ÉCOLE DU PÉTROLE ET DES MOTEURS
INSTITUT FRANÇAIS DU PÉTROLE
228-232, Avenue Napoléon Bonaparte
92852 RUEIL-MALMAISON CEDEX - FRANCE
Tel.: +33 (0)1 47 52 62 80 - Fax: +33 (0)1 47 52 70 82

What energy sources will power transport in the 21st century?

Pierre-René BAUQUIS

January 2004

Les cahiers de l'économie - 55

Series: “Analysis & Synthesis”

For further information, please contact:
Denis Babusiaux - Tel. +33 (0)1 47 52 62 80

Abstract

Following some reminders of the historical context, the author sets out a vision of the future based on a range of possible solutions enabling energy needs in the transport sector to be met over the course of the 21st century.

In the case of road transport, it transpires that two broad types of response are feasible:

- the one currently fashionable, which calls for large-scale use of the new “winning combination” formed by hydrogen and fuel cells;
- the other, which has attracted little media attention, entails extensive use of synthetic hydrocarbons accompanied by a major penetration of electrical power in the form of rechargeable hybrid vehicles.

The thesis argued by the author is that the second option is likely to win out.

This view is based on an economic analysis highlighting the very substantial handicaps affecting the hydrogen option, which derive from thermodynamics, according to the author, and cannot be overcome by technological progress.

What energy sources will power transport in the 21st century?

by Pierre-René Bauquis

Associate professor at the Ecole Nationale Supérieure du Pétrole et des Moteurs (IFP School)
Former Director of Strategy and Forward Planning, TOTAL group
E-mail: pr_bauquis@hotmail.com

Dedicated to James Lovelock.

The dangers of futurology:

"Dangerous, smelly, uncomfortable, completely ridiculous, and destined for rapid oblivion – such is the self-propelled carriage which Messrs Benz and Daimler have recently presented in Germany to Kaiser Wilhelm" (G. Clémenceau*, La Justice,* 1882, quoted by Rougemont).

Introduction

A major feature of the industrial revolution of the 19th and 20th centuries was the radical transformation in transport systems. The 20th century in particular has seen the extraordinary rise of the car and the aeroplane, both modes of transport almost exclusively reliant on the use of petroleum fuels.

The upshot is that worldwide energy consumption in the transport sector stood in the year 2000 at 1.9bn TOE (1.9 billion Tons of Oil Equivalent), or approximately 20% of world energy consumption (9.3bn TOE of commercial energy produced and consumed in 2000).

More than 95% of energy consumption in the transport sector is met by petroleum oil, compared with approximately 1.8bn TOE (out of total world liquid hydrocarbon production of 3.7bn TOE in 2000). Transport, whose demand for petroleum products absorbed around one-third of total world oil production at the time of the first oil shock (1973), now takes up approximately a half (47%-51% according to different sources and methods of calculation).

Land transport alone accounts for over 75% of world energy consumption linked to the transport sector.

When one sets out to analyse what might be the future of transport systems during the course of the 21st century, and specifically, the future of land transport, two key issues begin to emerge:

- How can the energy needs of this sector be met given the future decline in oil production (whether that production is of the so-called conventional or non-conventional type)? [*] The current status of this problem, referred to as the "peak" in global production, is illustrated in figure 1 (see Note).

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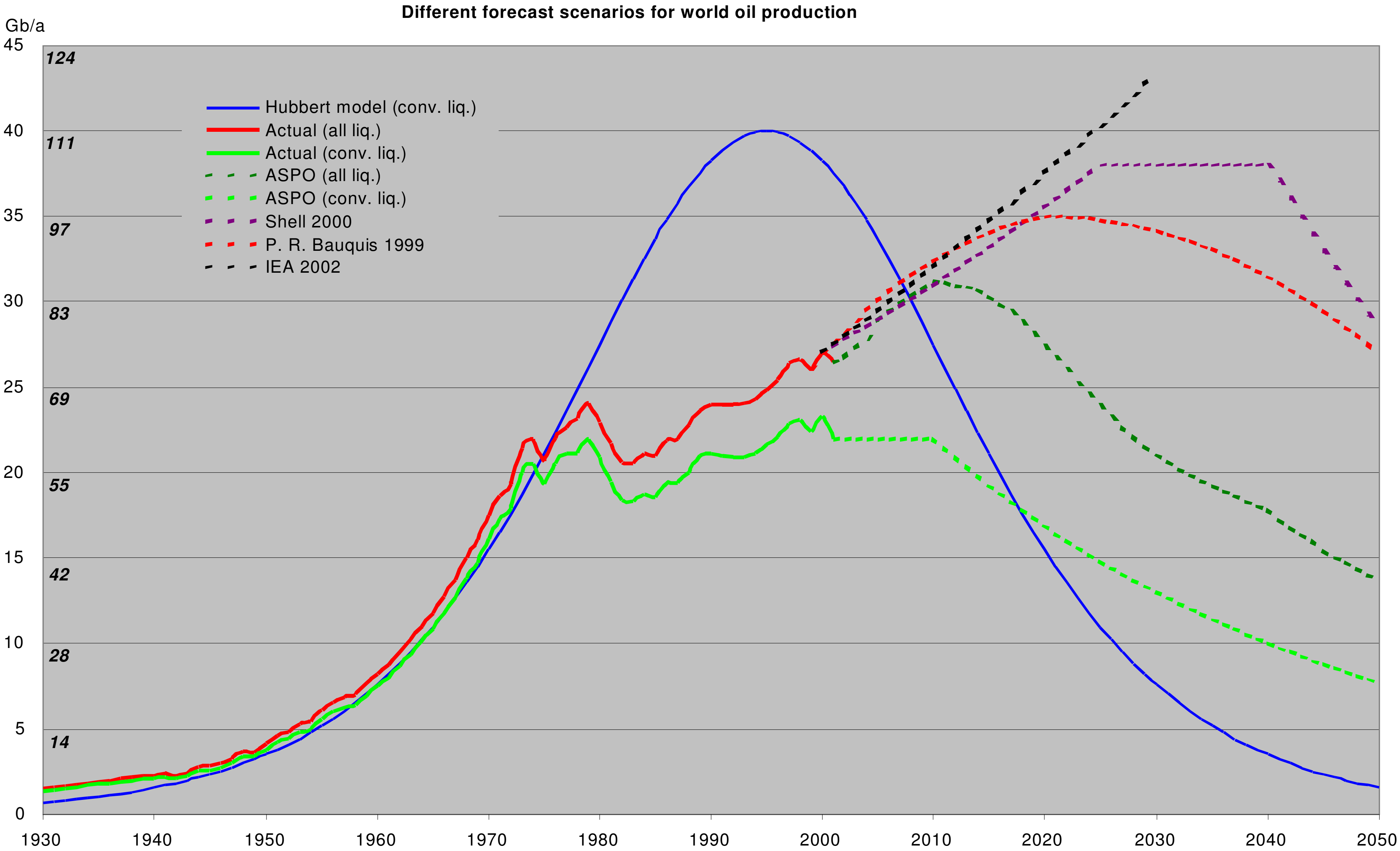
[*] NB: In 1999, the author published an article devoted in part to the peak, followed by the decline in world oil production, entitled "What are the energy sources for the medium term (2020) and the long term (2050) ?".

This publication can be found in the *Revue de l'Energie* (special 50th anniversary issue 509 – September 1999).

The present article develops further the reflections presented in this 1999 article.



Source : ASPO Uppsala 2002 press release - USGS mean estimates 2000 (Shell) - Author

* Best fit for a Hubbert curve based on current estimates of oil reserves. PRB/VL

Figure 1

- How can we ensure that emissions of greenhouse gases, CO_2 in particular, are gradually brought under control by the transport sector during the course of the 21st century?

The aim of the present article is essentially to answer to the first of these two questions, but any such answer is inseparable from analysis of the issue of greenhouse gas emissions.

The question of the future of land transport has other important dimensions, such at the development of urban areas, the role of public transport and the issue of traffic accidents. These aspects are not addressed here. The "transport requirement" issue underlying the question of energy requirements for transport is the most problematic: the danger of futurology is falling into the either-or intellectual trap of thinking in terms of social utopia or technological utopia.

A multiplicity of congresses, conferences and articles has been devoted to the question of future transport systems, and especially to the future of the car. Most of these articles and conferences go no further than a relatively near time horizon, and few look at the period after 2020. At present this is producing one dominant message: the problems raised by the future of land transport can apparently be resolved by a new "winning combination" of hydrogen plus fuel cells.

Before attempting to explore whether the future over the long term (2020-2050) and the very long term (2050-2100) is likely to lead to the emergence of the dominance of this new "winning combination", it is as well to look again at the past in order to understand better why and how land transport came to be dominated by the present "winning combination": the internal combustion engine and petroleum fuels (gasoline and diesel).

