth edition, has seen an increasing number of students enrolling, with the participation of international students as well as locals. The course started as an elective course and is now compulsory for students with a minor in management of industrial processes.

The course covers some basic knowledge on main physical, sensory and cognitive capabilities, anthropometry, and biomechanical modelling. Main emphasis is given to manual material handling, hand intensive tasks and associated musculoskeletal disorders, methods and tools of risk assessment. Few hours are devoted to illustrate health and safety legislation, technical standards as well as the principles of work measurement techniques. Class tutorials, consisting in the analysis of case studies and in exercises for risk assessment method application, are of significant help for students in learning the course contents. Finally, the course introduces the principles of human-machine interaction and the concepts of usability of tools and equipments.

In essence, the course aims at providing the basic knowledge on ergonomics for manufacturing systems to future production engineers as well as process and product designers, emphasizing how a better involvement of the human element in the design of manufacturing processes and operation management may reduce the physical and mental workload sustained by the operator, improve his/her well-being and the system productivity (in the respect of gender issues and of people with special needs). Since activation of the course, the number of students focusing their Master thesis on ergonomic aspects has steadily increased. In many cases, the final work was developed within a six month student internship at FGA.

More recently, a course on ergonomics and workplace design has been activated for Ph.D. students, coming from the different areas of engineering and industrial design, with the aim of spreading the ergonomics culture beyond traditional boundaries. Likewise, the course is now offered within the Master in Safety Engineering and Risk Analysis, traditionally addressed to civil and plant engineers.

Three-year Ph.D. scholarships have been granted following the cooperation agreement and participation in joint research projects has also been pursued. The projects, run at the regional level, involved the three local universities, trade unions as well as employers’ associations. A first research project, developed between 2009 and 2010, focused on the applicability of ergonomics in the workplace; in particular, on a proposal for an integrated and interdisciplinary approach to ergonomics and risk assessment which combines physical, cognitive as well as environment ergonomics. A second project supported by INAIL (Italian Workers’ Compensation Authority) is now in place, seeking to develop a toolkit for a holistic workplace risk assessment. In addition to standard observational methods, attention is posed at risk estimation in the design phase, so to ensure early evaluation of new products and in production planning. As in the first project, results will be made public through the project website www.ergonomia.corep.it, hopefully helping to spread the ergonomic culture in the workplace and to aid compliance with health and safety legislation.

5. CONCLUSIONS

In manufacturing, control of risks at manual workplaces is a requirement commanded by legislation, care for health of workers and economic considerations. End target of ergonomics is to combine the human and economic dimension of sustainability and social responsibility by optimizing system performance and human well-being.

Ergonomics can be involved in all stages of planning, design, implementation, evaluation, maintenance, redesign and continuous improvement of work systems. Yet, anticipating the ergonomic analysis as early as possible in project development is fundamental to reduce ergonomic critical issues in the plants.

For such proactive process to be successful, it is crucial that all parts of product and process development are linked to and communicate with the ergonomics process.

Education plays a necessary role to spread the ergonomic culture at the workplace. Close cooperation between academia and industry may help integrating different perspectives and hopefully closing the gap between industry, practitioners and researchers.

ACKNOWLEDGMENTS

Authors wish to acknowledge cooperation with CRF (Fiat Research Centre) in the persons of M. DiPardo, S. Lamacchia, D. Lionello.

6. REFERENCES

[1] Delios A. (2010) How can organizations be competitive but dare to care? *Academy of Management Perspectives*, 24 (3), 25-36.

[2] Pfeffer J. (2010) Building sustainable organizations: the human factor. *Academy of Management Perspectives*, 24 (1), 34-45.

[3] Dul J., Bruder R., Buckle P., Carayon P. et al. (2012) A strategy for human factors/ergonomics: developing the discipline and profession, *Ergonomics*, 1-27. DOI: 10.1080/00140139.2012.661087

[4] Waters T., Putz-Anderon V., Garg A., Fine L. (1993). Revised NIOSH equation for the design and evaluation of manual lifting tasks. *Ergonomics*. 36, 749-766.

[5] ISO 11228-1:2003. *Ergonomics – Manual handling – Part 1: Lifting and carrying*.

[6] EN 1005-2:2003/prA1:2008. *Safety of machinery – Human physical performance – Part 2: Manual handling of machinery and component parts of machinery*.

[7] ISO 11228-2:2007. *Ergonomics – Manual handling – Part 2: Pushing and pulling*.

[8] Ciriello V.M., *Snook* S.H. (1983). A study of size, distance, height and frequency effects on manual handling tasks. *Human Factors*, 25 (5).

[9] Ciriello V.M., Snook S.H., Blick A.C., Wilkinson P.L. (1990). The effects of task duration on psychophysically determined maximum acceptable weights and forces. *Ergonomics* 33 (2), 187-200.

[10] Snook S.H., Ciriello V.M. (1991). The design of manual handling tasks: revised tables of maximum acceptable weights and forces. *Ergonomics* 34 (9),1197-1213.

[11] Ciriello V.M., Snook S.H., Hughes G. (1993) Further studies of psychophysically determined maximum acceptable weights and forces. *Human Factors* 35 (11), 175-186.

[12] ISO 11228-3:2007. *Ergonomics – Manual handling – Part 3: Handling of low loads at high frequency*.

[13] EN 1005-5:2007. *Safety of machinery – Human physical performance – Part 5: Risk assessment for repetitive handling at high frequency*.

[14] Occhipinti E. (1998). OCRA: a concise index for the assessment of exposure to repetitive moments of the upper limb. *Ergonomics*. 41,1290-1311.

[15] Occhipinti E., Colombini D. (2005). The occupational repetitive action (OCRA) methods: OCRA index and OCRA checklis. *Handbook of human factors and ergonomics methods,* eds. Boca Raton, Florida: CRC Press 2005, 15, 1-14.

[16] Occhipinti E., Colombini D. (2007). Updating reference values and predictive models of the OCRA method in the risk assessment of work-related musculoskeletal disorders of the upper limbs. *Ergonomics.* 50,1727-39.

[17] Colombini D., Occhipinti E. (2006). Preventing upper limb work-related musculoskeletal disorders (ULWMSDS): new approaches in job (re)design and current trends in standardization. *Applied Ergonomics* 37 (4), 441-50

[18] Otto A., Scholl A. (2011) Incorporating ergonomic risks into assembly line balancing. *European Journal of Operational Research*. 212, 277-286.

[19] Takala E.P., Pehkonen I., Forsman M., Hansson G.A., Mathiassen S.E., Neumann W.P., Sjøgaard G., Veiersted K.B., Westgaard R.H., Winkel J. (2010) Systematic evaluation of observational methods assessing biomechanical exposures at work. *Scand J Work Environ Health*. 36, 3-24.

[20] Schaub, K. et al. (2000) Ergonomics screening of assembly tasks in automotive industries. In: *Proceedings of the IEA 2000/HFES 2000 congress, 44th annual meeting of the human factors and ergonomics society – ergonomics for the new millennium*, 29 Juli–4 August 2000, San Diego, USA. 5-759–5-762.

[21] Schaub, K. et al. (2008) Ergonomics risk assessments in automotive and electrical industry based on the dual European concept of health and safety at work. In: *NES 2008 abstracts, ergonomics is a lifestyle, 40th annual conference of the Nordic ergonomics society*, Reykjavı´k, Iceland, 11–13 August 2008, 230.

[22] Landau, K. (2008). Musculoskeletal disorders in assembly jobs in the automotive industry with special reference to age management aspects. *International Journal of Industrial Ergonomics*. 38, 561–576.

[23] Scaub K., Caragnano G., Britzke B., Bruder R. (2012) The European Assembly Worksheet. *Theoretical Issues in Ergonomics Science*, 1-23. DOI: 10.1080/1463922X.2012.678283

[24] Hagg G.M. (2003) Corporative initiative in ergonomics – an introduction. *Applied Ergonomics*, 34, 3-15.

[25] Dul J., Neumann W.P. (2009) Ergonomics contributions to company strategies. *Applied Ergonomics*, 40 (4), 745-752.

[26] Chaffin D., Andersson G.B.J., Martin B.J. (2006) *Occupational Biomechanics* (4th Edition) J. Wiley & Sons, New York.

[27] Feyen R., Liu Y., Chaffin D., Jimmerson G. and Joseph B. (2000) Computer –aided ergonomics: a case study of incorporating ergonomics analyses into workplace design. *Applied Ergonomics*, 31, 291-300.

[28] Lämkull D., Hanson L., Örtengren, R. (2009) A comparative study of digital human modelling simulation results and their outcomes in reality: A case study within manual assembly of automobiles. *International Journal of Industrial Ergonomics*, 428-441.

[29] DiPardo M., Riccio A., Sessa F., Naddeo A., Talamo L. (2007) Methodology development for ergonomic analysis of work-cells in virtual environment. *SAE Paper n. 2007-08B-391*.

[30] Spada S., Sessa F., Corato F., (2012), Virtual Reality tools and statistical analysis for human movement simulation. Application to ergonomics optimization of workcells in the automotive industry. *Work*, 41, 6120-6126.

[31] Cavatorta M.P., Ghibaudo L., Marchetti P., Spada S., DiPardo M., Baracco A. (2012) Enhancing cooperation between the industrial world and the academia in the area of ergonomics. In: *IEA 2012,18th World Congress on Ergonomics*, 12-16 February 2012, Recife, Brazil.

[1]ISSUES OF SUSTAINABLE TRANSPORT

Bruno Dalla Chiara, Ivano Pinna

UDC: 621.112

Summary
The purpose of this paper is a general framing on the role and impact of the transport systems, the road one in particular, in the general energy consumption and on the impact – on the other hand – of consumption on the operational cost of the different transport modes as well as on how consumption evolved in recent decades.
These elements are essential for a clearer understanding of where and how much energy efficiency can impact on land transport modes and provide the ground for some general considerations on the energy demand in the road transport. The environmental impact is a consequence of the energy use and some main considerations are also proposed on it.
European solutions for a transport system compliant with the energy supply and the environment can thereafter be analyzed: measurable analyses - as the well-to-wheel - on the base of experiences and recent EU legislation can be provided too.

Key words: Transport systems, energy use, well-to-wheel analysis, sustainable motorized mobility

PITANJA ODRŽIVOG TRANSPORTA

UDC: 621.112

Rezime
Cilj rada je analiza opšteg oblika uloge i uticaja transportnih sistema na put i potrošnju energije sa jedne strane i operacione troškove različitih tipova transporta kao i na to kako je potrošnja goriva evoluirala tokom poslednjih decenija.
Ovi elementi su suštinski za jasno shvatanje kada i koliko mnogo veća energetska efikasnost mogu uticati na tipove kopnenog transporta i da obezbede neka opšta razmatranja o zahtevima za energijom u drumskom saobraćaju. Uticaj sredine je značajan na potronju energije i neka glavna razmatranja će biti prikazana.
Evropska rešenja za transportne sisteme određena su potrebom za snabdevanje energijom i okruženjem i mogu se analizirati - merivim analizama kao i na osnovu iskustava uvođenjem novih EU zakona.

Ključne reči: transportni sistemi, korišćenje energije, „well to wheel“ analiza, održiva motorizovana mobilnost

[1] *Received August, 2011, accepted September 2012*

Intentionally blank

ISSUES OF SUSTAINABLE TRANSPORT

Bruno Dalla Chiara[1], PhD, Associate professor, ***Ivano Pinna***, MSc, Contract Researcher

UDC: 629.3

1. INTRODUCTION

The lecture intends to deal specifically with the following broad topics on the demand and use of energy in the transport systems, namely:

- How much do the transport systems impact the use of energy;
- How has energy consumption evolved in transport systems;
- How much does the use of energy impact within each transport mode;
- What is the involvement of governments in the use of oil for traction;
- What solutions can be prospected in a changing economy, including both the traction of vehicles and public administrations' economic interests.

The paper gathers and synthesises, at first, a general framing on the role and impact of transport systems in the general energy consumption, with related evolution, and – on the other hand – on the impact of consumption on the operational cost of the different transport modes. These elements are essential for a clearer understanding of where and how much energy efficiency can impact the different transport modes and for providing the ground for any general consideration on the energy demand in the transport systems.

A perspective on consequent engines and motor vehicles is provided thereafter.

2. IMPACT OF THE TRANSPORT SYSTEMS ON THE ENERGY USE

The transport field is mainly characterized by the use of vehicles with distributed energy use, with the exception – in general terms – of those systems operating on fixed installations such as railways, subways, cableways and the so-called automated people movers (Dalla Chiara, Degioanni, 2008); in the large majority of cases, as it is specified further on, the combustion of the energy resource is developed directly on the vehicles, be they on road, sea, inland waterways or air; besides the engine, they are usually also provided with a fuel tank.

Almost all these transport systems are based upon oil derived fuel, and the alternatives are featured by significant limits; transport systems operating on fixed installations do not strictly depend on it since – as well known – they use, with the exception of Diesel traction, electrical lines supplied by power stations, irrespectively on the energy source used to supply such stations. The transport field is moreover the only sector to be almost exclusively based upon a sole primary source, oil (Dalla Chiara, Ricagno, Santarelli, 2008).

[1] Bruno Dalla Chiara, Ph.D., M.Sc. in Mechanical Engineering, Politecnico di Torino, Dept. DIATI-Transport Engineering, Corso Duca degli Abruzzi 24, 10129 Torino – IT, bruno.dallachiara@polito.it

From the data of the Italian Ministry of the Economic Development in 2010, it is estimated that this dependence for Italy was nearly 93.4% for its use in transport system (road, rail, ...), though in reduction with respect to 2005, when black oil was used for nearly the 97%; some figures at European level of the beginning of the decade (EU White Book on transports of 2001, [COM/2001/0370 def.]) estimated this value at the 98%; in the USA it was estimated at the 96% in the same period, reduced at the 93.2% in 2010 [US Transportation Energy Data Book 2011, Ed30]). The Withe book on Transport Systems of 2011 reports a figure of 96% in EU.

According to Eurostat, the impact in Europe (EU-25) of the transport systems in the overall use of the energy consumed in the EU countries in 2004 resulted to be equal to 30.7%; such value has grown around 32 (2006) to 33-34% (2008) in the following years (Dalla Chiara, 2010; Dalla Chiara, Ricagno, Santarelli, 2008; EIA, 2006 and 2008). The impact of the transport systems in Europe is greater by nearly 10% versus the world average (estimate, 20.42% in 2003), on the grounds of the greater motorised average mobility versus other continents. Europe actually shows a variability in the impact of transport consumption versus the overall final values reported for the different countries (Unione Petrolifera - I, 2009, 2011) (Figure 1).