Some historical background

For millennia, human beings developed transport systems based on the energy supplied by animal muscle. Specifically, over the last 40 or 50 centuries, they have simultaneously improved the characteristics of horses and the ways in which they can be harnessed.

Immediately the steam engine made its first faltering movements, people began to dream of using it for land transport. That dream became reality in the first transport revolution with the arrival of the steam locomotive. This long period of development has as its milestones Denis Papin's machine (1698), followed by Cugnot's (1769) and subsequently those of James Watt and Murdoch (both *circa* 1780). In the end, it was the English who achieved supremacy in the steam engine field, which is probably why trains run on the left in most countries.

However, it was a Frenchman, Amédée Bollée, who took to its furthest extreme the experimental transfer of steam traction to automotive vehicles. On 9 October 1875, he travelled from Le Mans to Paris in his "Obéissante" after having obtained the first "licence to travel on the roads". Despite this licence, he collected 75 traffic tickets along the way, which the Prefect of Police, unaware that he was setting a dangerous precedent, "cancelled" 48 hours after "Obéissante" arrived in Paris.

I have quoted this anecdote at perhaps too great a length because it illustrates the fact that successes and fashions in any given era are not the driving factors for the future over the long term. Those factors are dependent in fact on "technological and economic potential", a rather abstract concept, but one which cannot be avoided by anybody seeking to define a possible future that is more than simply crystal-ball gazing or based solely on current intellectual fashions (versions of the future that are politically correct or have good media potential).

For example, if 1875 marked both the culmination and the imminent demise of the steam-propelled automobile, it was because a very self-effacing competitor had just arrived on the scene. On 16 January 1861, Beau de Rochas filed the patent for the first four-stroke internal combustion engine. At the same time, Pierre Michaux was finalizing his design for the first pedal-driven "velocipede". A philosopher of transport might see more than just chance in this coincidence, given that the two inventions have in common the fact that they convert alternating upward and downward thrusts into continuous rotational movement!

Over the twenty years that followed, the car as we know it, or something very similar, was born. It was during this exciting period that the small number of great names emerged, to whom we owe the first serially manufactured vehicles: Gottlieb Daimler and Carl Benz in 1886, Panhard and Peugeot in 1891, Rudolf Diesel in 1897 and Louis Renault in 1898, among others.

But the supremacy of the internal combustion engine did not come about immediately. Indeed, the last twenty years of the 19th century were to witness a tight contest between the first "petroleum cars" and electrically driven cars.

It is worth bearing in mind that the first car to achieve 100kph was electrically powered (Camille Jenatzy's "Jamais Contente" at Achères, near Paris, in 1898). Furthermore, it should not be forgotten that on the very eve of losing this contest, the electric car, just like the steam automobile in 1875, seemed to be on the verge of winning it. At the "two-seater car competition" held in 1898 by the very recently founded Automobile Club de France, electric cars were by far the most appreciated. This led to an article that should give food for thought, written by the best commentator on scientific issues of the time, *H. E. Hospitalier*, in the 9 July 1898 issue of "*La Nature"* (a forerunner of the ecological press). He writes in this piece that "it is now certain that the gasoline-driven carriage cannot become a system for the use of public conveyances in any large town or city". Here again, the immediately present event hid the underlying trends from observers. For a few short years this journalist seemed to have been correct, given that in 1901 a "Krieger" electric car travelled 307km (Paris to Châtellerault) without being recharged. Then, just as steam automobiles did, electric vehicles disappeared, or almost, retaining only a small number of micro-niche markets in the vast and constantly changing system tree which is land transport.

During the 19th century, engineers and inventors had explored almost all possible avenues for self-propelled vehicles: vehicles running on compressed gas (David Gordon 1825, Samuel W. Wright 1828), on pressurized air (Carl Hoppe 1862) and even ammonia (Charles Tellier 1867). The most surprising thing is that the first patent for an internal combustion engine (filed by the Swiss citizen Isaac de Rivaz), dated 1805, was for an engine running on hydrogen.

It should also be remembered that Champrobert designed the first hybrid "gasoline/electricity" vehicles between 1901 and 1906. These distant ancestors of today's Toyota Prius were abandoned due to their complexity and vulnerability to breakdown, but the concept was in fact the same as today's. The 6HP "combined car" conceived by Champrobert was actually equipped with a gasoline engine which kept electrical storage cells charged, and it was the latter that powered the electrical drive system that turned the wheels. Even then, the aim was to permit the combustion engine to operate at constant, or almost constant, rpm to optimize its efficiency.

In this vast cauldron of intellectual and technical activity which marked the beginnings of the modern car, four breakthroughs stand out as having symbolic importance due to the fact that they are still a focal point today for reflection on the energy sources that will power the road vehicles of the future (cf. figure 2).

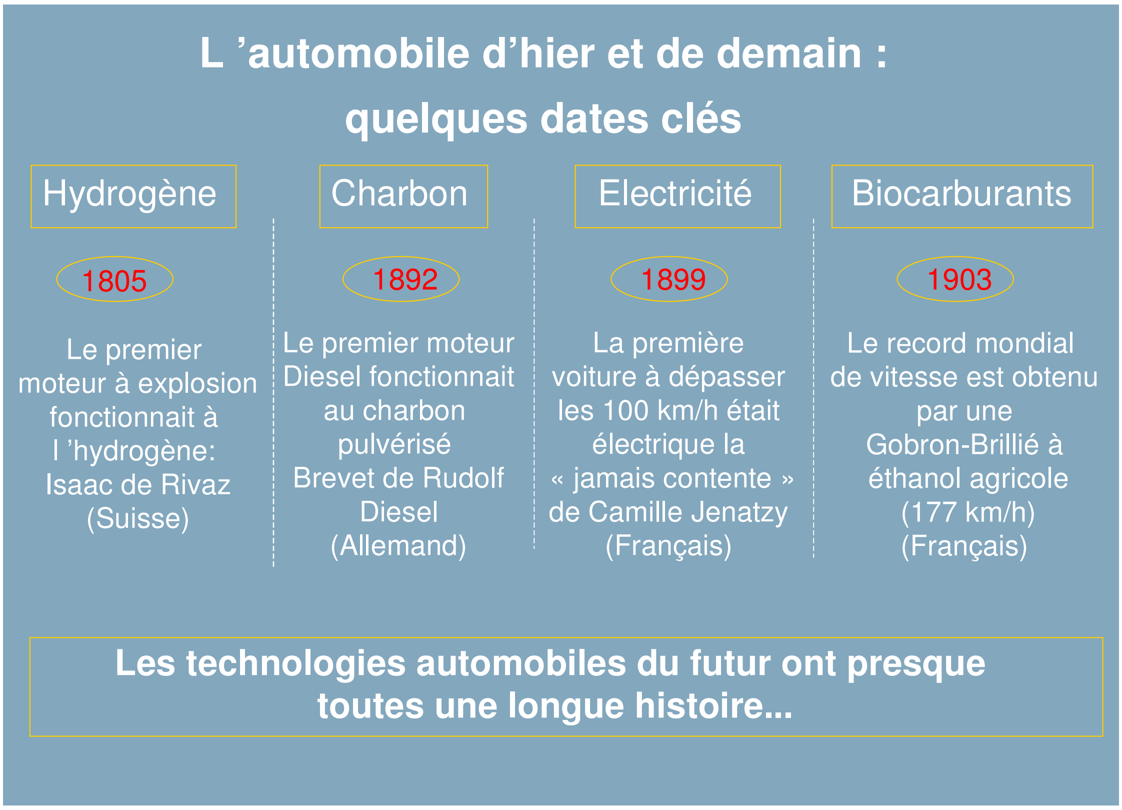
This historical summary essentially suggests the main answers to the questions raised by the cars of tomorrow or the day after tomorrow: what energy sources will they use, and for what drive systems?

What will be the energy requirement for tomorrow’s transport systems?

Any attempt to consider what the vehicles of tomorrow (2020-2050) or the day after tomorrow (2050-2100) might be can be based on several different approaches: should the starting point be the technology, that is to say, what we know we can achieve today and what we may hope to develop tomorrow as “economically acceptable” solutions? Or should we start out from the energy resources available to us today and tomorrow? Or should we begin with the environmental constraints (local and global) and their constantly increasing importance?

In actual fact, futurology obliges us to use an approach that combines all three of these fundamental dimensions, in order to attempt to define one or more plausible versions of the future.

But first we should bear in mind the nature of cars at the present time, the fleets that exist today and their broad characteristics in use, characteristics that derive from their energy requirements.



L ’automobile d’hier et de demain :
quelques dates clés

Hydrogène

1805

Le premier moteur à explosion fonctionnait à l ’hydrogène: Isaac de Rivaz (Suisse)

Charbon

1892

Le premier moteur Diesel fonctionnait au charbon pulvérisé Brevet de Rudolf Diesel (Allemand)

Electricité

1899

La première voiture à dépasser les 100 km/h était électrique la « jamais contente » de Camille Jenatzy (Français)

Biocarburants

1903

Le record mondial de vitesse est obtenu par une Gobron-Brillié à éthanol agricole (177 km/h) (Français)

Les technologies automobiles du futur ont presque toutes une longue histoire...