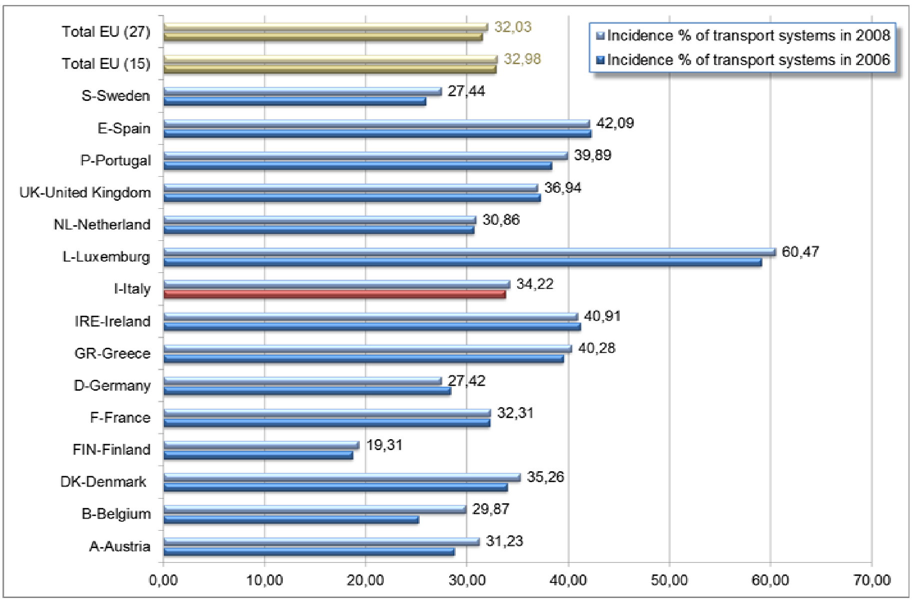


Figure 1 *Impact of the energy consumption of transport on the final domestic consumption in Europe and in the relevant nations, data of 2006 and 2008 (Dalla Chiara, 2010; Unione Petrolifera, 2009, 2011; Eurostat)*

3. EVOLUTION OF ENERGY CONSUMPTION IN TRANSPORT SYSTEMS

Within the framework of motor transports, the road one – according to publications referred to EU25 (European Commission, 2004, 2005, 2006) – involves a share on the overall energy consumption (tons of oil equivalent) of approximately 82.5%, and is therefore predominant - at continental scale - over the other modalities (EC, Eurostat, Campbell, 2007); railways are estimated below 3% approximately (**Error! Reference source not found.***)*.

***Table** 1 EU-25, consumption by transport modality in 1990 and 2004, in 1000 tep or toe, tonne(s) of oil equivalent (European Commission,2007; Eurostat)*

Transport modes	1990	2004	1990-2004 variation (%)	Share on the overall energy consumptions 2004 (%)
Road	227957	290013	27%	82.5%
Railway	9125	9250	1%	2.6%
Air	28378	47420	67%	13.5%
Inland navigation	6578	5047	-23%	1.4%

To start answering the second question, the circulating vehicles need to be considered; in the 2nd half of the 20th century, the number of cars in the European countries has witnessed continuous growth (Figure 2*)*, as also comprehensible in (Woldeamanuel et al., 2009).

In 2008 approximately 176.5 million circulating vehicles out of the 806 million ones in the whole world (Figure 3), were circulating in the sole China, a datum which represented approximately 21% of the circulating fleet the world over (Dalla Chiara, 2010; Unione Petrolifera -I, 2009, 2011).

To define actual consumption, we need also to examine the use people make of such circulating fleet, which is connected to both the average distance covered and relevant occupancy rate.

However, more worrisome data concern the future (The Worldwatch Institute, 2007): the European population is of approximately 500 mln. inhabitants, i.e. one fifth of the overall population of China and India.

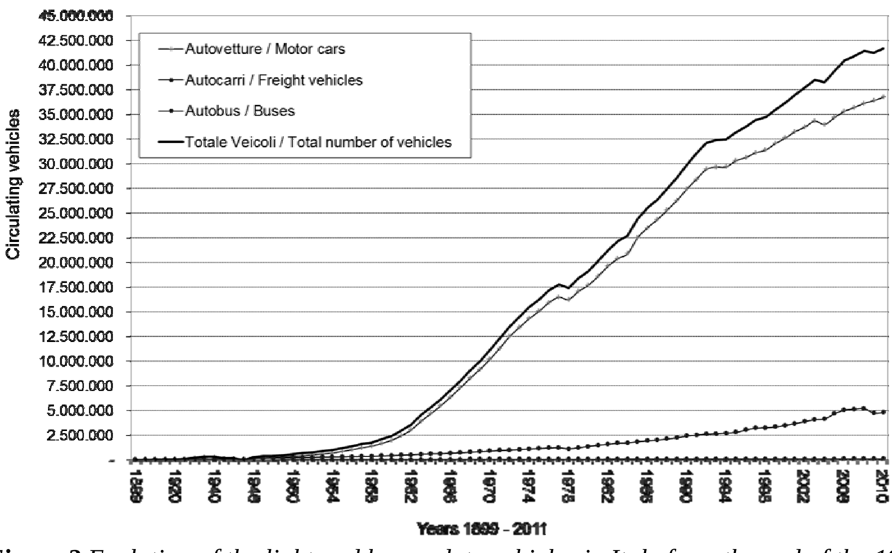


***Figure 2** Evolution of the light and heavy-duty vehicles in Italy from the end of the 19th century until today (Maggi, 2005; ANFIA-I, various years)*

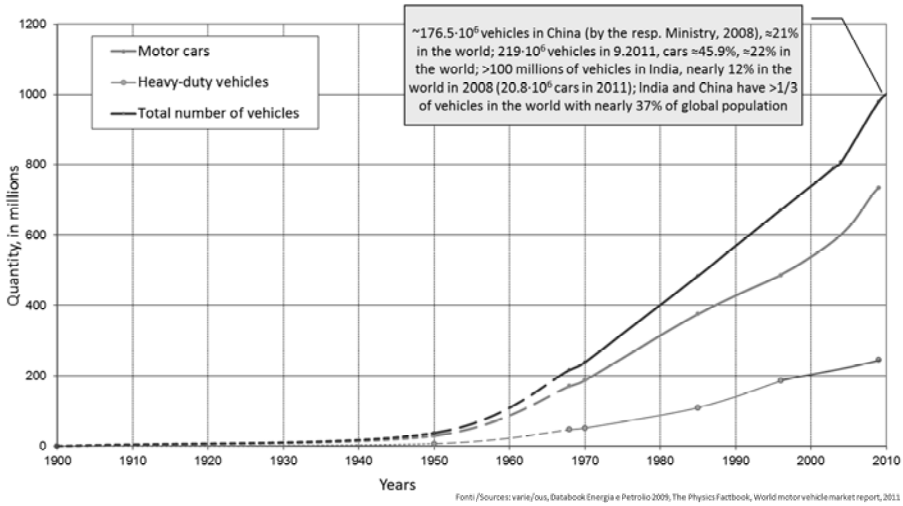


Figure 3 *Vehicles circulating in the world: approximate trend on the basis of few known data and estimates from different sources (Sources: miscellaneous; Unione Petrolifera,2009, 2011; The Physics Factbook, World motor vehicle market report, 2010)*

Subsequently, if - as it can be expected today – these two countries reached an average level of motorisation equal to the European one, the conditions might come to a head, since the demand of oil in these Countries might grow at a very fast rate, with an expectable subsequent increase in the sale price except – of course – in case of strongly competitive alternative resources. If we consider China, in 40 years oil consumption moved from approximately 11 million tons per year (1965) to up to approximately 327 million in 2005 (Dalla Chiara, 2010): a 2,900% increment in consumption for an average increase of something like 72.5 % every year.

As far as railway transport (Trenitalia, 2005) is concerned, the consumption values in Italy are recorded around approximately one million toe (Figure 4), a value which can be considered consistent to the one reported in **Error! Reference source not found.** Other data on energy use are reported in (CIFI , 2010).

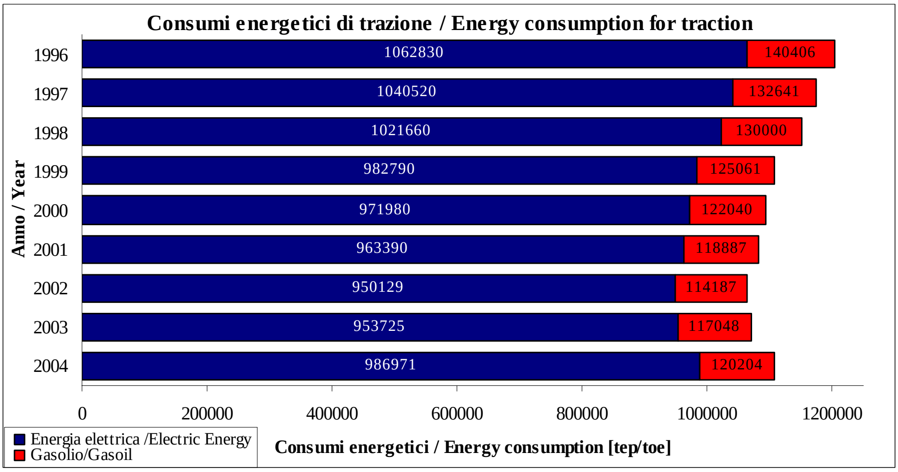
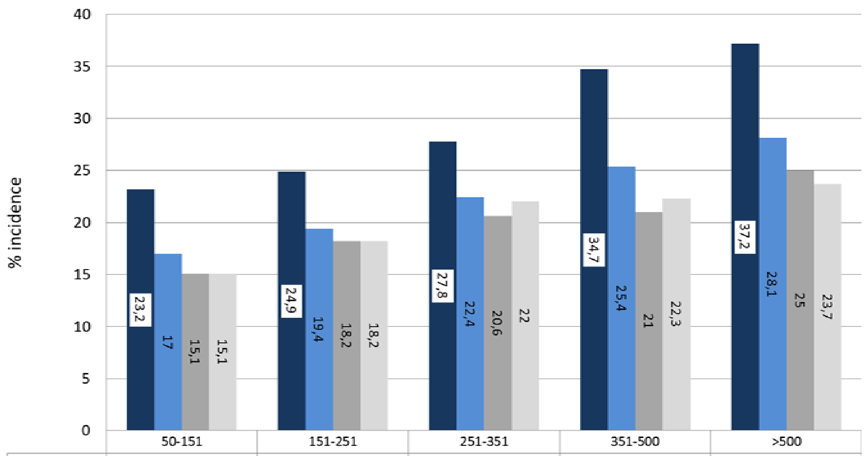


Figure 4 *Energy consumption in the last few years (Dalla Chiara, 2010; Trenitalia, 2005)*

4. IMPACT OF THE USE OF ENERGY IN THE TRANSPORT MODES

The impact of energy consumption in road transport is extremely variable also because of the use of vehicles from 2 up to 10 and more wheels; as an example we can mention – in 2008 – an exceptional impact of energy consumption on the running cost of freight - i.e. referred to heavy-duty means – equally to approximately 25 to 35%, with further peaks up to 37% in 2011. The incidence of freight transport by road, including industrial and commercial vehicles, on the overall road transport energy consumption, was approximately 39.5% in 2008.

The pure indicative example reported Figure 5 shows the run - incidence of cost of gasoil on road transport, on the base of Italian Ministerial data; obviously the values vary according to the total weight and the average run of the heavy-duty (industrial) or commercial-duty vehicles.



	50-151	151-251	251-351	351-500	>500
>=26 T	23,2	24,9	27,8	34,7	37,2
11.5T<x<26T	17	19,4	22,4	25,4	28,1
7.5T<x<11.5T	15,1	18,2	20,6	21	25
3.5T<x<7.5T	15,1	18,2	22	22,3	23,7

Figure 5 *Run - incidence of cost of gasoil on road transport, on the base of Ministerial data 2011 (example for Italy)*

Figure 6 reports the impact of road freight transport (transport of goods) on the overall energy consumption in road transport: a value close to 40% in Italy; data from the Transportation Energy Data book (2012, data of 2010) in the US allow to estimate around 22% for medium and heavy trucks.

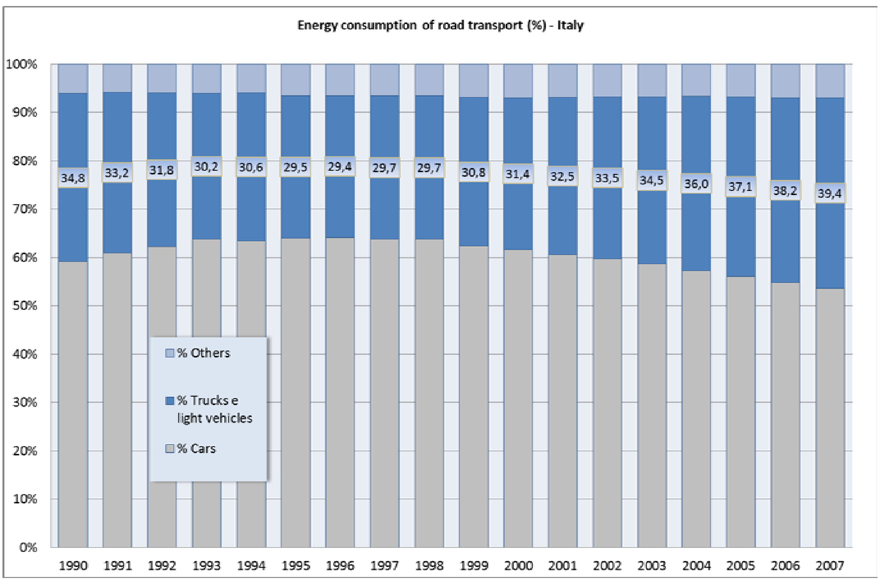


Figure 6 *Impact of road haulage (transport of goods) on the overall energy consumption in road transport.*

If we observe, on the other hand, the impact on the operational cost of energy consumption in railways, subways and tramways, some indicative data – similar to one another – emerge:

~4-5%, indicatively, for the Italian railways, on the overall running cost, according to some unofficial data of 2009;

~11% for the public transport in Milan, taken as an example, as energy cost on the 2009 budget, approximately 50% (5.3%) for rail systems and subway in the specific case (official data of 2009);

~6% as energy impact on the budget in case of the traction for the automated metro operating in Turin, plus an equivalent value for other electric power supply means (indicative data of 2009).