Cars of yesterday and tomorrow: some key milestones			
Hydrogen	Coal	Electricity	Biofuels
1805	1892	1899	1903
The first internal combustion engine, running on hydrogen: Isaac de Rivaz (a Swiss)	The first diesel engine, running on pulverized coal. Patent filed by Rudolf Diesel (a German)	The first car to travel faster than 100kph was electric: Camille Jenatzky’s “Jamais Contente” (a Frenchman)	The world speed record was won by a Gobron-Brillié running on bioethanol (177kph) (French)
Almost all the automotive technologies of the future have a long history behind them…			

Figure 2

The transport sector in the year 2000

	The transport sector worldwide (*)		The transport sector in France (*)	
	TOE mil.	%	TOE mil.	%
Road transport	1,500	80	40	76
Air transport	200	10	6	12
Maritime transport	100	5	3	6
Other transport modes	100	5	3	6
	1,900	100	52	100
Total energy consumption	**9,300**		**200**	
Transport, % of total	**20%**		**25%**	

(*) Rounded figures
(for precise detailed figures, see World Energy Outlook 2000
published by IEA).

Figure 3

Figure 3 shows that the energy consumption breakdown of France's transport sector is similar to that which exists worldwide.

If we wish to take a long-term (2050) or very long-term (2100) view of the future of transport, a second set of "scaling" factors can be seen to be necessary. These are the assumptions made in terms of demographic trends, global energy consumption and economic development up to these same time horizons. These factors are summarized in figure 4. Where the past is concerned, the data are IEA and OECD statistics rounded to the nearest significant digit. As for the future, they are the author's. These scaling parameters bring out two major phenomena that are likely to feature strongly in the 21st century:

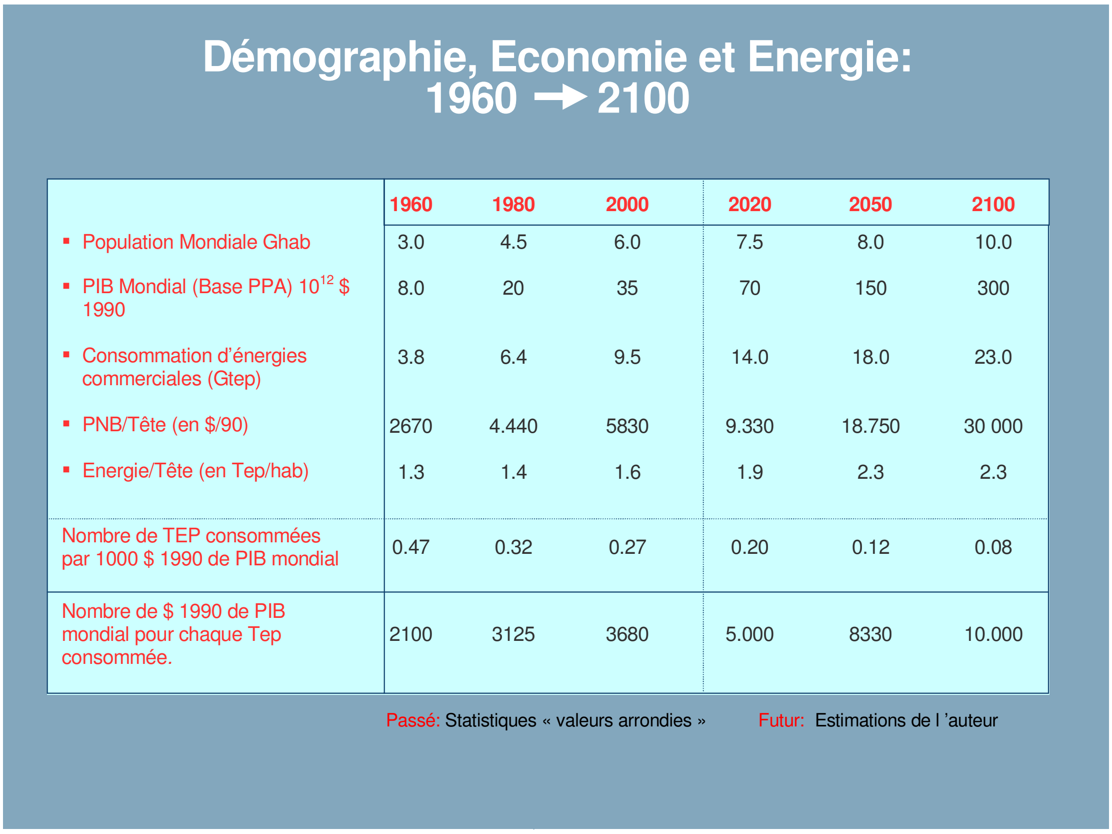
- A very sharp slowing in world population growth. Certain authors even forecast a decline in total world population after 2050.
- The relative slowing of economic growth, and especially the "dematerialization" of that growth and a sharp decline in its "energy intensiveness", that is to say, the total quantities of energy consumed per quantity of wealth or unit of world GDP.

It would of course be possible to discuss these broad assumptions *ad infinitum* and run through numerous different scenarios, but this would be at the price of blurring the picture or even making it impossible to interpret the future of the transport sector at all. The advantage of a simplified, but single central vision of the future, even if its validity is debatable – insofar as it is not actually absurd – is that it can be used to attempt an analysis of the future. The scaling provided by figures for population, energy and the economy to the 2050 and 2100 time horizons enables us to lay down an overall vision of the future energy requirements of the transport sector, and this is summarized in figure 5:

- We began by assuming that land transport would remain dominant in terms of energy requirements throughout the 21st century, absorbing three-quarters of total production by 2100 — as is now the case. This reflects the maintenance of the appetite for individual mobility, coupled with economic growth in the emerging or "non-OECD" countries.
- We also hypothesized a slowdown in the growth of consumption. This is the result of three closely interlinked phenomena: technological progress, an assumption as to increasing intervention by legislators and regulators in vehicle performance and use, and an increase in the cost of petroleum-based fuels linked to the decline in world oil production from around 2020 on (or 2030-2040 if sharp price rises occurring prior to the peak in world oil production were to postpone and smooth out this peak).

In the next paragraph, we shall try to show that the chosen figures are compatible with certain hypotheses as to the future development of global fleets (PV – private vehicles; UV – utility vehicles) and unit consumption levels, which are forecast to diminish sharply.

- And lastly, our long-term view of oil production (see figure 1) is for a decline to begin around 2020, or rather when the cumulative total for production has reached 1,500 billion barrels (compared with a cumulative total of 800 billion barrels in 2000). According to this vision of the future, the key question is what sources of energy will be capable of providing the 3.4bn TOE in 2050 and the 4bn TOE around 2100 that will be necessary to meet the requirements of the transport sector as we envision it at these time horizons (see figure 5).



Démographie, Economie et Energie: 1960 → 2100

	1960	1980	2000	2020	2050	2100
▪ Population Mondiale Ghab	3.0	4.5	6.0	7.5	8.0	10.0
▪ PIB Mondial (Base PPA) 10^{12} $ 1990	8.0	20	35	70	150	300
▪ Consommation d'énergies commerciales (Gtep)	3.8	6.4	9.5	14.0	18.0	23.0
▪ PNB/Tête (en $/90)	2670	4.440	5830	9.330	18.750	30 000
▪ Energie/Tête (en Tep/hab)	1.3	1.4	1.6	1.9	2.3	2.3
Nombre de TEP consommées par 1000 $ 1990 de PIB mondial	0.47	0.32	0.27	0.20	0.12	0.08
Nombre de $ 1990 de PIB mondial pour chaque Tep consommée.	2100	3125	3680	5.000	8330	10.000

Passé: Statistiques « valeurs arrondies »　　Futur: Estimations de l 'auteur

Population, Economics & Energy

1960 – 2100

* World population (billions)

* World GDP (PPP basis) $\$10^{12}$ (1990 dollars)

* Commercial energy consumption (TOE billions)

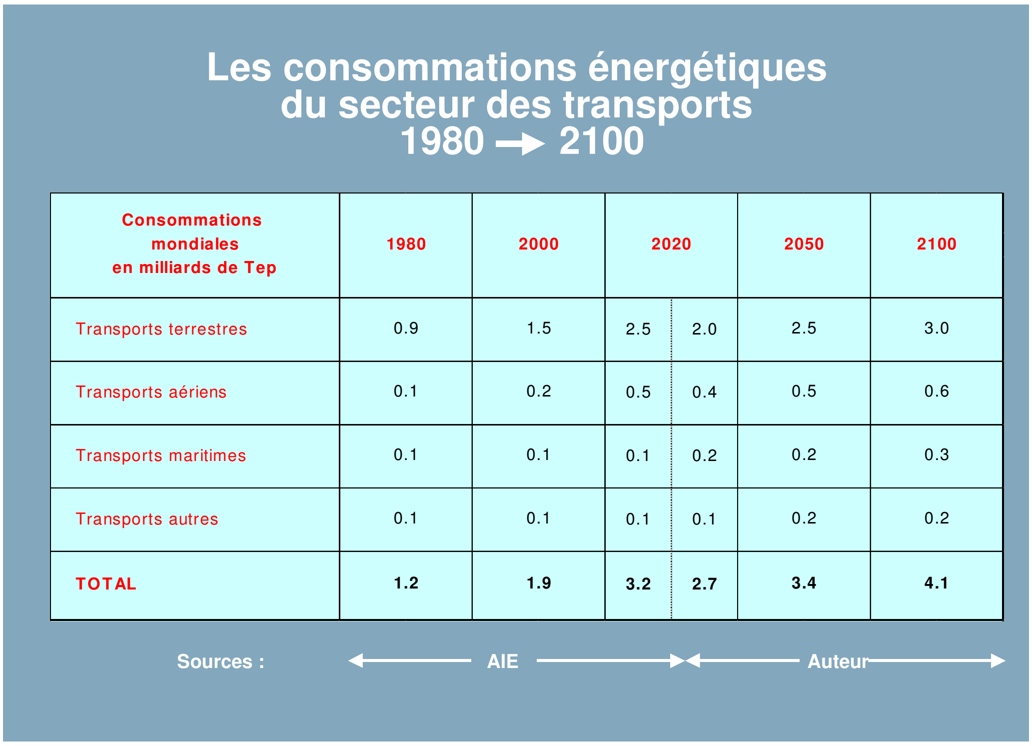
* Per capita energy (per capita TOE)

* TOE consumption per $1,000 of world GDP

* Number of 1990 $ for each TOE consumed

Past: “rounded” statistical data　　**Future:** author’s data

Figure 4



Les consommations énergétiques du secteur des transports 1980 → 2100

Consommations mondiales en milliards de Tep	1980	2000	2020		2050	2100
Transports terrestres	0.9	1.5	2.5	2.0	2.5	3.0
Transports aériens	0.1	0.2	0.5	0.4	0.5	0.6
Transports maritimes	0.1	0.1	0.1	0.2	0.2	0.3
Transports autres	0.1	0.1	0.1	0.1	0.2	0.2
TOTAL	**1.2**	**1.9**	**3.2**	**2.7**	**3.4**	**4.1**

Sources : ← AIE → ← Auteur →

Transport Sector Energy Consumption

1980 – 2100

World consumption in TOE billions

Land transport

Air transport

Maritime transport

Other modes of transport

Sources: IEA Author

Figure 5

The underlying economic assumption is that there will be a major shift upward in the prices for all forms of energy, this being linked to the issue of the peak in oil production worldwide, followed by a decline. Oil has in fact been playing a role for over fifty years now as the price leader for the whole range of energy sources, and its price has risen, very roughly, fourfold in real terms since the 1970s, due to the oil shocks over the period 1973-1979, despite one or more countershocks (1998-2003 prices were at $25/bbl, compared with $6/bbl in real terms — i.e. in constant year 2000 dollars) from 1968 to 1972. This initial and very substantial increase in real terms put a sharp brake on growth in demand for oil (roughly 6% a year between 1950 and 1973, and 1.5% annually since then: see figure 1). A second oil shock will be needed at some point between now and 2020 to bring about an adjustment to the total halt in the growth of production of natural liquid hydrocarbons. This shock will have a number of consequences:

1. It will permit large-scale development of savings on the use of all forms of

energy.
2. It will permit maximum development of the potential of renewable energy sources.
3. It will permit a sharp reduction to be achieved in unit consumption by cars.
4. It will stimulate large-scale production of synthetic liquid hydrocarbons.
5. It will stimulate production of hydrogen at competitive cost levels using nuclear power or renewable energy sources,
6. And lastly, it will stimulate a major relaunch of nuclear power generation around the world, using new industrial systems (indeed, the fourth generation from around 2020).

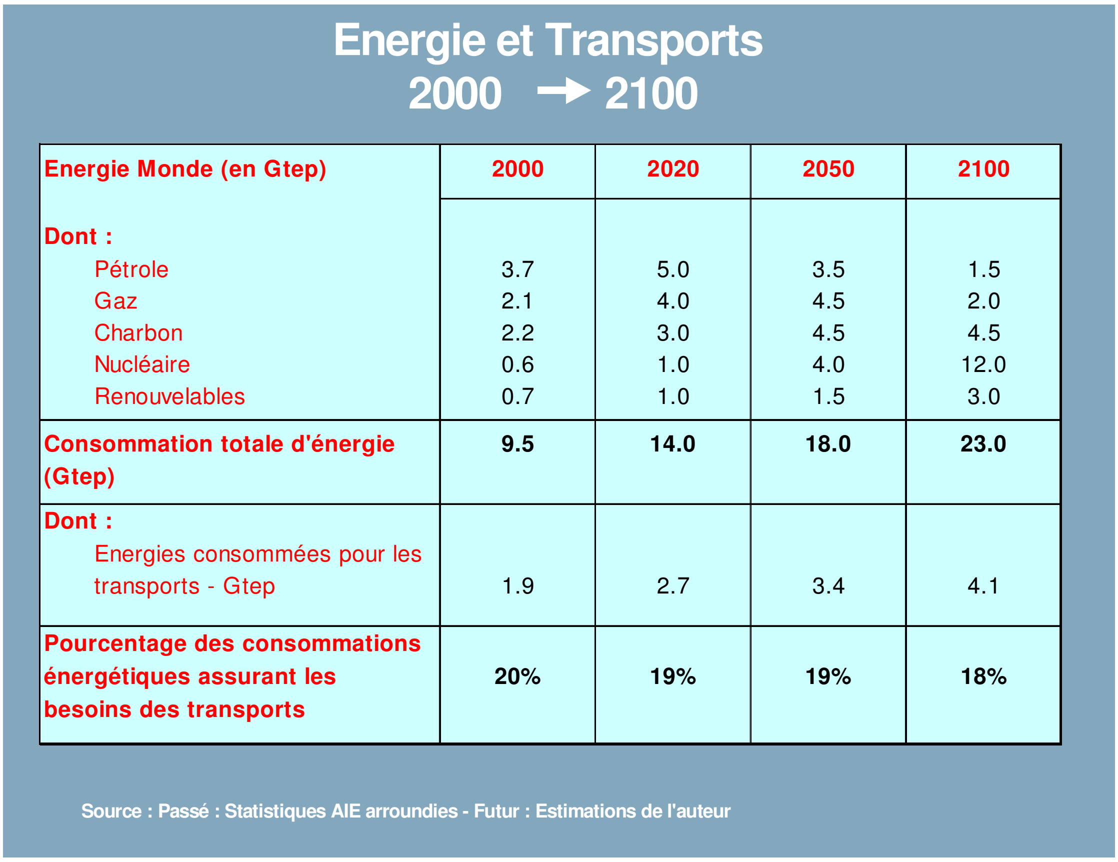
The size of the shock estimated by the author to be necessary is of the same order of magnitude as a further quadrupling of the crude oil price (a move from $25/bbl barrel over the period 1998-2003 to $100/bbl between 2015 and 2025 in constant year 2000 dollars).

The manner in which this second shock might come about is of little importance. To take a metaphor from geology, we could say that we are confronted with a problem of tectonics: future shifts must result in a cessation of the accumulation of stress. In tectonics, that can be achieved by a brutally sudden break in a major rock fault or by individually small movements in a large number of faults. Similarly, the shift of the entire global energy system to a new equilibrium can be achieved by some catastrophically sudden event affecting the price of crude oil, as happened in 1973 (although this was followed by a range of aftershocks), or by a series of many smaller adjustments.

Once this new equilibrium has been reached, the question arises as to what might take over from oil as price leader for all the other forms of energy. The thesis here is that oil will fill this role for many years to come, but the price of oil will be very tightly linked to the cost of the various synthetic liquid hydrocarbons, and the latter will therefore act as “invisible price leaders” in the system.

In this new context, political price control (by OPEC or other actors) will no longer be required.

The new situation will not be risk-free. For example, in the case of biofuels, the new pricing of energy sources runs the risk of ensuring that the “competition for arable land and water” becomes pitiless, forcing some regions to sacrifice their production of food resources. Likewise, this movement in prices will lead to temptations to indulge in a frantic race to develop biotechnologies, GMOs or other techniques to enhance yields in biomass production for energy use.