It is unmistakable that, in case of urban traction, the more frequent acceleration and braking phases lead to a greater impact of energy consumption versus the case of medium to long distance traction, as it is the case of the national railway service; such impact is even more obvious in case of high acceleration and braking in comparison with the conventional subways, as it is the case in the automated metro.

However, in order to provide an appropriate analysis on energy consumption, fully satisfactory on a methodological point of view, related to all transport systems, the well-to-wheel (WTW) index, a tool which was firstly proposed and consolidated in the automotive industry, but which is rarely applied to the other modes, needs to be adopted.

WTW is an absolute energy index, whose function enables the comparison between combinations of different propulsion technologies and different fuels or energy carriers (i.e. hydrogen and electricity, which - once they are produced - can be considered as fuels), obtained from the most various primary sources.

The WTW index, which can be defined as the integration of all the processes required to produce and distribute a fuel (starting from the primary energy source) and use it in a vehicle **Error! Reference source not found.**EC, 2004), consists of the combination of two more specific sub-indexes, namely: well-to-tank (WTT) and tank-to-wheel (TTW).

WTT considers the amount of energy required to make the fuel available from the primary energy source (energy expenditure for extraction, for the chemical processes of transformation and for transport) up to the supply into the car tank, in a broad meaning; it is usually expressed in MJt/MJf, where MJt is the overall amount of energy spent to make available such MJ of fuel and MJf is the energy contained in the fuel stored in the vehicle tank.

On the other hand, TTW considers the amount of energy used to move a means of transport along a given distance, which depends on the combination of the fuel and of the propulsive technology used.

On the analysis point of view, the assessment of the WTW index is provided by ratio:

$$WTW \quad \left[\frac{MJ_t}{km}\right] = WTT \quad \left[\frac{MJ_t}{MJ_f}\right] \cdot TTW \quad \left[\frac{MJ_f}{km}\right] \tag{1}$$

In the automotive industry, TTW can be determined through standardized guiding processes, where the speeds and the driving conditions (i.e. stops at the traffic lights and slopes) are as close to reality as possible.

It must be set forth that the calculation of WTW for the rolling stock is a complex exercise, mainly because of the very little experience in the sector.

Other significant limits are the standard pathway on which the consumption of the different trains may be calculated, as well as the broad heterogeneity of the circulating stock and the relevant performances. Because of the lack of availability to the public of data coming from an energy counter either on board the locomotives (Dalla Chiara, Ricagno, Santarelli, 2008)**Error! Reference source not found.** or at the sub-stations, with connected rail traffic, three alternative options can be taken into account, namely:

the use of empirical formulas, which are to be specific for each section and for each type of train; this option is nevertheless more functional in a case study, since - because of the broad heterogeneity of lines and means - it cannot provide general indications as the car WTW instead does;

use of other empirical formulas based upon the resistances of the train and - therefore - on the equation of motion: in this case, only an estimate of the consumption can be obtained and some inaccuracy needs to be accepted; furthermore, the section covered by the train whose TTW is being calculated is not taken under consideration;

the use of analytical models for the dynamics of the train motion; this would though require high accuracy data which are often difficult to be found; finally, the time required to run such analysis would be too long to be justified in practice.

In the car industry, furthermore, the mass of the vehicle has little significance and can be taken into account, within the WTW; on contrary, it plays a far more important role in railways, since it prevails on the weight of the transported passengers. This is why - as related to the sole comparison between different trains - analysing and proposing the data in MJf/(p·km) is not always exhaustive but - sometimes - it would be more meaningful to consider the load handled, e.g. in MJf/(t·km).

Another parameter to be known in order to determine the WTW of the trains is the load factor or utilization degree, which, reporting the number of passengers as a percentage of seats available on the train, quantifies its occupancy and - therefore - establishes an index for its utilisation.

Table 2 introduces the WTT of the traditional fuels and of the energy vectors which can be taken into consideration as their main alternatives (i.e. hydrogen and electricity) produced from different primary sources.

Table 2 *WTT of the most common and promising fuels in the European context*

FUEL	WTT [MJ_t/MJ_f]
Petrol	1.14
Gasoil	1.16
Compressed natural gas	1.19
Hydrogen from natural gas	1.82
Hydrogen from electrolysis (from wind power)	1.74
Hydrogen from electrolysis (European mix)	4.58
Electricity (European mix)	2.86
Electricity (European coal mix)	2.59
Electricity from wind power	0.04
Electricity from nuclear power	3.73

Table *3* introduces the TTW of the main propulsion techniques which are currently available on the automotive market, i.e. the ICE's (Internal Combustion Engines), and the ones the manufacturers are developing for the utilisation of electricity (electric and hybrid motors) and hydrogen (Fuel Cell – FC).

Table 3 *TTW of the main propulsion technologies in the car industry in 2010*

PROPULSION TECHNOLOGY	TTW [MJ_f/km]
ICE – petrol*	1.91
ICE – gasoil*	1.72
ICE – compressed natural gas	1.9
ICE – hydrogen	1.67
ICE-hybrid – petrol	1.62
ICE-hybrid – gasoil	1.41
Electric car (batteries)	1.1
FC – hydrogen	0.91

As far as the TTW of the rolling stock is concerned, we have decided in a previous research (Dalla Chiara, Ricagno, Santarelli, 2008) to take at first into account three high-speed trains: the French TGV, the German ICE and the Spanish AVE, i.e. the trains whose consumption was measured (in 1997) and whose results are available in the literature (Table 4).

Table 4 *TTW* and TTWFL for some types of European trains*.

TRAIN	TTW [MJ_f/(t·km)]	[t/seat]*	[t/seat]$_{FL}$	utilization degree	TTW* [MJ_f/(p·km)]	TTW$_{FL}$ [MJ_f/(p·km)]
TGV	0.148	0.914	0.966	65%	0.209	0.143
ICE	0.104	1.294	1.336	51%	0.263	0.138
AVE	0.136	1.305	1.346	66%	0.268	0.183

In order to obtain the TTW*(taking into consideration the actual average occupation of the means) of the trains in MJ/(p·km), the following ratio needs to be applied:

$$TTW^{*}\left[\frac{MJ}{pkm}\right]=TTW\left[\frac{MJ}{tkm}\right]\cdot\left[\frac{t}{seat}\right]\cdot\left[\frac{p}{seat}\right]^{-1} \qquad (2)$$

In order to assess the effects of the different energy performances between private car and train, a case study which tales into exam – as an example - the connection between Turin and Milan was also developed (Dalla Chiara, Ricagno, Santarelli, 2008).

The two cities are connected by a motorway, by a conventional railway line and by a high speed railway line. The purpose is to calculate the absolute energy consumption of car, bus, Intercity train, interregional passenger train and high speed ETR 500, supposing we need to transport - with the real factors of utilisation - 1,000 people within a given time slot.

In order to calculate the absolute energy expenditure of each mode, the WTW* needs to be multiplied by the transported passengers and by the kilometres covered by every means.

The result of the study shows that the most energetically efficient means to cover the Turin-Milan line resulted to be the ETR 500 (Figure 7), which has to run a shorter travel, with lack of stops, with respect to the traditional trains and railway.

As regards air transport, in the last decades, Europe as well as the most industrially developed countries witnessed an expansion of it, mainly as related to passengers. IATA (International Air Transport Association) measured the impact of the cost of fuel on the airline activities, identifying that:

it represented 14% of the overall cost in 2003;

the impact grew up to 29% in 2007;

a new increment up to 32% was witnessed in 2008.

It is worth reminding, nevertheless, the contextual increment of the cost of oil per barrel. ATA (Air Transport Association), which represents the main airlines of the USA, declared that the cost of fuel influences the air fare by approximately 40% (2008).

As far as maritime transport is concerned, the development of the traffic of goods loaded in containers has involved the development of progressively larger and more capacious ships (Dalla Chiara, 2009, 2010).

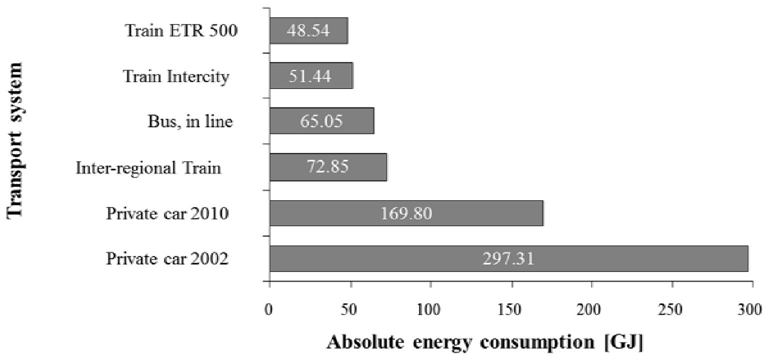


Figure 7 *. Absolute energy consumption on the Turin-Milan (I) line for the modes of transport taken into consideration as case study*

5. INVOLVEMENT OF GOVERNMENTS IN THE USE OF OIL FOR TRACTION

In such context, which is therefore characterised by the almost exclusive use of oil derived fuel in the transport systems, a direct involvement of the Italian Governments – irrespectively on the periods of time, but in any case starting from the second half of the past century – and – in some cases – of other European countries appears plainly; this fact can be particularly documented as related to road transport in Italy: from the tax composition related to one liter of fuel in a given moment (data of 2005, Italy), it results that the tax or fiscal component involves approximately 60.4% of it.

It can then be calculated how much the consumption for transport - mainly the road one - has influenced the state revenue, because of its impact:

Income for petrol excise duty in 2005 = 0,5631 €/litre · 18,765,833,333 litres = 10,567,040,750 €;

Income for gas oil excise duty in 2005 = 0,4114 €/litre · 29,084,720,238 litres = 11,965,453,906 €;

Total revenue for excise duties in 2005 = 10,567,040,750 + 11,965,453,906 = 22,532,494,656 €

Such value can also be estimated on the basis of the average distance yearly covered by the vehicles in Italy, which is equal to approximately 12,500 km according to the analyses of data collected by the “National Transport Account” for several years, multiplied by the average consumption and the money income associated to the excise duty.

The data, obtained theoretically, can be compared and then confirmed by the ones which are found in the State Budget, an abstract of which is reported in Figure 8.

UNITA' PREVISIONALE / CAPITOLO / ARTICOLO DENOMINAZIONE		RESIDUI	COMPETENZA
1.1.12 ACCISA E IMPOSTA ERARIALE DI CONSUMO SUGLI OLI MINERALI, LORO DERIVATI, PRODOTTI ANALOGHI E RELATIVE SOVRIMPOSTE DI CONFINE			
Entrate derivanti dall'attivita' ordinaria di gestione			
ACCISA E IMPOSTA ERARIALE DI CONSUMO SUGLI OLI MINERALI, LORO DERIVATI E PRODOTTI ANALOGHI			
IMPOSTA RISCOSSA IN VIA ORDINARIA	INIZ.	1.955.484.768,34	22.209.270.000,00
	VARIAZ.		322.091.133,00
	DEFIN.	1.955.484.768,34	22.531.361.133,00
	VERSATO	5.330.597,76	21.222.423.358,32
	DA VERS		41.924,23
	DA RISC	1.782.265.828,18	3.760.624,39
	TOTALE	1.787.596.425,94	21.226.225.906,94
	RISC	5.290.510,55	
	MG/MNE	167.888.342,40	1.305.135.226,06
	RS31/12	1.786.068.376,80	

Figure 8 *Abstract of the State budget (Italy): 2005 excise duty.*

The aforementioned excise duty derived data can be added to the income connected to V.A.T., namely:

- Yearly revenue for V.A.T. on petrol = 0.2032 € · 18,765,833,333 litres = 3,813,217,333 €
- Yearly revenue for V.A.T. on gas oil = 0.18452 € · 29,084,720,238 litres = 5,366,712,578 €
- Total V.A.T. yearly revenue in 2005 = 3,813,217,33 € + 5,366,712,578 € = 9,179,929,911 €
- Subsequently, in 2005 the consumption of fuels involved, as excise duty and V.A.T., State revenue of approximately 31,712,424,567 €. This value can be added to the V.A.T. for the purchase of vehicles and the road tax.

The last decades have witnessed an economic cycle by which an increase of the road infrastructure was accompanied by the increase of the circulating fleet and vice versa, as well as by fuel consumption, hence of the State income: an economically profitable circle for industry, Governments, manufacturers and infrastructure managers.

Having available the data of the vehicle fleet, the average distance covered per year and the average emissions of the vehicles (EC, 2004, 2005; Jørgensen M.W.e Sorenson, 1997 Strelow, 2006), the total emissions in Italy can be estimated per means of transport.

An assumption derived from the previous observations is the possible payment for the use of the natural resources utilised to meet the requirements of transport and mobility, namely:

Not realistically, the oxygen, to be accompanied to the well-known considerations on CO2 which arose in the international panorama, which is instead a combustion product;

More realistically, the road soil, meant as payment for the use of the infrastructure on the basis of the actual distance covered (road pricing), with the support of transport telematics; this choice is considered important, and it has already been made by the Netherlands for the payment of the road tax in the forthcoming years.

This would impact the transport demand – by generating awareness on the actual utilisation of the distances covered by means of one own's motor vehicle – and a correction can be applied on the related market. In many countries, the current tax system responds to a logic which does not depend on the mileage covered, but is a function of the power and emission class of the engine.

6. POSSIBLE SOLUTIONS IN A CHANGING ECONOMY

What has arisen from the previous remarks implies that, in Europe, we should not necessarily expect an increase in either mobility or in the consumption related to it, whilst safety, quality and efficiency – mainly as far as energy is concerned – are to be pursued (Deflorio et al., 2008).

Subsequently, our economic system, in the European countries, seems to be passing from a context prevailingly based on production - which is both industrial and civil, the latter is meant specifically as building of transport infrastructures - to another one based upon efficiency, quality and safety.