Energie et Transports
2000 → 2100

Energie Monde (en Gtep)	2000	2020	2050	2100
Dont :				
Pétrole	3.7	5.0	3.5	1.5
Gaz	2.1	4.0	4.5	2.0
Charbon	2.2	3.0	4.5	4.5
Nucléaire	0.6	1.0	4.0	12.0
Renouvelables	0.7	1.0	1.5	3.0
Consommation totale d'énergie (Gtep)	**9.5**	**14.0**	**18.0**	**23.0**
Dont : Energies consommées pour les transports - Gtep	1.9	2.7	3.4	4.1
Pourcentage des consommations énergétiques assurant les besoins des transports	**20%**	**19%**	**19%**	**18%**

Source : Passé : Statistiques AIE arrondies - Futur : Estimations de l'auteur

Energy and Transport

2000 – 2010

World energy (TOE billions)

Including:

Oil
Gas
Coal
Nuclear
Renewables

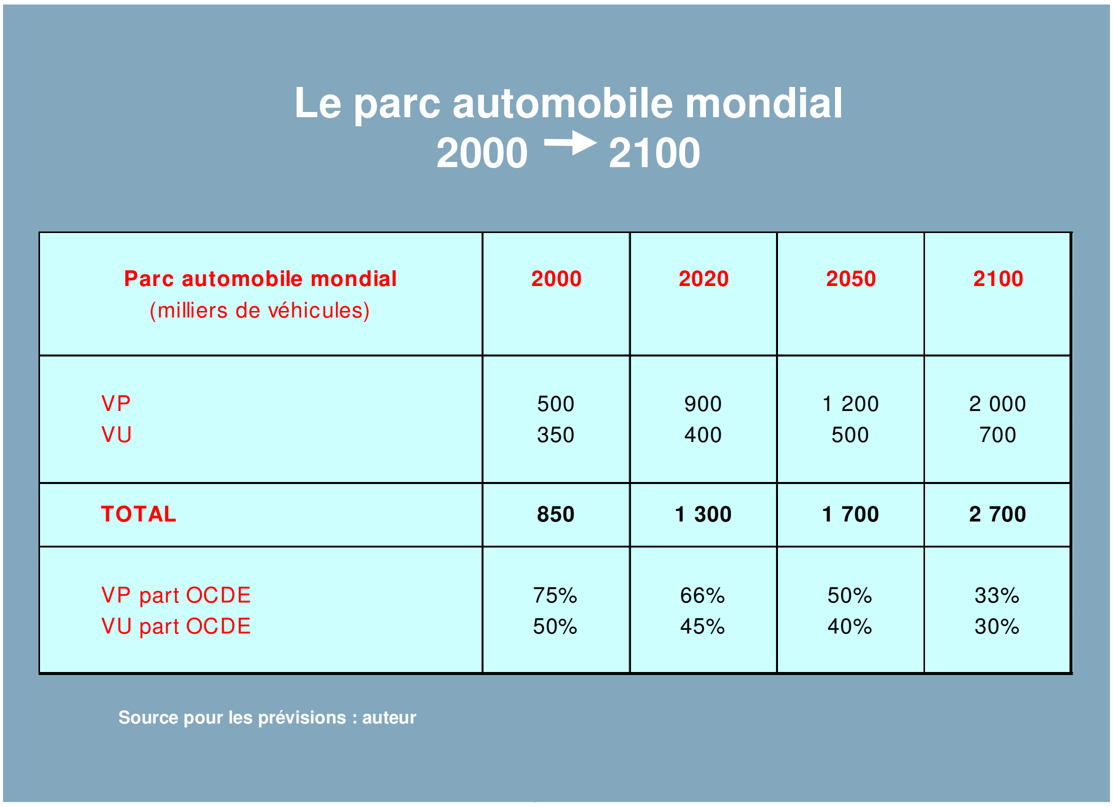
Total energy consumption (TOE billions)

Including:
Transport energy consumption in TOE billions

Percentage of energy consumption taken up by transport
Source: Past – rounded IEA statistics — Future – Author's estimates

Figure 6

NB: the virtual stability, or indeed slight decline, in the percentage of global energy taken up by the transport sector (20% in 2000 against 18% in 2100) runs counter to certain forecasts, which see a substantial increase in transport's share (to 50% or more!).



Le parc automobile mondial
2000 → 2100

Parc automobile mondial (milliers de véhicules)	2000	2020	2050	2100
VP VU	500 350	900 400	1 200 500	2 000 700
TOTAL	**850**	**1 300**	**1 700**	**2 700**
VP part OCDE VU part OCDE	75% 50%	66% 45%	50% 40%	33% 30%

Source pour les prévisions : auteur

The world car fleet

2000 – 2100

The world car fleet

(thousands of vehicles)

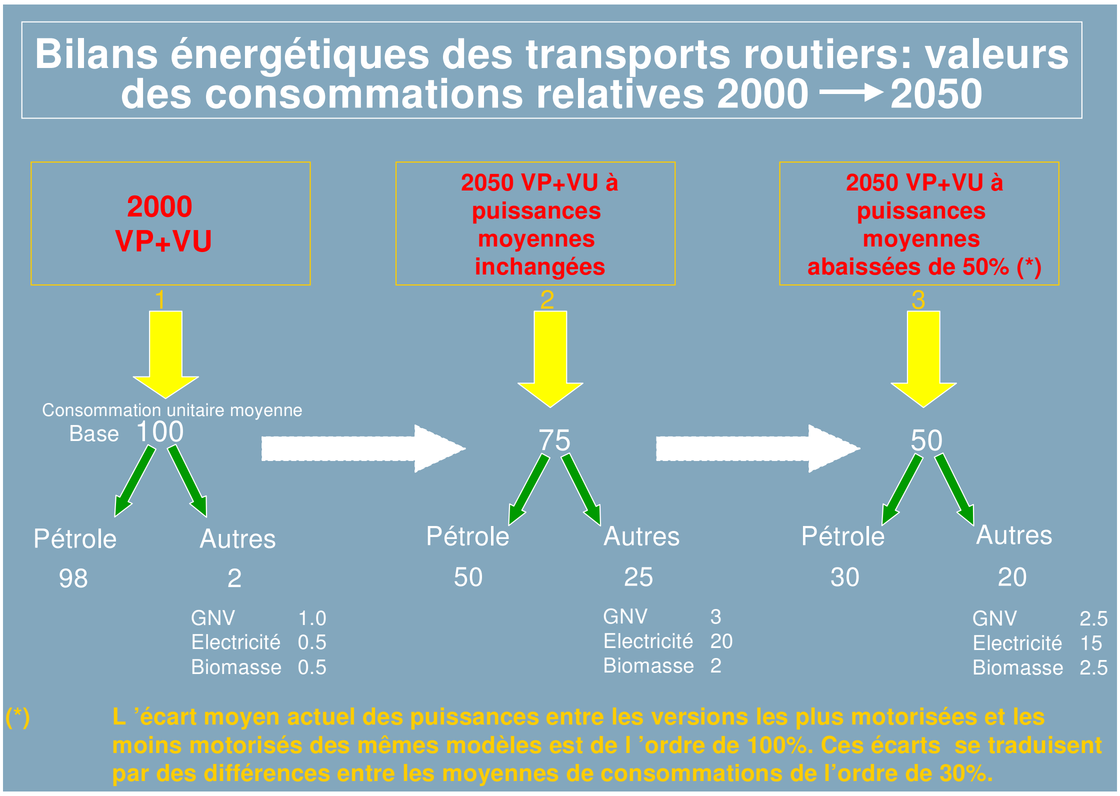
Private vehicles
Utility vehicles
TOTAL
OECD % PV
OECD % UV

Source for forecast figures: author

Figure 7

* In this table, it is assumed that the “geography” of the OECD remains unchanged from its year 2000 configuration.

The table does not derive from any study (which would need to take into account changes in public transport modes, urbanization, kilometres travelled annually, and so on). This is no more than an estimate and is provided here to verify the general consistency of the figures put forward by the author for energy consumption in the transport sector.



Bilans énergétiques des transports routiers: valeurs des consommations relatives 2000 ⟶ 2050

2000
VP+VU

2050 VP+VU à puissances moyennes inchangées

2050 VP+VU à puissances moyennes abaissées de 50% (*)

1

Consommation unitaire moyenne
Base 100

Pétrole	Autres
98	2

GNV	1.0
Electricité	0.5
Biomasse	0.5

2

75

Pétrole	Autres
50	25

GNV	3
Electricité	20
Biomasse	2

3

50

Pétrole	Autres
30	20

GNV	2.5
Electricité	15
Biomasse	2.5

(*) L 'écart moyen actuel des puissances entre les versions les plus motorisées et les moins motorisés des mêmes modèles est de l 'ordre de 100%. Ces écarts se traduisent par des différences entre les moyennes de consommations de l'ordre de 30%.

Road transport energy balance: relative consumption 2000 - 2050

PV + UV 2000

PV + UV 2050
average power levels unchanged

PV + UV 2050
average power levels reduced by 50%

Average unit consumption
Base 100

Oil Other

NGV
Electricity
Biomass

Oil Other

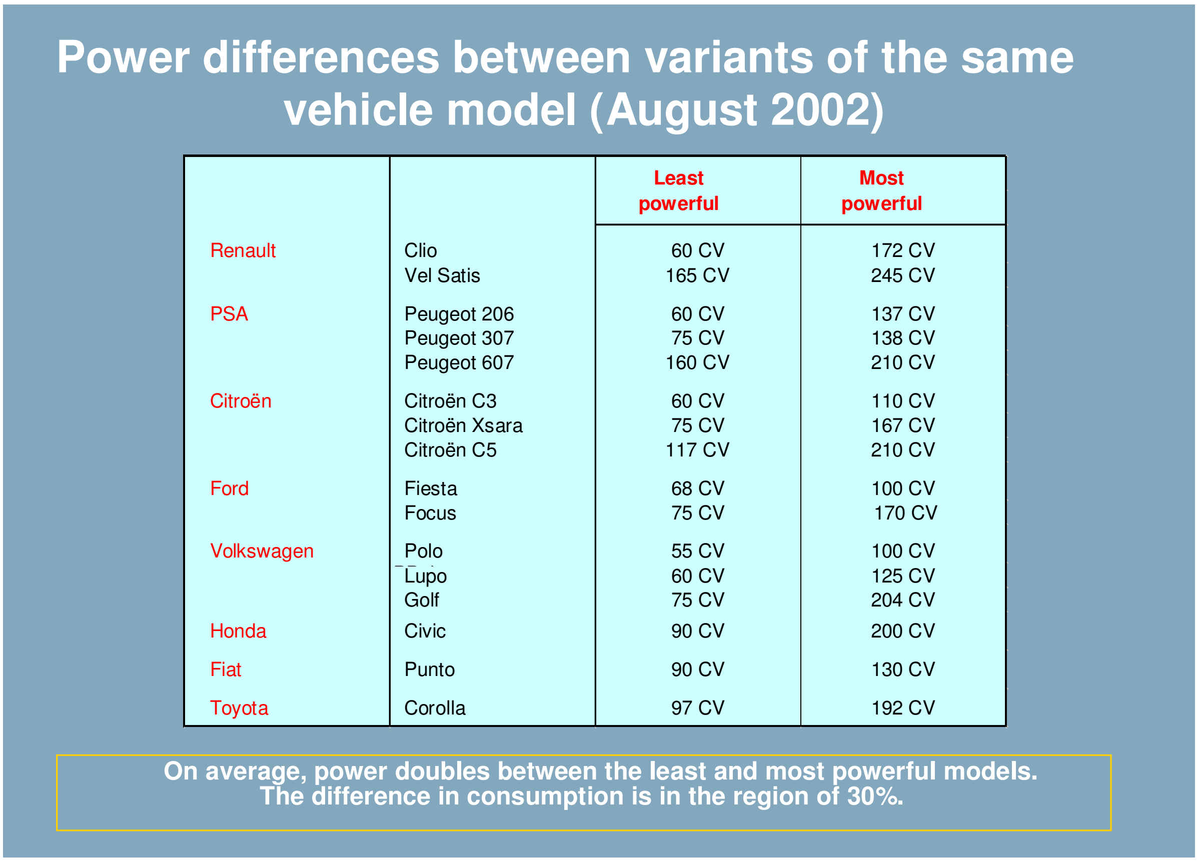
NGV
Electricity
Biomass

Oil Other

NGV
Electricity
Biomass

(*) The average power gap between variants of the same model from the most to the least powerful engine systems is currently in the region of 100%. Such gaps are reflected in differences in average consumption of the order of 30%

Figure 8



Power differences between variants of the same vehicle model (August 2002)

		Least powerful	Most powerful
Renault	Clio	60 CV	172 CV
	Vel Satis	165 CV	245 CV
PSA	Peugeot 206	60 CV	137 CV
	Peugeot 307	75 CV	138 CV
	Peugeot 607	160 CV	210 CV
Citroën	Citroën C3	60 CV	110 CV
	Citroën Xsara	75 CV	167 CV
	Citroën C5	117 CV	210 CV
Ford	Fiesta	68 CV	100 CV
	Focus	75 CV	170 CV
Volkswagen	Polo	55 CV	100 CV
	Lupo	60 CV	125 CV
	Golf	75 CV	204 CV
Honda	Civic	90 CV	200 CV
Fiat	Punto	90 CV	130 CV
Toyota	Corolla	97 CV	192 CV

On average, power doubles between the least and most powerful models.
The difference in consumption is in the region of 30%.

What will be the energy sources for transport in 2050 and 2100?

The physical limitations on available resources of liquid and gaseous hydrocarbons and the constraints imposed by greenhouse gas emissions, for both hydrocarbons and coal, appear to lead to a sharp worldwide reduction in the relative importance of fossil energy sources during the 21st century. Figure 6 summarizes this second set of “scaling” parameters, which must channel our consideration of the issues raised for the long term by the need to meet the energy requirements of transport.

One question must be answered in any consideration of the end of the 21st century: annual global oil production would, in our view, be in the region of 1.5bn TOE by 2100, whereas transport alone will need approximately 4bn TOE. For this reason, there can be no question of simply continuing to use current energy sources, especially given that over 95% of the transport sector is reliant on oil. There is no difficulty in extrapolating present modes of transport to 2020 and the energy consumption associated with them. But a breakpoint is already on the horizon before 2050: at that date the world would be producing oil at the rate of 3.5bn TOE (that is, a level roughly similar to current production) but transport alone would need almost all this energy. It is clear that 100% of oil production cannot be earmarked for transport alone: due to its economic value as a raw material (petrochemicals, solvents, waxes and paraffins, bitumens, etc.), or as a source of heat for individual consumers (factories, crops, housing, etc.), the transport sector is likely to be able to rely at best on approximately 60% of total production by 2050, this being some 2.5bn TOE, and, logically, a lower percentage after that date. We will assume, and it is probably an optimistic assumption, that natural hydrocarbons could still supply 1bn TOE of energy for the transport sector at the 2100 horizon. Already in 2050, a “deficit” of 1bn TOE for the transport sector would therefore need to be filled by other forms of energy, bearing in mind that we have already integrated into our forecasts major impact from technological progress and legislation aimed at reducing vehicle consumption. According to the assumptions used here, this impact cuts average unit consumption by the PV + UV fleets to 50% between 2000 and 2050 (see figures 7, 8 and 9).

So, put in broad terms, the problem is to determine what sources of energy might be able to supply to the transport sector the 1bn TOE that is missing in 2050 and the 3bn TOE in 2100, energy that natural liquid hydrocarbons cannot provide.

There are two ways in which this question can be answered, and they can in fact be combined.

The first possible answer is that synthetic hydrocarbons (or equivalent chemical compounds used as fuels: alcohols, esters, and so on) will be produced to fill the gaps. The second possible answer is the massive introduction of new sources or vectors of energy in the transport sector, with hydrogen or electricity being, on the face of it, the most likely candidates — it should not be forgotten that their use in the field of land transport has been envisaged (in the case of hydrogen) or actually implemented (electricity) for over a century (see figure 2).

- **Synthetic hydrocarbons**

These come in three families, two of which already have a long history: those produced using biomass (ethanol, methanol, plant oils, EMC, ETBE, etc.) and those produced from fossil energy sources, GTL (gas-to-liquids) and CTL (coal-to-liquids), these being variants of the Fischer-Tropsch process, or using direct hydrogenation (variants of the Bergius process). These first two process families are familiar and their potential is periodically re-evaluated. However, biomass fuels, as well as those obtained by Fischer-Tropsch synthesis, seem to have limitations on their potential for large-scale production. Given the orders of magnitude involved, these synthetic hydrocarbons, which we already know how to produce, might permit the problem to be solved up to 2050, but this is very unlikely beyond that date. Conversely, we will not discuss here the research on production systems for liquid synthetic hydrocarbons based on more exotic methods, whose chances of economic success currently appear very slim (methane polymerization or “homologation”, bioprocesses based on various single-cell cultures, and others). We shall mention only one such “exotic” system, since it seems to us to have genuine potential: the production of hydrocarbons using hydrogen made using renewable energy sources, or, more probably, nuclear power. This system might be called “hydrogen carbonization”.

The limitations differ according to whether one considers biofuels or Fischer-Tropsch fuels. In the case of biofuels, they stem from a problem of increasing costs as demand rises, and, secondly, increasing arable land and water requirements (with the latter being itself produced in the future with an expanding energy content: pumping from ever greater depths, large scale desalination, and so on).

It should be remembered that the net yield of biofuels is, at best, in the region of 1 TOE per hectare per year, a figure applicable to both alcohol and oilseed fuel types, and will probably remain broadly at the same level for future cellulosic biomass conversion systems. “Competition for land” will therefore limit the development of biofuels to approximately 10% of requirements over the period 2050–2100, and this will use some 15% of arable and forest land. Even a “GMO revolution” seems incapable of overcoming these barriers to expansion, doing no more than push the levels up and the dates back at which those barriers are encountered.