However, on the grounds of the world scenario, one of the main challenges our society is facing is the procurement and management of the energy flows, as well as the consequences of their use on both people and the environment in the wide meaning of the word.

Such issues are highly influencing all the sectors of energy consumption, in particular as related to the transport sector, which nowadays depends almost exclusively on oil.

On this basis, an important step has been taken with the EU Directive 2009/33/EC of the European Parliament and of the Council on the promotion of clean and energy-efficient road transport vehicles.

This aims to stimulate the market for clean and energy-efficient road transport, and especially – since this would have a substantial environmental impact – to influence the market for standardised vehicles produced in larger quantities: passenger cars, buses, coaches and trucks; the aim is to ensure a level of demand for clean and energy-efficient road transport vehicles which is sufficiently substantial to encourage manufacturers and the industry to invest in and further develop vehicles with low energy consumption, CO2 emissions, and pollutant emissions.

The approach is based on the internalization of external costs by means of lifetime costs of fuel, CO2 emissions and pollutant emissions of the vehicles.

$$C_{op} = C_{amb} + C_{fuel} \left[€ \right]$$
$$C_{amb} = C_{CO_2} + C_{NO_x} + C_{NMHC} + C_{PM} \left[€ \right] \quad (3)$$

The directive considers only the emissions occurring during the Tank-To-Wheel (TTW) energy use and emissions. Following the methodology described by the Directive is possible to obtain details of various vehicle categories and sub-categories (Figure 9).

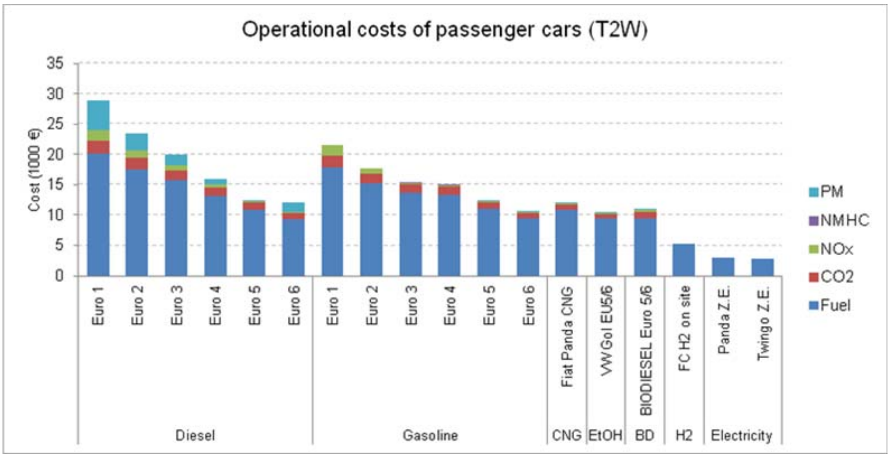


***Figure 9** Operational costs of passenger cars (Santarelli,De Oliveira-Politecnico di Torino, 2011)*

Technology is offered as a crosswise solution to the energy issue, as a tool through which Man can remedy the fact that the resource which is prevailingly being utilized to enable transport may become scarce, or that it may be perceived as such, by improving efficiency or rationalizing the consumption of his own activities (also with telematic systems, "ITS" or Intelligent Transport Systems) and developing a structure which can be sustainable with a limited supply of fossil fuels.

The conclusive message could then be summarized as follows: the improvement of what exists can be pursued in terms of quality, safety and efficiency of both engines and transport systems, also through the support of telematics and "ITS"; the intent would be trying to develop independency in transport on the almost sole energy resource, i.e. oil, in order not to be chained by it and temporarily immobilised: the path is the one of both efficiency and alternative energies. In this perspective, the railway system results therefore to offer a good and even optimum solution – wherever is it appropriate to meet both mobility and freight – because of its own constitution.

7. CONCLUSIONS

Energy supply for transport could take a large number of different pathways as shown in Figure 10. Alternative fuels will gradually become a much more significant part of the energy mix: no single substitution candidate, however, can be foreseen. Fuel demand and greenhouse gas challenges will most likely require the use of *a great variety of primary* *energies*. There is rather broad agreement that all sustainable fuels will be needed to resolve the expected supply-demand tensions.

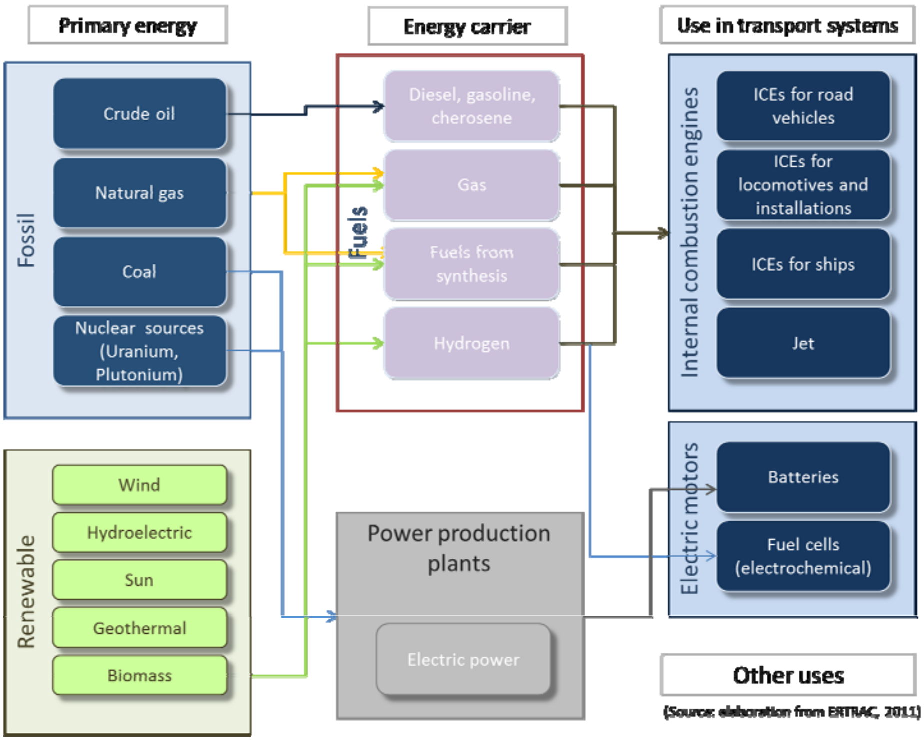


Figure 10 *Energy pathways in transport and other sectors (Source: modifications from a basis by ERTRAC)*

As regards instead the road vehicles, Figure 11 reports a possible scenario for the future traction and propulsion, on the base of the WTW analysis, interaction of the production with the territory and energy availability (Report of the European Expert Group on Future Transport Fuel, 2011).

Therefore the problem might be to reverse partially to the Smart Grid a sector which weights for nearly one third of the overall energy consumption and which aims to exit from the monopoly of that energy source that it chose at the beginning of the last century: as a matter of fact, various alternative solutions, from the engine (ICEs) efficiency to the hybrid-electric and full-electric vehicles (charged on the SG, with a quote likely variable from Nation to Nation and from Region to Region), to a higher load on public transport based on electric power, to alternative primary energies, including Natural Gas, may arise in the next future.

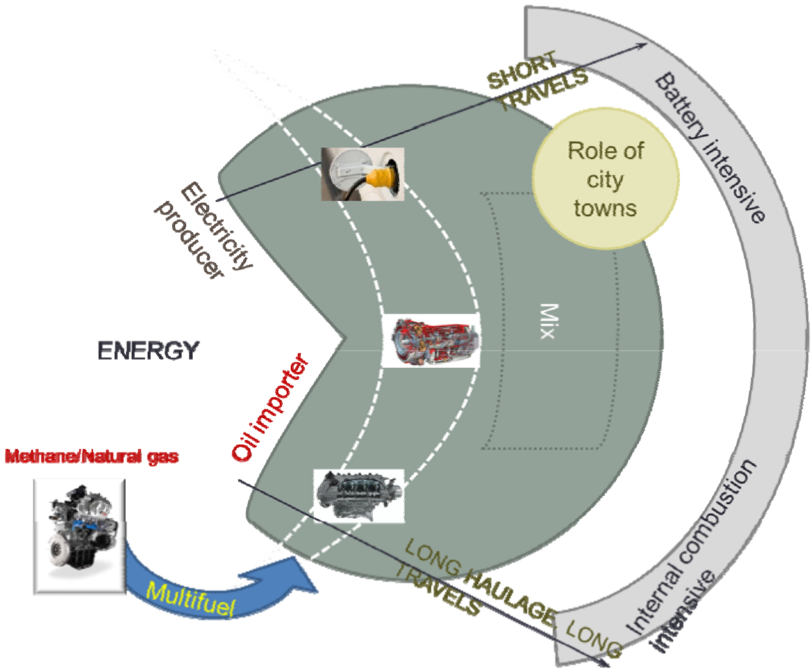


Figure 11 *A perspective on road vehicle traction and propulsion on the basis of WTW analysis, interaction of the prodiction with the territory and energy availability (Politecnco di Torino, 2011)*

8. REFERENCES

[1] Collegio Ingegneri Ferroviari Italiani (CIFI), Proceedings of the congress "Per un uso attento dell'energia nel trasporto su ferro", at the Politecnico di Milano, 28.01.2010

[2] Dalla Chiara B., "Sistemi di trasporto intermodali: progettazione ed esercizio", 2009, ISBN: 978-88-8482-299-4, pp. 288. Ed. EGAF

[3] Dalla Chiara B., "Domanda ed uso dell'energia nei sistemi di trasporto", VII Conference on "Energia: 2010 ed oltre" on "Efficienza energetica nei trasporti", Politecnico di Torino, 3.03.2010

[4] Dalla Chiara B., Ricagno R. and Santarelli M., Sostenibilità energetica dei trasporti: analisi dei consumi e della soluzione ferroviaria, Ingegneria Ferroviaria, vol. LXIII, pp. 531-543, N. 6, 2008.

[5] Dalla Chiara B., Pinna I., Demand and use of energy in transport systems: new perspectives and consequent choices, Società Italiana Docenti di Trasporti, 6 and 7.10.2011 Palazzo Badoer, 6th October 2011 –Scientific Seminar on "Energy, environment and innovation in sustainable transport systems"

[6] Dalla Chiara B., "Considerazioni sulla domanda ed impiego di energia nei sistemi di trasporto / Considerations on the demand and use of energy in the transport systems", Ingegneria Ferroviaria, vol. LXV, ISSN: 0020-0956. Numero 7-8, pp. 673-685, July-August 2010

[7] Dalla Chiara B., Degioanni P e Fumarola F.P., "Riepilogo di sistemi di trasporto innovativi", Ingegneria Ferroviaria, anno LXIII, n. 1, 2008

[8] Deflorio F., Dalla Chiara B. and Barosso M., “Controllo accessi in aree urbane: comparazione di strategie basate su sistemi telematici (ITS) mediante modelli di micro-simulazione del traffico”, in “Interventi e metodologie di progetto per una mobilità sostenibile”, Seminario scientifico 2008, editors Vittorio Astarita, Sergio d'Elia, Demetrio Carmine Festa, ISBN 978-88-568-1230-5, pp. 189-203
[9] EIA – Energy Information Administration, International Energy Outlook, June 2006
[10] European Commission, The annual energy and transport review for 2004, December 2005
[11] European Commission, Energy and Transport in Figures 2005, 2005
[12] European Commission, European Energy and Transport: scenarios on energy efficiency and renewables, 2006
[13] European Commission, European Energy and Transport: scenarios on high oil and gas prices, 2006
[14] European Commission, Well-to-Wheel analysis of future fuels and powertrains in the European context: WELL-to-WHEEL REPORT, Version 1b, January 2004
[15] European Commission, Eurostat, G. Campbell, Panorama of Transport, Edition 2007, Luxembourg
[16] Maggi S., “Storia dei trasporti in Italia”, Ed. Il Mulino, ISBN-13: 9788815105516, 2005
[17] Report of the European Expert Group on Future Transport Fuel, Alternative Fuels, December 2011
[18] Strelow H., Statistic in focus: Passenger Transport in the European Union, September 2006
[19] The Worldwatch Institute, State of the World 2007, our urban future, 2007
[20] Trenitalia, Rapporto Ambientale 2005, 2005
[21] Jørgensen M.W., Sorenson S.C., Estimating Emissions from Railway Traffic, Report for the Project MEET – Methodologies for Estimating air pollutant Emission from Transport, July 1997
[22] Unione Petrolifera, “Data book”, Energia e Petrolio, 2009 and 2011
[23] Woldeamanuel Mintesnot G., Cyganski R., Schulz A.e Justen A., Variation of households’ car ownership across time: application of a panel data model, Transportation, Springer (NL), ISSN 0049-4488, Issue Volume 36, Number 4 / July, 2009, pp. 371-387

[1]FUTURE PERSPECTIVES OF THE TWO-STROKE SPARK IGNITION ENGINEDESIGN OF THE MOTOR VEHICLES FROM THE ASPECT OF HIGH STRENGTH STEELS APPLICATIONS

Patrizio Nuccio, PhD full professor

UDC: 621.112

Summary

As more stringent emission limits and low consumption requirements necessary for all current vehicle propulsion systems also apply to s.i. 2-stroke engines, one of the most important design modifications that can cope with these constraints involves performing the scavenging process using pure air, which means not only fuel-free air but also oil-free air.

Current two stroke s.i. engines are therefore equipped with a gasoline direct injection systems (GDI) and are the lubrication apparatus has also been modified in order to reduce both pollutant emissions and oil consumption.

After a short introduction on the two stroke s.i. engine, some examples of this kind of engine that apply these new technical solutions are presented and analyzed.

The second part of the paper presents the research activities conducted at the Energy Department Politecnico di Torino on two stroke s.i. engine over the last two decades.

After presenting the first experience gained a two stroke prototype engine, the first experimental results obtained on two mass-produced crankcase scavenged 2-stroke engines, the Benelli FB-1226 and the Husqvarna WR 250, provided with gasoline direct injection, are presented. These experimental results refer to a comparison between a carburettor or gasoline indirect injection fuel feeding system with a direct fuel injection system, as far as fuel consumption and pollutant emissions are concerned.

As satisfactory results were obtained, the direct injection apparatus was mounted onto a new prototype engine and the first experimental tests once more showed encouraging results, as far as fuel consumption and pollutant emissions are concerned.