In the case of Fischer-Tropsch synthesis fuels, the limitations are also economic in nature, but are linked to the future cost, which will logically be rising, of CO_2 emissions and the costs, also rising, of their raw materials (gas or coal). This is so because these processes are, and will continue to be, energy intensive. This constraint will perhaps not yet have become problematic by 2020, but beyond that date it will be. Well before 2050, the approximate date at which, due to resource-related constraints, it would be necessary to switch from GTL to CTL. Large-scale use of GTL or CTL to produce synthetic fuels presupposes that we have been able to solve, at a reasonable cost, the problem of the sequestration of the CO_2 emitted by the facilities producing these fuels.

We have already said that there are three available families of synthetic hydrocarbons, mentioning the third only briefly, which we might call “carbonized hydrogen”. This would involve the production of hydrogen using renewable energy sources or nuclear power, and “carbonizing” it at source, thus totally avoiding the costly logistics that would be necessitated by the transportation of massive quantities of hydrogen, its distribution and its storage on vehicles.

This concept of “hydrogen carbonization” does not appear to have been effectively explored over the last half-century, but it is very attractive in theory. It can be implemented using a method analogous to Fischer-Tropsch: the coal would produce carbon monoxide (by partial oxidation of the coal or biomass), which would then be combined with hydrogen, in all likelihood using energy of “nuclear” origin. It might be thought that there will be implementations of this that would be economically more efficient, based on direct hydrogenation of carbon materials (successors of the Bergius processes developed in Germany in parallel with the Fischer-Tropsch process in the run-up to the Second World War).

Naturally, the ideal would be to use the CO_2 as a source of carbon, which would combine CO_2 sequestration and hydrogen carbonization.

All in all, if “conventional” or new synthetic fuels, such as carbonized hydrogen, were to come up against technological and economic limitations, there are still the other possible heavyweight challengers: hydrogen and electricity.

- ## Hydrogen

There has been a vast amount of literature since 1875 (Jules Verne, *The Mysterious Island*) telling us that hydrogen is the fuel of tomorrow, because it is inexhaustible and ideally clean, insofar as only water is produced when it burns.

Enormous numbers of articles, books and seminars address this topic: an article in the 1930s warned the French to beware of the German army of the future, which would be equipped with trucks running on hydrogen! The advertising put out by certain industrial groups has no hesitation in asserting the reality of a radiant future in the transport sector, built on the lightest of all atoms.

One observation cannot be avoided in any review of the literature on hydrogen: the relative lack of detail where its production is concerned, which is the real issue, whereas there are long passages on how it is stored and used in engines, turbines and fuel cells. These descriptions underline the cleanliness of hydrogen vehicles, which emit only water locally, but usually neglect the economics and the CO_2 emissions upstream in hydrogen production cycles.

This is so because hydrogen is not a source but a vector of energy, and in order to produce it, other energy sources need to be employed first. After having been produced by electrolysis early in the century, 98% of hydrogen is now made using hydrocarbons or coal, at a production cost ranging between two and five times that of the hydrocarbons used to produce it. This ratio is around 2:1 when the process starts out from “expensive” hydrocarbons – the reforming of natural gas or naphtha in Europe for example – and around 5:1 when the raw material is “cheap” hydrocarbons – natural gas in an exporting country or heavy refinery residues supplying a partial oxidation unit (POx) in Europe or the USA. This is illustrated by figures 10 and 11. If the reason for turning to hydrogen for transport is the increasing scarcity of hydrocarbons and the concomitant increase in their cost, this method of obtaining it cannot therefore provide a lasting answer to the problem to be solved. The use of coal to produce very large quantities of hydrogen will in fact be similarly limited by the costs associated with the emission of CO_2 or its segregation.

There remain the other possible techniques for producing hydrogen. Although in theory the production of hydrogen using biological processes (bacteria, algae) is feasible, we are currently a long way from potentially economically viable processes. The current gap varies by a factor of 100 to 1,000 according to the different studies or the processes envisaged. On the other hand, the production of hydrogen by electrolysis (as used at the beginning of the 20th century) or the thermal breakdown of water based on more or less complex thermochemical cycling is closer to the threshold of economic viability.

For example, in Europe and the USA at the present time, using electrical current at €20/MWH or €25/MWH, the cost of hydrogen obtained on a large scale by electrolysis would be two or three times higher than hydrogen produced by reforming or partial oxidation. If massive use of electrolysis or thermochemical cycling were envisaged, this would boil down to saying that in order to produce massive quantities of hydrogen, we would need to have massive quantities of electricity or low-cost calories non-productive of CO_2 emissions. Unless there are unexpected breakthroughs in the area of renewable energy sources, it would for this reason be nuclear power that would have to provide the hydrogen needed over the long term to provide the transport systems of tomorrow (like the hydrogen that might possibly be used directly as an energy vector).

Let us suppose that this key problem for the production of hydrogen has been resolved. We need then to ask ourselves whether hydrogen is a good or bad energy vector for transport. Our answer here is that according to our economic assumption – a quadrupling of the price of hydrocarbons – nuclear hydrogen becomes competitive. But the reactors needed to produce hydrogen with nuclear power are still to be developed: these will probably be HTR reactors or other types of system of fourth generation design, combining good energy yield with efficient use of fissile fuels.

Nevertheless, hydrogen is and will remain a very poor energy vector where land transport is concerned. It might however have advantages for air transport: we look at this question below. Both these assertions are based on an analysis of hydrogen's technological and economic fundamentals, of which the main characteristic is that it has very high energy density per unit mass, but a very poor energy-volume ratio, irrespective of the form in which it is carried and stored.

A few figures are enough to illustrate the very poor energy-volume ratio of hydrogen, this being the only critical factor for land transport. The transportation of hydrogen by pipeline costs now, and will cost in the future, approximately twice as much as for natural gas, which itself costs around five times more in terms of logistics than the transportation of liquid hydrocarbons. These characteristics are intrinsic and thermodynamics will not change as the technology progresses. We can therefore say as of now that in 2050 and in 2100, hydrogen logistics based on piping, whether massive or capillary in type, will cost around ten times more per unit of energy carried than the logistics for liquid hydrocarbons. The factor of ten is in fact a minimum calculated on the basis of the energy capacity of transportation pipes alone, leaving aside all the other factors which generate extra cost in the context of hydrogen logistics: specific safety-related problems and the difficulty of transporting very large quantities on land other than under pressure in pipes.

Furthermore, the carrying aboard vehicles and the storage of hydrogen are around one hundred times more costly than for conventional fuels, gasoline, diesel or kerosene. And this is very likely to remain the case no matter what type of storage is chosen for hydrogen: very high pressure tanks (at 400 or even 800 bars), cryogenic liquid hydrogen (at – 253℃), in chemical combination (hydrides) or adsorbed (carbon nanotubes, for example). In all these cases, except that of cryogenic liquefied hydrogen, the technological and economic difficulty relates to the low mass of the hydrogen stored compared with the mass of the tank required. For example, in the case of pressurized hydrogen, the mass of the hydrogen stored in the tank is no more than roughly 2% or 3% of the mass of the tank if it is in metal, although it may reach around 10 percent for composite tanks pressurized to 350 or 700 bars.

Likewise, in the case of hydrides, it does not appear to be the case that the mass of useable hydrogen can in practice exceed 2% to 3% of the total mass of tank plus hydrides.

The good energy efficiency of hydrogen as expressed in terms of energy per unit mass can therefore be seen in fact to be totally cancelled out by the fact that when non-liquefied it requires a container whose mass, whatever its shape, will be in the region of twenty times that of the hydrogen it contains (see figure 12).

Where the cryogenic liquefied hydrogen solution is concerned, the limitations relate more to the volume of the tank rather than its mass. They are also linked to the need for "boil-off" (evaporation of the cryogenic liquid is necessary to produce the frigories to keep the temperature constant) and the high level of energy consumption required for the liquefaction of hydrogen (around 25% to 30% of the load).

Hydrogen emissions, however limited, are obviously not acceptable for private vehicles, which need to able to be left in garages and closed parking areas for indefinite periods.

The announcement by a car manufacturer at the World Petroleum Congress in Rio de Janeiro in September 2002 that a "zero boil off" cryogenic tank had been developed for onboard use in cars would, if true, be a major breakthrough. However, it is difficult to imagine on what physical principles a genuine “zero boil off” tank might be based.

All in all, hydrogen can therefore be seen to be a very poor energy vector in terms of its cost at three key stages in its use: its production, its logistics – whether massive or capillary – and its storage on vehicles.

The high energy efficiency of its use in fuel cells, even if these were cheap, does not seem to be capable of offsetting these major economic handicaps. The fact that there may be exceptional circumstances in various locations around the world (Iceland for example) where local circumstances might justify the use of the hydrogen vector in economic terms does not invalidate the above conclusions.