Key words: Two stroke spark ignition engine, Gasoline direct injection

IZGLEDI ZA BUDUĆNOST DVOTAKTNIH BENZINSKIH MOTORADIZAJN MOTORNIH VOZILA SA ASPEKTA PRIMENE ČELIKA POVIŠENE JAČINE

UDC: 621.112

Rezime

Strože granice emisije i niske potrošnje goriva se zahtevaju od svih vrste pogonskih sistema vozila. Ovi zahtevi se primenjuju i na dvotaktnim benzinskim motorima. Jedna od

[1] *Received August, 2011, accepted September 2012*

najvažnijih konstruktivnih izmena koja može omogućiti zadovoljenje postavljenih zahteva je korišćene čistog vazduha za proces ispiranja, što znači ne samo čist vazduh bez goriva već i čist vazduh bez ulja.

Postojeći dvotaktni benzinski motori sa sistemom za direktno ubrizgavanje goriva (GDI) imaju izmenjen sistem za podmazivanje kako bi se smanjila emisija izduvnih gasova i potrošnja ulja.

Nakon kratkog uvoda o dvotaktnim benzinskim motorima, u radu su prikazani i analizirani primeri ove vrste motora kod kojih se primjenjuju nova tehnička rešenja.

U drugom delu rada prikazana su istraživanja benzinskih dvotaktnih motora koja su realizovana tokom zadnje dve decenije rada departmana za energiju na Politehnici u Torinu.

Prva iskustva su stečena na prototipu dvotaktnog motora. Dok su prvi rezultati dobijeni sa dvotaktnim motorima iz serijske proizvodnje Benelli FB-1226 i Husqvarna WR 250, koji su imali sistem direktnog ubrizgavanja benzina. Dobijeni eksperimentalni rezultati su služili za upoređenje potrošnje goriva i emisije izduvnih gasova karburatorskih ili motora sa indirektnim ubrizgavanjem benzina sa motorima koji su imali sistem sa direktnim ubrizgavanjem benzina.

Zadovoljavajući rezultati su dobijeni postavljanjem sistema za direktno ubrizgavanje na prototip novog motora. Prvi eksperimentalni rezultati su više nego ohrabrujući u pogledu potrošnje goriva i emisije izduvnih gasova.

Ključne reči: dvotaktni benzinski motor, benzinski motor sa direktnim ubrizgavanjem

FUTURE PERSPECTIVES OF THE TWO-STROKE SPARK IGNITION ENGINE

Patrizio Nuccio[1], PhD, professor

UDC: 621.1

NOMENCLATURE

- ABDC after bottom dead center
- BBDC before bottom dead center
- bmep brake mean effective pressure
- bsfc brake specific fuel consumption
- fmep friction mean effective pressure
- GDI gasoline direct injection
- GII gasoline indirect injection
- imep indicated mean effective pressure
- isfc indicated specific fuel consumption

1. INTRODUCTION

The reciprocating spark ignition engine has been described to Eugenio Barsanti and Felice Matteucci, who registered the layout of this new engine at the *Accademia dei Georgofili* in Florence in 1853, as shown in figure 1. The two-stroke engine has instead been attributed to the engineer Dugald Clerk (1881), see figure 2, who patented his design at the end of nineteenth century; the employment of the area below the piston as a charging pump, as shown in figure 3, was than credited to Joseph Day (1855–1946).

Thanks to its low cost, the two stroke engine immediately became popular and was largely used during the twentieth century for outboard motors, motorcycles, mopeds, scooters, tuk-tuks, snowmobiles, karts, ultralight airplanes, model vehicles, lawnmowers, etc.

Some car manufacturers also utilized two-stroke engines in the past; for example: the Swedish Saab Company, the German manufacturers DKW and Auto-Union and the Japanese manufacturer Suzuki, which also adopted the same type of engine in the 1970s (the LJ10 had a 359 cm^3 air-cooled, two-stroke, in-line two-cylinder engine). The production of cars powered by two-stroke engine came to an end in the 1980s in West Europe, but Eastern countries continued production until about 1991, with the Trabant and Wartburg in East Germany.

[1] Patrizio Nuccio, Ph.D., M.Sc. in Mechanical Engineering, Professor, Energy Department, Politecnico di Torino, Italy, Corso Duca degli Abruzzi 24, 10129 Torino – IT, patrizio.nuccio@polito.it

Many improvements were gradually introduced in the two stroke engine, for example:

- a loop-scavenged system; this reversal flushing flow was patented by Adolf Schnürle in 1925 (see figure 4);
- the expansion-chamber exhaust-pipe system to enhance power output by improving its volumetric efficiency thanks to the unsteady flow gas dynamic behavior[1];
- rotating and reed valves for the intake system and variable exhaust port timing, in order to improve performance and reduce fuel consumption and pollutant emissions.

However, despite the great popularity of the two stroke engine, the more stringent EPA emission limits issued in the USA at the end of seventies forced vehicle industries to direct their attention towards four-stroke engines, as they are less polluting than two stroke engines and consume less fuel. Many other countries in both Europe and elsewhere soon gave up the two-stroke s.i. engine.

One of the most important recent design modifications that make it possible to deal with these constraints is to perform the scavenging process using pure air, which means fuel-free air: the direct injection was thus introduced. For example, in 1995 the Orbital Engine Co. developed a fuel-injection and combustion system that they used on a two-stroke crankcase-scavenged engine, with three cylinders and total displacement of 1200 cm^3, see fig. 5 [2,3,4]. The Orbital fuel injection system (see figure 6) consists of air-assisted direct injection, which is achieved by means of a fuel metering injector, that introduces the fuel into a pre-chamber. This injection is independent of the piston position. The pre-chamber is also supplied with air from a small compressor which performs a rich mixture; this mixture is then introduced into the main combustion chamber by means of the direct injector. In this way the air and fuel can be mixed and a stratified charge can also be achieved.

A similar fuel injection system was also utilized for the Aprilia Ditech SR 50 scooter which was equipped with a 50 cm^3 two-stroke engine [5], as shown in figure 7. The air-assisted injection system was fed by a small compressor that was housed in the crank-case and which sent air at 5-6 bar.

A premixed charge injected into the cylinder, was also adopted in the Piaggio FAST Injection System for practical applications on a 50 cm^3 scooter engine [6]. In this case, a reciprocating compressor was installed on the head and was actuated by the engine crankshaft, as shown in figure 8. A rich mixture was prepared by a carburettor in the cylinder of the compressor and then injected into the cylinder of the engine.

The Institut Francais du Petrole (IFP) also developed a compressed air assisted fuel injection system (IAPAC) in a two-stroke engine which allowed the fuel to be introduced separately from the scavenging air, in order to minimize fuel short-circuiting, as shown in figure 9 [7].

This is a crank-case scavenged engine in which the fuel injector was placed upstream from a poppet valve in the head; when the poppet valve opens after the scavenging process, a rich mixture flows into the cylinder and a stratified charge is also created.

The Lotus Company of Norfolk, UK, has recently set up a prototype direct-injection two-stroke engine for alcohol fuels, called *the Omnivore* [8]. The *Omnivore* is a single cylinder spark ignition engine, as figure 10 shows, which has been designed to optimize auto-ignition operating conditions for many fossil and renewable fuels. This two-stroke engine is provided with three independent mechanisms: a charge trapping valve system, a controlled exhaust valve and a variable compression ratio device to control the final compression stroke temperature. Furthermore, the direct fuel injection leads a drastic reduction in the unburned fuel in the exhaust duct during the scavenging process.

Many others examples of innovative two-stroke s.i engines could mentioned here (for example the Peugeot FC5 50 cm^3 engine, the Bimota 500 V2 45, or the Lotus stratified charge engine), but for the sake of brevity they have been omitted, although mention is made of the Toyota S2-50 two-stroke s.i. engine, as it presents similar features to the prototype engine developed at the Politecnico di Torino. This engine, see figure 11, shows a reverse flow scavenging system, actuated by means of five actuated poppet valves (two for inlet ducts and three for exhaust ones), two fuel injectors and an external scavenging pump, that is, a Roots compressor driven by the engine. In this manner, the crankcase can be utilized for the lubrication system, as in the four stroke engine, thus avoiding the high oil consumption that is typical of conventional two-stroke engines.

2. PROPOSALS FOR A NEW GDI TWO-STROKE ENGINE - POLITECNICO DI TORINO (1986 – 2007)

The research activities that have been carried out on 2-stroke engines in the Energy Department Laboratories at the "Politecnico di Torino" since the second half of the eighties are here reported. The work was intended to substantially reduce the pollutant emissions and fuel consumption of 2-stroke engines for motorcycle applications. In those early years, emission limits were becoming increasingly more severe, as far as 4-stroke engines are concerned, and it seemed obvious that 2-stroke engines would undergo analogous constraints.

The first prototype was built by modifying a Cagiva T4E 350 engine, a mass-produced single-cylinder 4-stroke engine for motorcycle applications. The modified Cagiva T4E 350 engine head is shown in figure 12.

The inlet port was placed on both sides of the cylinder wall, according to the scheme in figure 13. As electronic direct fuel injection technology was not yet available, this early version of the prototype engine (1986-88) still utilized an electronic indirect fuel injection apparatus, which delivered the fuel to the intake manifold near the inlet ports. The injection timing was suitably delayed to reduce fuel losses to the outlet during the scavenging process.

Picture 14 shows the modified Cagiva T4E 350 engine at the test bench. The Roots compressor, which was necessarily utilized as an external scavenging pump, can be seen (A), along with a by-pass valve (B) which was used to vary the engine load without throttling the compressor inlet. This by-pass valve was used, instead of the usual throttle valve placed upstream from the scavenging pump, to control the engine at part-loads.

The first encouraging experimental results carried out on this prototype led to further research developments, despite some technical problems at the test-bench, related to the engine clutch, gearbox and transmission. These problems made it necessary to prepare a new single-cylinder prototype engine.

As at that time electronically controlled direct injection technology was becoming available, it was decided to use this kind of apparatus for the new engine. However, in order to tune up the new fuel feeding system and evaluate the magnitude of the improvements, the GDI apparatus was first tested on mass-produced crankcase scavenged 2-stroke engines.

The employed engines were mass-produced, namely a "Benelli FB-1226" and a "Husqvarna WR 250", which were suitably modified for GDI operations. Both the above mentioned mass-produced engines are crankcase-scavenged two-stroke engines, however they show quite different manufacturing features and performances, as they are intended for very different uses. They were selected for laboratory tests for this reason and to check whether the GDI strategies were advantageous in both cases.

An up-to-date electronically controlled injection apparatus was fitted to the cylinder head of the "Benelli" and the "Husqvarna" engines, which were also set up with indirect injection equipment or with a carburettor, in order to compare the performances. The same injection system was used for the GDI operations and to feed fuel to the prototype engine.

The first tested engine (Benelli) was employed to compare the torque characteristic at wide open throttle operating conditions, using both the indirect and the direct fuel injection strategies. The original exhaust system of this engine was also replaced with an expansion-chamber exhaust-pipe system to evaluate the impact of direct gasoline injection with this optimised exhaust configuration. Finally, a comparison of the performance of the indirect and direct fuel feeding systems was carried out at full load.

The second tested engine (Husqvarna) was employed to repeat the comparison of the indirect-versus-direct fuel injection systems at part-load operating conditions, that is, on a cubic-type power characteristic. Some useful hints were gained on the basis of the previously described experience, concerning, for instance, the number, size and location of the scavenging ports that had to be employed in the second prototype engine.

3. THE "BENELLI FB-1226" ENGINE AND THE MAIN MODIFICATIONS FOR GDI OPERATIONS

The mass-produced "Benelli FB-1226 engine is a single-cylinder crankcase-scavenged two-stroke engine with the inlet, exhaust and transfer ports governed by the piston movement. Its main features are: stroke 78 mm, bore 75 mm, displacement 345 cm^{3,} geom. compression ratio 8.2 (actual compression ratio 5.6).

Its original fuel feeding system employed a carburettor. An injector was placed in the intake duct, instead of this carburettor, for indirect fuel feeding. Another injector was placed at the engine-head, for direct fuel feeding. A comparison between the two fuel feeding systems was therefore possible.

A cutaway view of the engine is shown in figure 15, in the indirect fuel injection setting. The injector drives the fuel spray into the intake duct, downstream from the throttle valve and upstream from the intake port.

Another cutaway view of the engine, in the direct fuel injection setting, is shown in figure 16. The injector is placed at the engine head for direct fuel feeding into the cylinder. The fuel spray, delivered towards the spark-plug electrodes, meets the scavenging air that comes up from the inlet ports below. The injector position, relative to the inlet and outlet ports, prevents the fuel from flowing into the exhaust duct during the scavenging process. Thanks to this layout, the injection can start before the outlet port is closed and yet the fuel losses, during the scavenging phase, are reduced or even totally avoided. Greater injection advances usually result in a better combustion process and engine performance, as the fuel has more time to vaporize and mix with the air. The same injector position has also been chosen by other researchers and has led to satisfactory results.

A comparison between the GDI and GII was carried out at different revolution speeds by operating the engine at full-load and with a constant air-fuel ratio, equal to the stoichiometric value. The procedure employed to set the stoichiometric air-fuel ratio is described in [9,10].

The engine is equipped with an appropriately tuned exhaust system, which was designed following the guidelines suggested in [11] for expansion-chamber exhaust-pipes.

The torque, power and brake specific fuel consumption (bsfc) versus revolution speed are shown in figure 17.

In the speed 1500 and 3000 rpm range, the torque and power of direct injection configuration result to be, on average, higher than those of indirect injection one. At higher revolution speeds the maximum torque and power values fall to about 3500 rpm, for indirect fuel injection, and to about 4000 rpm, for direct fuel injection, respectively. This probably depends on the different thermal conditions and exhaust manifold behaviour (owing to different sound speeds in the gas), which takes place with indirect and direct fuel injection. The maximum direct injection torque is about 4% lower than the maximum indirect injection torque, while the maximum direct injection power is about 10% greater than the maximum indirect injection power. As far as bsfc is concerned, an average improvement of about 30% was observed over the whole tested speed range.

The HC emissions versus the revolution speed are shown in figure 18. Here, the direct injection HC emissions are much lower than those of indirect injection over the whole tested speed range. The HC reduction is about 80%, on average.

The NOx and CO emissions (not reported here for the sake of brevity) show oscillating behaviour for the various tested revolution speeds, but no particular trend can be observed in the comparison between GDI and GII.

4. THE TWO-STROKE "HUSQVARNA WR 250" ENGINE AND THE MAIN MODIFICATIONS INTRODUCED FOR GDI OPERATIONS

The second engine employed for a performance comparison between direct and indirect fuel feeding systems, is a single-cylinder spark-ignition crankcase-scavenged two-stroke engine, named "Husqvarna WR 250" [12].

The crankcase, which acts as a scavenging pump, sucks the external air through a reed valve. The scavenging process is performed inside the combustion chamber by means of folded cross-flows. The cylinder is made of aluminum alloy and the spark-plug is placed in the centre of the cylinder head. The combustion chamber has a domed shape and annular squish area, with the same axis as the cylinder. The crankcase is also made of aluminum alloy and contains the transmission shafts and gears along with the clutch and the electric generator. A centrifugal controlled valve, hereafter referred to as "CCV", is fitted in the exhaust pipeline and has the task of reducing the duct area at low speeds, to improve engine performance.

In its original setting, the "Husqvarna WR 250" engine has a power output of 49.5 CV (36.4 kW) at 8'500 rpm. The main geometrical features of the engine are: stroke 70.70 mm, bore 66.65 mm, displacement 246.67 cm^3, geom. compression ratio 14.9, real compression ratio with closed "CCV" 9.55, real compression ratio with open "CCV" 7.68.

Picture 19 shows the "Husqvarna WR 250" engine at the test bench in, with the eddy current dynamometer The electronic high-pressure injector mounted onto the engine head for direct fuel injection is shown in the same figure.

Therefore, the engine at the test bench is equipped with two independent fuel feeding systems:

the original carburettor apparatus

the high-pressure direct fuel injection system, with the injector placed in the engine head to deliver the spray into the combustion chamber.

During the bench tests with the GDI system, the same amount of oil that would be provided by the carburettor-fed engine, is supplied by an independent lubrication system (2 % of oil per volume in the oil and fuel mixture). This is to ensure that the different performances do not depend on the different kinds of lubrication systems.

An independent lubrication system was therefore necessary. For this purpose, a dedicated oil injector was placed in the intake manifold just upstream from the crankcase reed valve and it was fed by an independent oil pump.

A comparison is shown in figure 20, in terms of power and torque, between the carburettor-fed engine and the GDI-equipped engine, under cubic load operating conditions. The main differences, at 3'000 rpm and 5'000 rpm, are below 5 %. The cubic law was chosen because it is closer to the actual working conditions of the engine in ground applications (motorcycle). This power requirement curve is close to the drag effect exerted against a vehicle on the road. The here employed cubic curve crosses the engine characteristic in correspondence to its maximum power, which, in this case, occurs at about 8500 rpm. The experimental test operating conditions were selected with reference to the ECE-40 driving-cycle, which involves a rather low maximum vehicle speed (50 km/h) and, as a consequence, a rather low power output. The air-fuel ratio employed with the GDI-equipped engine is not as rich as the air-fuel ratio employed with the carburettor-fed engine, but is as rich as possible, to make the engine run steadily.

The "bsfc" of the carburettor-fed engine and of the GDI-equipped engine are shown in figure 21. The "bsfc" reduction is evident over the whole tested rotation speed range. This reduction is very noticeable at low speeds (over 50 % at 3'000 rpm), but also appreciable at high speeds (about 12 % at 5'000 rpm).

The unburned hydrocarbon emissions HC are shown in figure 22, for the carburettor-fed engine and for the GDI-equipped engine. These HC emissions were measured in terms of hexane, with a non-dispersive infrared absorption detector ("NDIR"). The "HC" reduction is impressive. The differences are more marked at low speeds, but the percentage is almost the same, over 85 %.

5. MAIN DESIGN FEATURES OF THE NEW PROTOTYPE ENGINE

On the basis of the above mentioned experimental tests and numerical simulation results, along with previous experience on an earlier two-stroke prototype engine, some useful hints have been gained, concerning the design, layout and scavenging principle of the present two-stroke prototype engine.

In this new prototype, the scavenging process occurs through a "unidirectional flow", as shown in figure 23, from the inlet ports located on the cylinder liner near the BDC, to the outlet ports located on the cylinder head, and it is governed by cam-actuated valves, like those of usual 4-stroke engines. In this way, the engine volumetric efficiency could be higher than the usual 2-stroke engine. Moreover, thanks to gasoline direct injection, the amount of the scavenging air can be enhanced, without the drawback of fuel losses through the outlet ports during the scavenging process. On the other hand, the crankcase can no longer be used as a scavenging pump, because the corresponding air flow would be insufficient. An external scavenging pump should therefore be employed and a by-pass valve is also necessary used to control the engine at part-loads, instead of the usual throttle valve placed upstream from the scavenging pump, as in the previous prototype (see picture

24). Furthermore, in the present set-up, the Roots compressor is driven by an external electric motor; in this way, the rotation speed of the compressor is independent of the engine rotation speed and can be varied to find the optimum operating conditions for the scavenging process. This is easily obtained through the use of an "inverter" device.

The crankcase can now be used as an oil tank and the whole lubrication system can also be a force-fed one, as in a four-stroke engine. For this reason, the typical oil losses of a fresh-oil lubricating system, like those of ordinary 2-stroke engines, are avoided. As a consequence, the connecting rod (made up of two parts) and the crankshaft (in a single piece) should be the same kind as those used in 4-stroke engines. The corresponding thin-walled bearings can be employed with a force-feed lubrication system, like those of current 4-stroke engines, instead of ball bearings with a total-loss lubrication system, like that of current 2-stroke engines.

The piston can also be similar to that of 4-stroke engines, except for its skirt length, which must be consistent with the intake-port requirements of a 2-stroke engine. A new crankshaft geometry that should be compatible with the greater piston length and with the different equilibration requirements is now necessary.

Finally, special cam profiles should be designed, to adequately actuate the exhaust valves in the engine head.

The main features of this engine prototype are shown in table I together with the exhaust and inlet port timing, which is also shown in figure 25. Moreover, the camshaft has to rotate at the same rotational speed as the crankshaft.

Table I *Main features of the new prototype engine*

Stroke	90 mm	Exhaust-valve opening angle	80° BBDC
Bore	86 mm	Inlet-port opening angle	55° BBDC
Displacement	522.8 cm^3	Exhaust-valve closing angle	40° ABDC
Geom. compression ratio	10.2	Inlet-port closing angle	55° ABDC
Actual compression ratio	8.7		

In order to reduce manufacturing costs and construction times, this prototype was built by modifying a 4-stroke, 4-cylinder automotive engine. The long-skirt piston, for adequate inlet-port operation, is shown in picture 26. Apart from the skirt length, the piston is similar to that of a 4-stroke engine.

The intake manifold is connected to the scavenging pump and to the engine combustion chamber by two inlet ports in the cylinder liner near the BDC, as show in figure 27.

A cutaway view of the engine head is shown in figure 28, in which the spark plug and the electronic injector can be observed. The injector is located in the centre of the engine head, in the place originally used for the spark plug, which was moved aside. The injector is therefore surrounded by the four engine valves, which are all now used as exhaust valves.

The electronic injector was provided by Siemens Automotive and it is operated by means of electronic apparatus, which allows both the injection duration and advance to be set.

The prototype engine is shown in picture 29 with the new valve train system and the exhaust ducts.

6. FIRST EXPERIMENTAL RESULTS OBTAINED ON THE NEW PROTOTYPE ENGINE

The first experimental tests on the 2-stroke prototype engine were carried out under low loads and intermediate rotational speed, that is, in this case, about 1'000 – 1'500 rpm, for precautionary reasons [13].

First, a comparison between the 2-stroke prototype engine and a reference 2-stroke engine was performed for the fuel consumption.

As the fmep of the two engines are very different, because the prototype is derived from a 4-stroke engine and its external scavenging pump is driven by an independent electric motor, the specific fuel consumption values of the two engines were evaluated with respect to imep: the indicated specific fuel consumption (isfc, referring to imep) is shown in the diagram of figure 30.

The isfc of the prototype is always lower, even for point "A", which should be compared with the isfc of the reference engine, extrapolated at a lower rotational speed. The isfc reduction for point “C” is about 37 %.

Apart from the fuel consumption, the pollutant emissions of the 2-stroke prototype engine and the reference 2-stroke engine were also measured.

Because of the different sizes, displacements and rated power outputs of the two engines, the respective specific values of the pollutant emissions were considered. The indicated specific pollutant emissions (referring to imep) are again considered in the subsequent diagrams.

The indicated specific HC emissions vs rotational speed are shown in figure 31, for the 2-stroke prototype engine and the reference 2-stroke engine. The HC emissions of the prototype are even lower than those of the reference engine, for each of the four tested operating conditions. For example, point "D" (where the prototype used almost the same A/F value as the reference engine at 1'500 rpm) shows an HC reduction of over 90 %, when calculated with either the bmep, or the imep.

These very high reductions occur for two reasons: 1) the scavenging process of the 2-stroke prototype engine is accomplished using fuel-free air, 2) the fuel can be sent to the combustion chamber after the exhaust ports have been closed, thanks to the GDI technique. Moreover, thanks to the force-feed lubrication system, the oil is not mixed with the fuel: it cannot flow to the exhaust during the scavenging phase and it does not take part in the combustion process.

The indicated specific CO emissions vs rotational speed are shown in figure 32, for the 2-stroke prototype engine and the reference 2-stroke engine. The CO emissions of the prototype are greater than those of the reference engine, for points "A", "B" and "C", and are lower, for point "D".

7. FINAL REMARKS AND SOME CONSIDERATIONS FOR FUTURE DEVELOPMENTS

An experimental investigation has been carried out on two different mass-produced crankcase-scavenged 2-stroke engines equipped with both an indirect fuel injection apparatus and an electronically controlled GDI system.

The comparison between the two fuel feeding systems was performed under full-load and cubic-load operating conditions.

The GDI system has led to great improvements, compared to the GII system, as far as HC emissions and "bsfc" are concerned. HC reductions of more than 80% were found, under both full-load and cubic-load operating conditions. Average "bsfc" reductions of 12% to 30% were found, depending on which operating conditions were adopted.

Furthermore, on the basis of these experiments, some design modifications have been developed on a 2-stroke engine prototype with a unidirectional scavenging flow and force-feed lubrication system. A new type of piston was manufactured and tested. The experimental results of bench tests carried out under low load and intermediate rotational speed operating conditions, for both the 2-stroke prototype engine and a commercial crankcase-scavenged 2-stroke engine using an indirect injection fuel feeding system were compared. A marked reduction in the fuel consumption and HC emissions was obtained. For example, a reduction of about 37% was found in the specific fuel consumption, along with a reduction of over 90% in the HC specific emissions at about 1'500 rpm with a slightly lean mixture, where the specific values were evaluated with reference to imep, due to the different fmep of the two engines.

Finally, some helpful suggestions for future improvements can be made, concerning the overhead cam-actuated exhaust valves, the spark-plug and injector position and the oil scraping effects on the cylinder liner.

The historical appeal of the two-stroke engine has not disappeared completely, due to its intrinsically simple and compact design.

Moreover, thanks to the consolidated developments in electronic techniques for automotive applications, renewed interest could once more arise in this kind of engine.

Therefore we trust that, after a temporary rest, the two-stroke engine is at last ready to perform its second “stroke”.

REFERENCES

[1] Robert Cramer, Jr.: Scavenging Systems For Two Stroke Engines," SAE Technical Paper n. 580382

[2] Houston, R. - Orbital Engine Company Pty. Ltd- et alii: Development of a Durable Emissions Control System on an Automotive Two-Stroke Engine. SAE P Technical paper n. 960361

[3] Houston, R., Cathcart G.- Orbital Engine Company: Combustion and Emissions Characteristics of Orbital's Combustion Process Applied to Multi-Cylinder Automotive Direct Injected 4-Stroke Engines. SAE Technical Paper n. 980153

[4] Worth, D. - Orbital Engine Company Pty Ltd. et alii: A New Approach to Meeting Future European Emissions Standards with the Orbital Direct Injection Gasoline Engine. SAE Technical Paper n. 2000-01-2913

[5] Ambler, M. and Zocchi, A. - Engine Division Aprilia S.p.A: Development of the Aprilia DITECH 50 engine. SAE Technical Paper 2001-01-1781

[6] Nuti, M., Pardini, R., and Caponi, D., "FAST Injection System: PIAGGIO Solution for ULEV 2T SI Engines," SAE Technical Paper 970362.
[7] Duret, P. and Moreau, J., "Reduction of Pollutant Emissions of the IAPAC Two-Stroke Engine with Compressed Air Assisted Fuel Injection," SAE Technical Paper 900801, 1990,
[8] Blundell, D., Turner, J., Pearson, R., Patel, R. et al., "The Omnivore Wide-range Auto-Ignition Engine: Results to Date using 98RON Unleaded Gasoline and E85 Fuels," SAE Technical Paper 2010-01-0846, 2010
[9] Badami, M., Marzano, M.R., Millo, F., Nuccio, P.: "Comparison between direct and indirect fuel injection in an s.i. two-stroke engine". SAE Technical Paper n. 1999-01-3311 - Small Engines Technology Conference & Exposition - Madison, Wisconsin, U.S.A., September 1999 – Also in 2000 *"SAE Transactions"*.
[10] Douglas, R.: "AFR and Emissions Calculations for Two-Stroke Cycle Engines". SAE Technical Paper N. 901599.
[11] Blair, G.P.: "Design and Simulation of Two-Stroke Engines". SAE inc. 1996.
[12] Antonelli, E., Nuccio, P., Dongiovanni, C., Marzano, M.R.: "A New GDI 2-Stroke Engine to Meet Future Emission Limits: The Design and Prototype Architecture", SAE Technical Paper n. 2004-32-0041, September 2004, Graz (Austria).
[13] Nuccio, P., Marzano, M.R.: “R&D of a New G.D.I. 2-Stroke Engine with a Unidirectional Scavenging Flow and a Force-Feed Lubrication System”. SAE Technical Paper n. 2007-32-0025

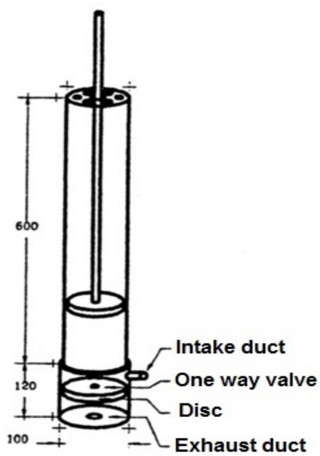


***Figure** 1 - The first layout of a reciprocating spark ignition engine registered by Eugenio Barsanti and Felice Matteucci at the Accademia dei Georgofili in1853*

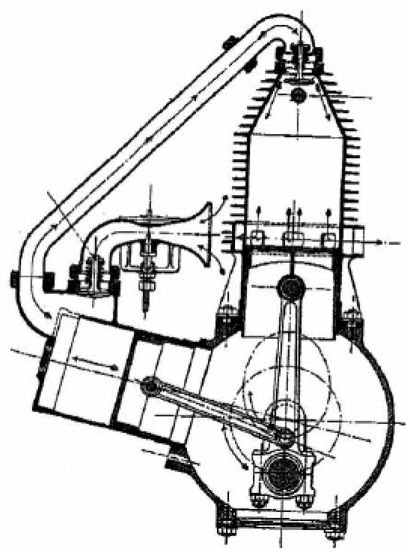


***Figure 2** – Two stroke engine designed by **<u>Dugald Clerk</u>** in 1881. It is clearly evident the external scavenging pump on the left side of the carter*

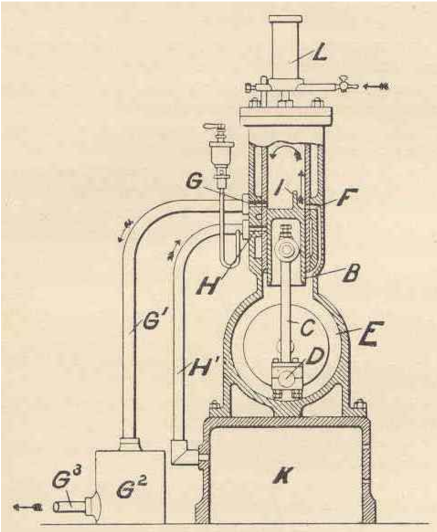


***Figure 3** – Two stroke crankcase-scavenged engine, patented by Joseph Day in 1892 in England and in 1905 in USA*

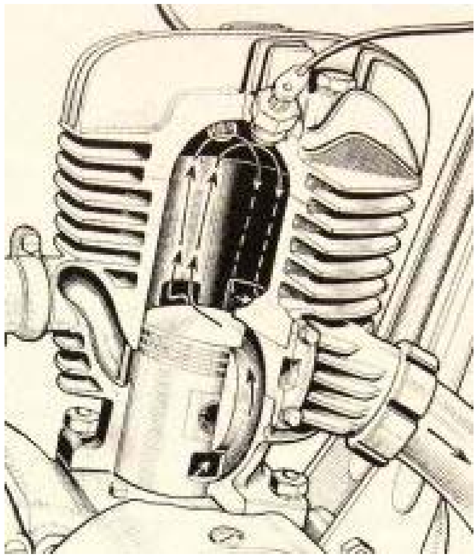


***Figure 4** - Loop-scavenged engine (reversal flushing flow) patented by Adolf Schnürle in 1925*

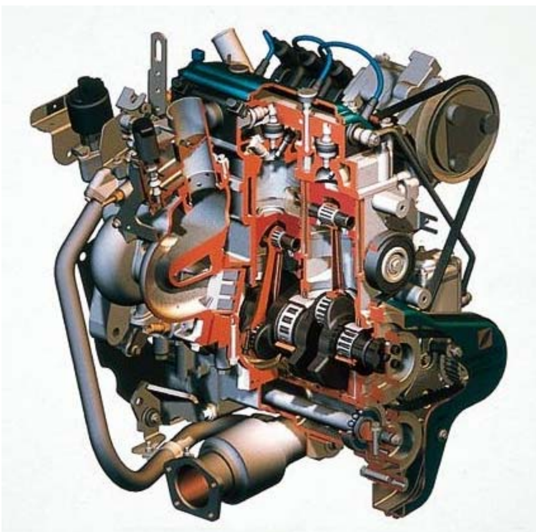


***Figure 5** - The Orbital three-cylinders two-stroke engine provided with an air assisted direct injection*

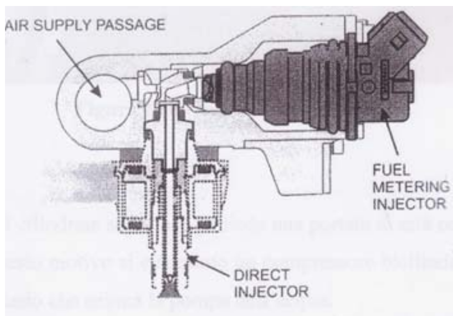


***Figure 6** - The Orbital fuel injection system with air assisted gasoline direct injection*

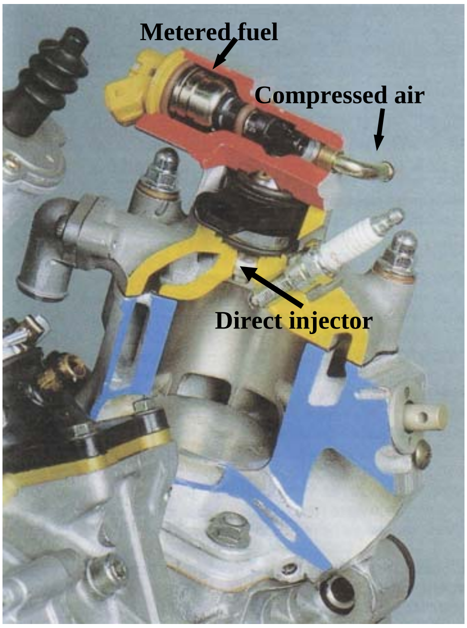


Figure 7 - *Aprilia Ditech two stroke engine equipped with air-assisted direct injection*

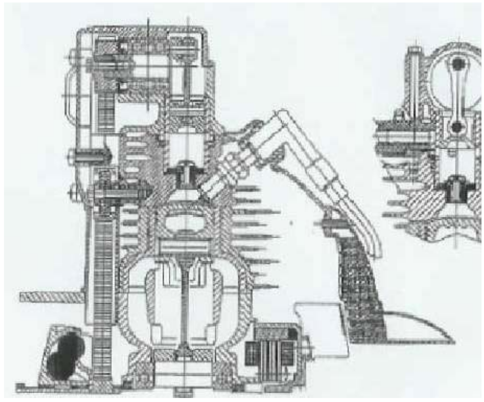


Figure 8 - *Piaggio FAST Injection System for two stroke engine*

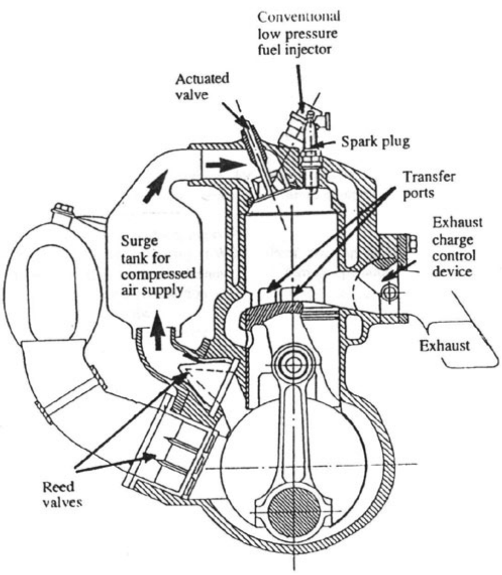


Figure 9 - *The two-stroke engine of the Institut Francais du Petrole (IFP) with a compressed air assisted fuel injection sys tem (IAPAC*

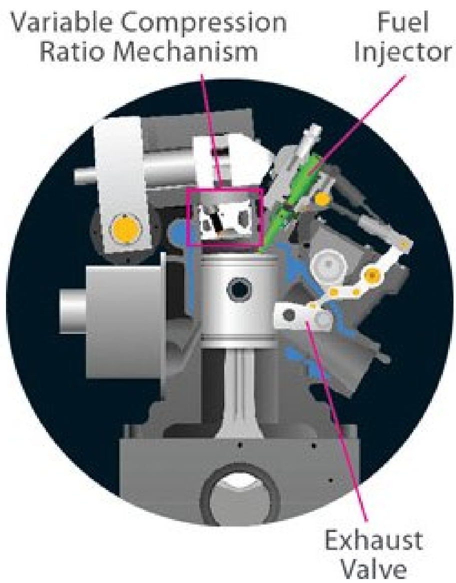


Figure 10 - *The Lotus single cylinder two-stroke spark ignition engine: "Omnivore"*

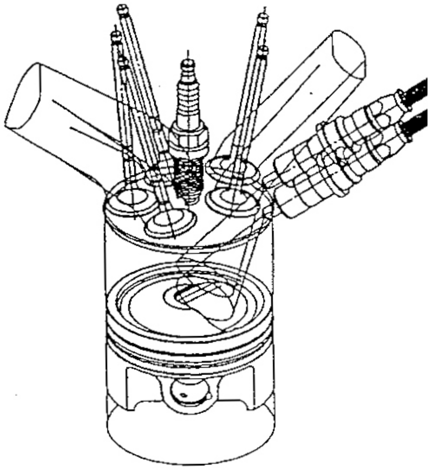


Figure 11 *- Cylinder scheme of the Toyota S2-50 two stroke s.i. engine*

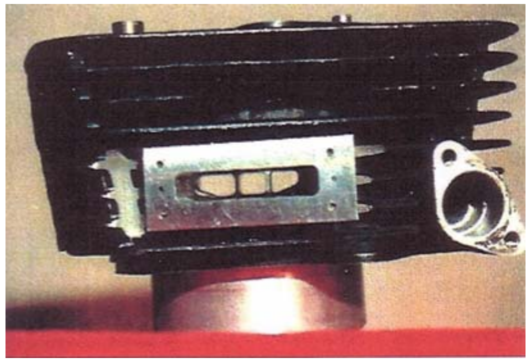


Figure 12 *- The modified Cagiva T4E 350 engine head with its inlet ports*

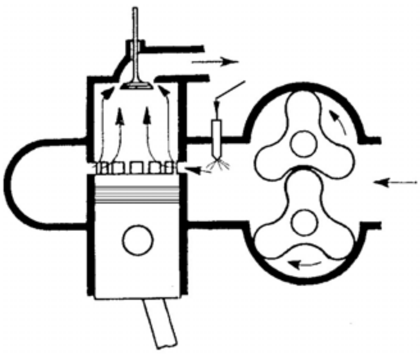


Figure 13 *- Schematic view of the unidirectional flow scavenging principle of the 2-stroke prototype engine with gasoline indirect injection*

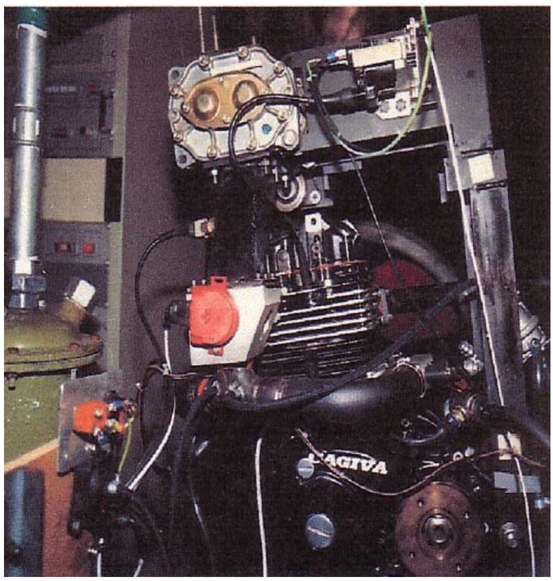


Figure 14 *- The modified Cagiva T4E 350 engine at the test bench. A: the external scavenging pump (Roots compressor). B: the by-pass valve*

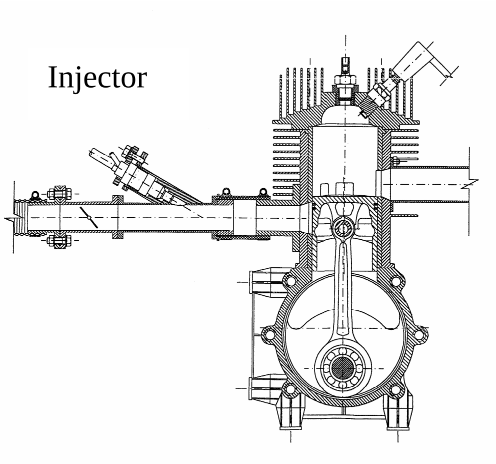


Figure 15 *- Cutaway view of the "Benelli FB-1226" engine, with the fuel feeding system for INDIRECT INJECTION. The fuel spray enters the inlet duct downstream to the throttle valve.*

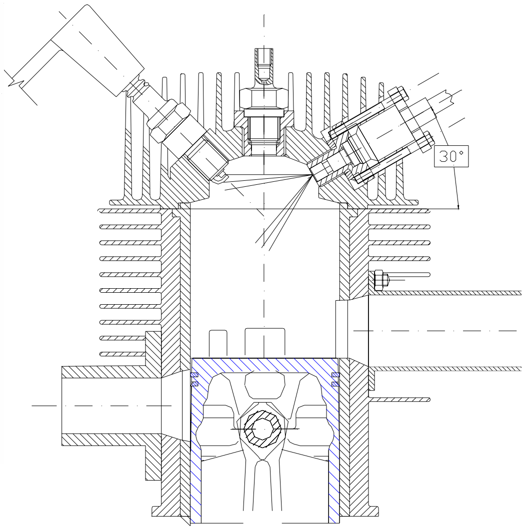


Figure16 *- Cutaway of the "Benelli FB-1226" engine, equipped with a DIRECT INJECTION fuel feeding system*

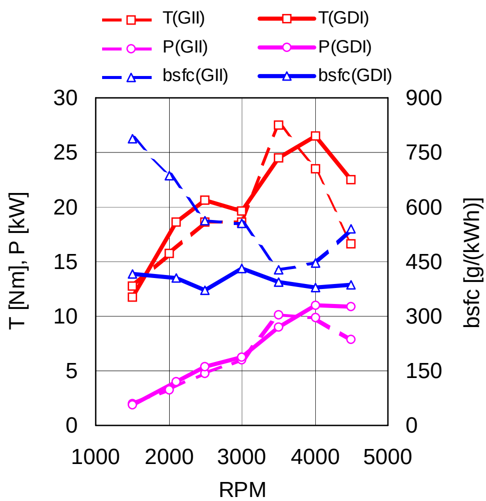


Figure 17 *- Comparison between direct and indirect fuel injection: torque, power and bsfc versus engine revolution speed at WOT.*

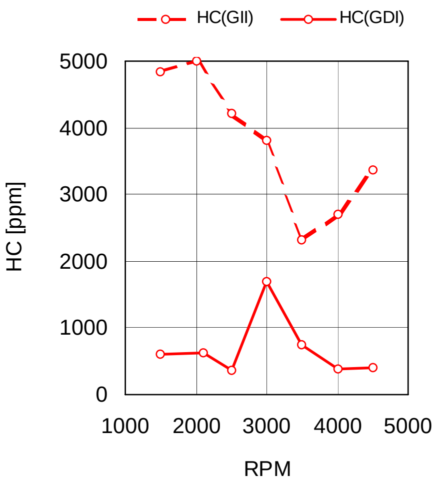


Figure 18 *- Comparison between direct and indirect fuel injection: HC emissions versus engine revolution speed at WOT.*

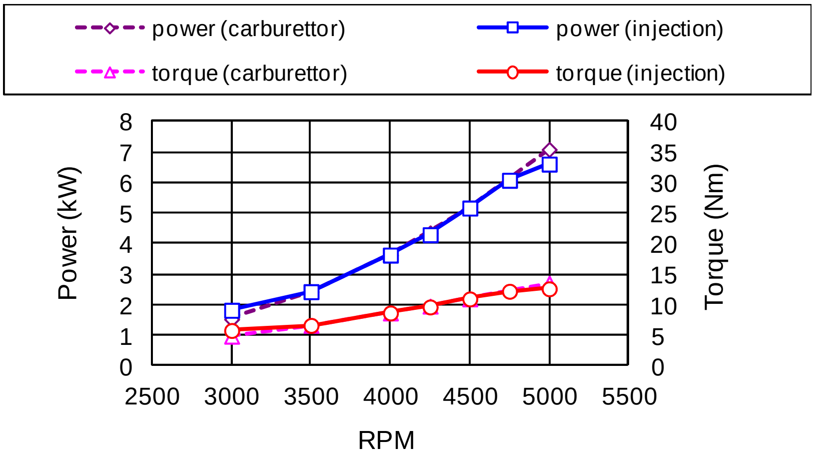


Figure 20 - Comparison between the power and torque output with the carburettor and "GDI" fuel feeding systems under cubic load operating conditions.

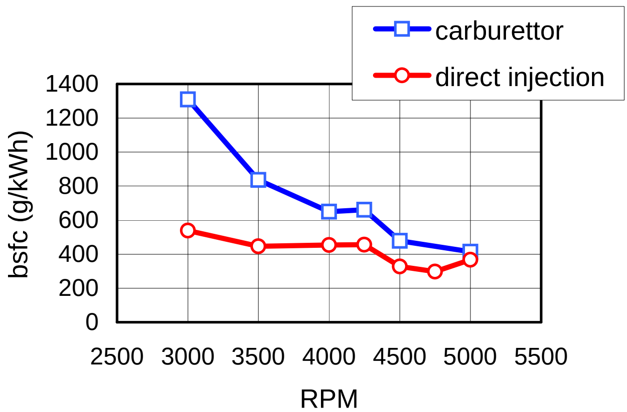


Figure 21*- Comparison between the "bsfc" of the carburettor and "GDI "fuel feeding systems under cubic load operating condition*

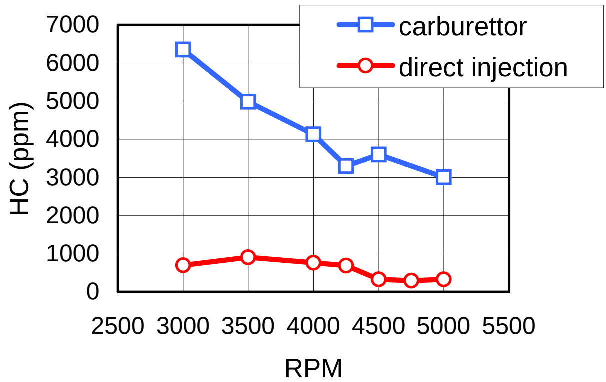


Figure 22 *- Comparison between the HC emissions (in terms of hexane) with the carburettor and "GDI" feeding systems under cubic load operating conditions*

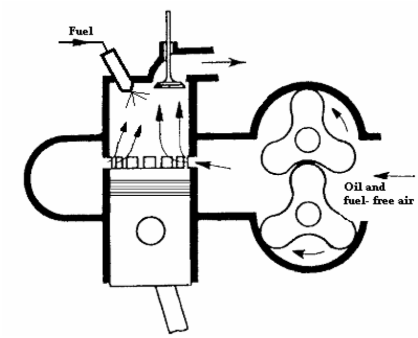


Figure 23 *- Schematic view of the unidirectional flow scavenging principle of the 2-stroke prototype engine*

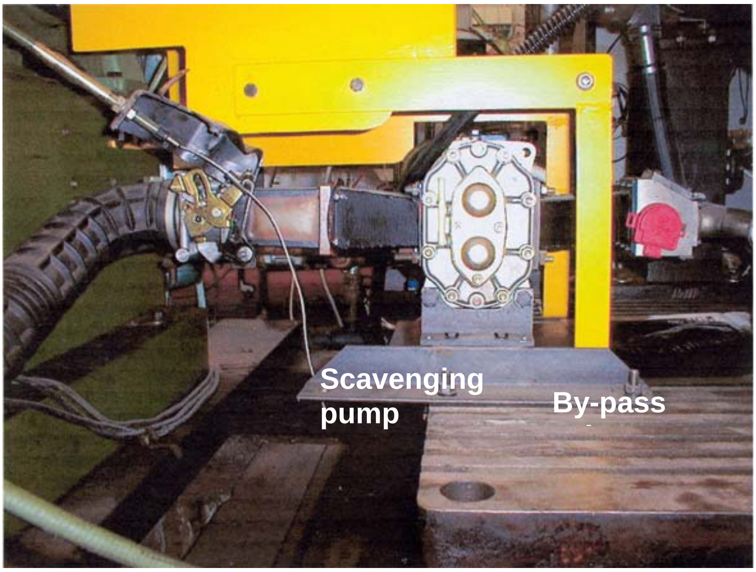


Figure 24 *- By-pass valve for load control of the prototype engine, located downstream to the scavenging pump*

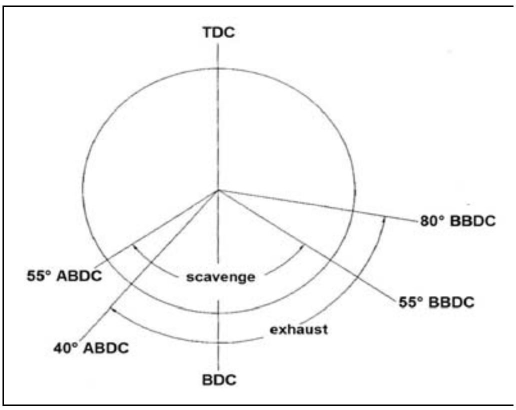


Figure 25 *– Exhaust valves and intake port timing of the new prototype engine*

Figure 26 *- Piston of the new prototype engine*

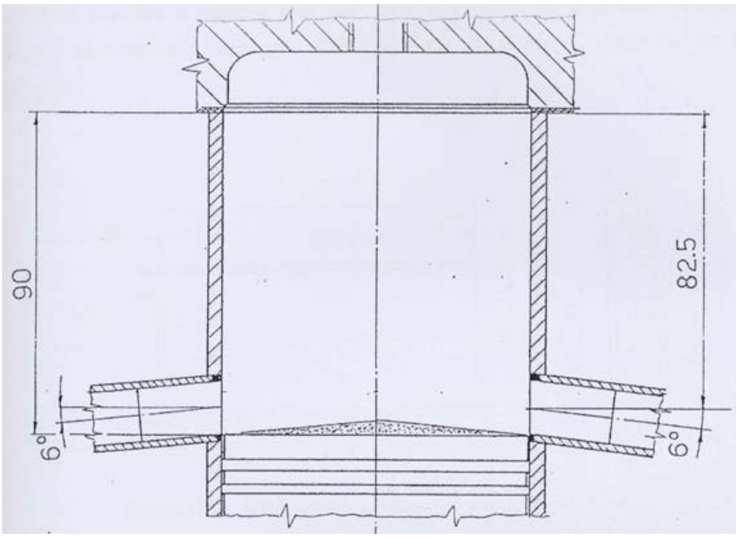


Figure 27 *– New prototype engine: cross-section of the inlet ports in the cylinder*

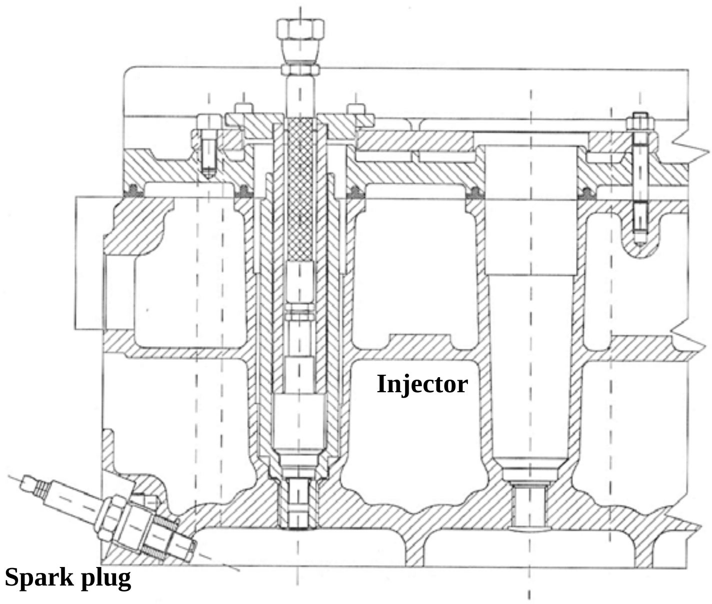


Figure 28 *- New prototype engine: longitudinal section of the head with the fuel injector*

Figure 29 - *View of the prototype engine with the valve train system and exhaust ducts*

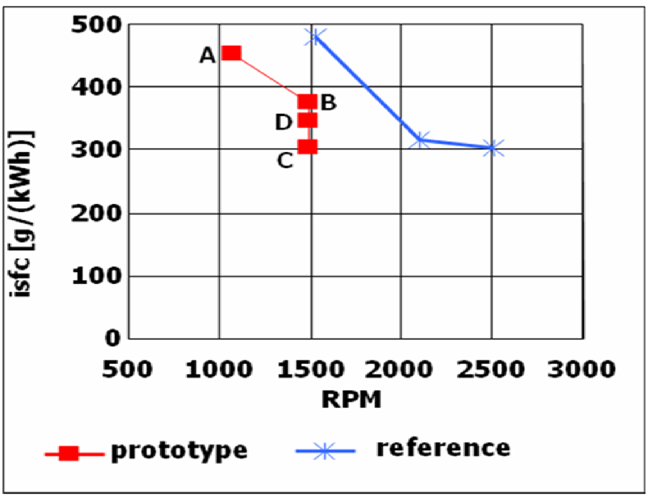


Figure 30 – *Indicated specific fuel consumption vs rotational speed for the 2-stroke prototype engine (A,B,C,D) and the reference 2-stroke engine*

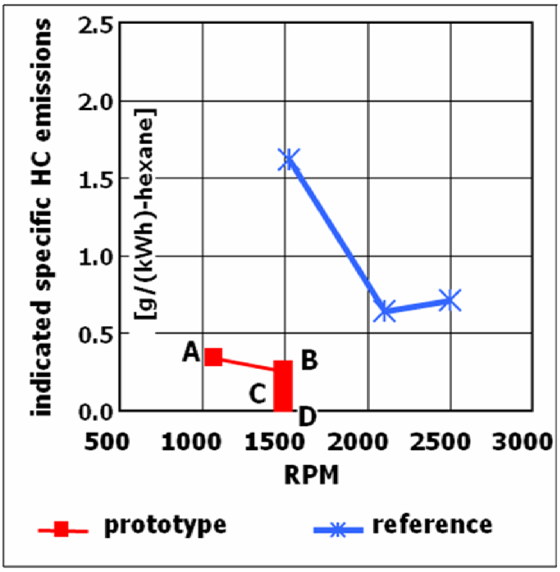


Figure 31 *– Indicated specific HC emissions vs rotational speed, for the 2-stroke prototype engine (A, B, C and D) and the reference 2-stroke engine*

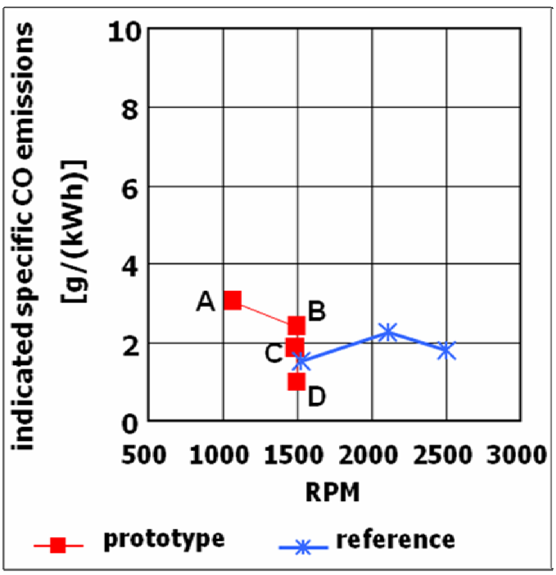


Figure 32 *- Indicated specific CO emissions vs rotational speed, for the 2-stroke prototype engine (A, B, C and D) and the reference 2-stroke engine*

MVM *Editorial Board*
University of Kragujevac
Faculty of Engineering
Sestre Janjić 6, 34000 Kragujevac, Serbia
Tel.: +381/34/335990; Fax: + 381/34/333192
www.mvm.fink.rs