The upshot of these technological and economic characteristics of hydrogen as used on vehicles is that it has very little chance of achieving dominance for land transport and is likely to remain restricted to a few small niches (e.g. urban public transport fleets running on liquid or high-pressure hydrogen). These niche markets would be, very broadly, the same as those for “all-electric” vehicles running on batteries. Despite the forty or so “gas stations” serving hydrogen that are in operation or definitely planned at the present time (2003), there is no sign justifying the expectation that hydrogen may win in the long run, even in the niche markets we have mentioned.

Conversely, where air transport is concerned, hydrogen might one day be able to take advantage of its key quality: its high energy density per unit mass: while this is almost beside the point on land, it could have advantages for air transport in the very long term, after 2050 perhaps. This idea is not a new one and has already led to a number of projects and even trials (the B57 bomber modified in 1957, the Tupolev 154, modified and renamed as the ‘155’, in 1988, etc.).

For aircraft, the problem of hydrogen’s large volume would mean that 20% to 30% of the volume of the fuselage would be devoted to cryogenic hydrogen tanks, which is unlikely to be a handicap impossible to overcome.

In actual fact, the question of whether hydrogen might be used (only in its cryogenically liquefied variant) in aviation deserves a whole study in itself: we have already seen that the “boil-off” issue rules out any large-scale penetration of liquefied hydrogen in land transport, whereas this is not a major obstacle for air transport based on wide-body aircraft. Furthermore, the weight saved has a high economic value for air transport but not for land transport. All in all, a profit-and-loss comparison of liquefied H_2 against synthetic fuels remains to be done for aviation, but the benefits of hydrogen are likely to be much more marked for air than for land transport. However, this does not rule out the possibility that other factors, such as NOx emissions from jet engines running on hydrogen, might hinder the development of this concept in practice.

Figure 12:

LIQUID HYDROCARBONS:

UNRIVALLED ENERGY DENSITY

kWh/kg

liquid hydrocarbons

Compressed natural gas

Hydrides

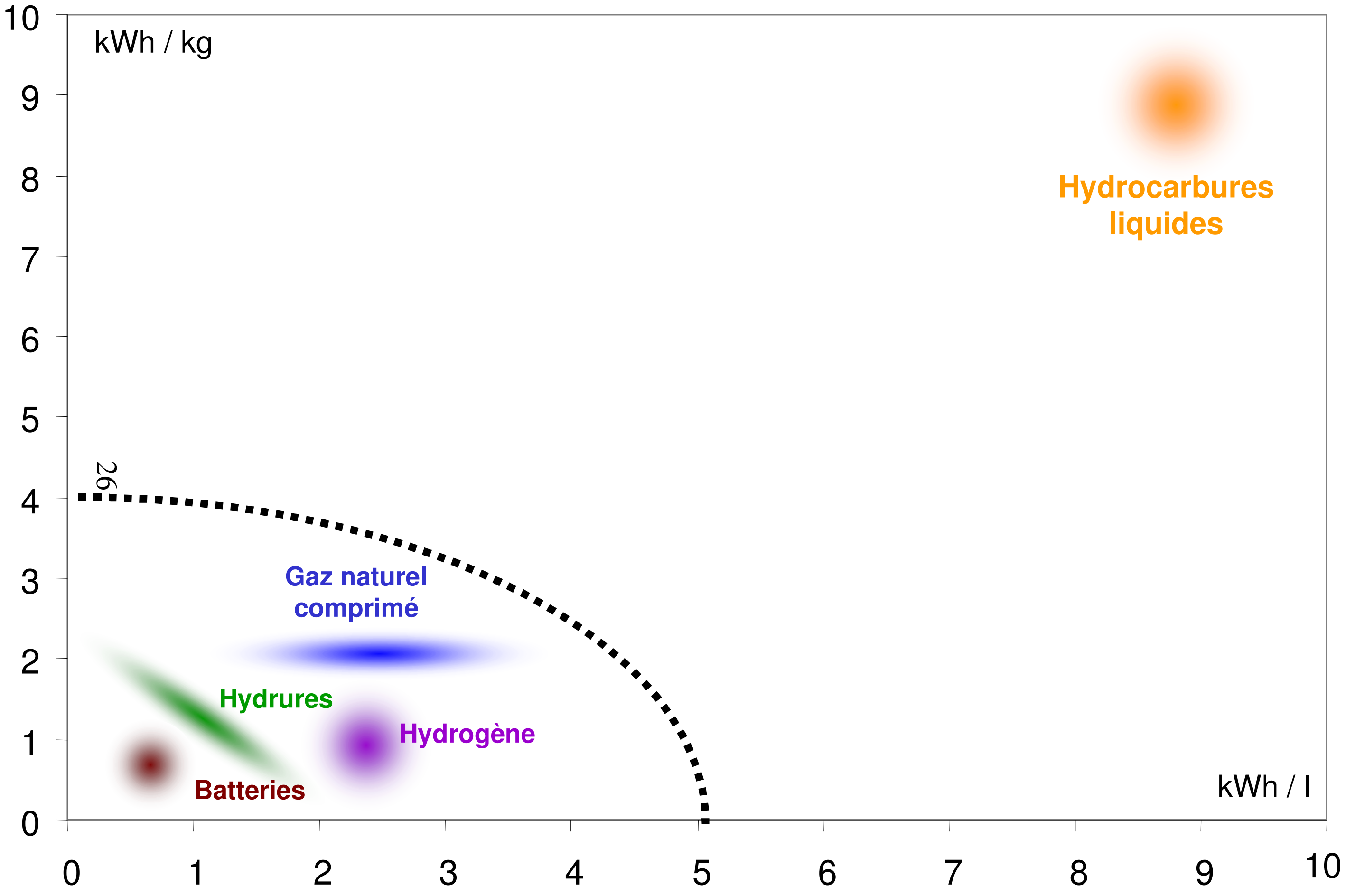
Hydrogen

Batteries

Compressed natural gas: steel or composite tanks

Hydrogen: liquefied or compressed to 5,000 to 10,000 PSI and held in a composite tank

LES HYDROCARBURES LIQUIDES :
UNE COMPACITÉ ÉNERGÉTIQUE INÉGALÉE



Gaz naturel comprimé : réservoir acier ou composite

Hydrogène : liquide ou comprimé de 5000 à 10000 PSI en réservoir composite

PRB / VL 2003

Illustration n° 12

- **Electricity**

Once again, as in the case of hydrogen, for over a century the problem has been the same: how to store a large quantity of electricity on a vehicle (see figure 12) and the time required to “store” it.

It is noteworthy that in seventy years the weight of the lead-acid batteries per stored kWh, as used in SITA garbage trucks, has remained virtually unchanged: the progress made has improved recharging time (cut by half), use life (doubled) and compactness (half the volume for the same power).

Figure 12 offers a comparison of the performance offered by different forms of energy from the point of view of storage on board automotive vehicles: the supremacy of liquid hydrocarbons is very striking.

When we fill the tank of our cars, we fail to realize that whether they run on diesel or gasoline we are filling the tank at the rate of 100km to 200km potential travel range every minute, whereas an electric vehicle can charge its batteries only at the rate of one or two kilometres per minute of charging time. But above all, the fuel tank of an average car provides a travel range before refuelling of over 500km (and the trend is toward 1,000km), while the battery in the same average car provides an effective range before recharging of no more than a hundred or so kilometres, a figure that is only a slight improvement, weight-for-weight, on those of a century ago.

The history of electrical storage cells is one of very slow progress over the course of the 20th century. Moreover, that progress has involved use of metals (cadmium, lithium) that are expensive and a source of pollution, if care is not taken to collect used batteries. This cannot allow any large-scale development commensurate with the size of the automotive markets: the technology for the production of lithium batteries and their recharging is almost as sophisticated as that of fuel cell manufacture and implementation.

In the absence of a sudden, unexpected technological breakthrough, “all-electric” vehicles will also remain limited to a few niches: urban utility vehicles such as garbage trucks, mini-vehicles for leisure use (golf courses) or services (baggage tractors in train stations), for example, plus a small number of captive, short-range fleets. These niches are more or less the same as those for hydrogen, liquefied or pressurized, and the competition between the two sources will determine the ultimate victor in these highly specific applications.

This pessimistic conclusion as to the future role of electric vehicles must however allow for a recent development which could play a major part in years to come: the arrival of hybrid vehicles on the scene. The idea, as we have seen, is not new, but the progress made in power electronics, complex automated regulation systems and the development of electrical transmissions and differentials have made it industrially feasible, at a cost level that, while undoubtedly high, is not prohibitive. The Toyota Prius has been on the market since 1997 and we can expect over the next few years to see a hybrid with enough battery capacity to enable recharging from the mains network. This would allow a third or half of energy consumption for vehicles used essentially in city or near-city areas to be taken from the electricity mains. Moreover, it is in fact the case that these modes of use apply today to the majority of the world vehicle fleet and the percentage is constantly rising (due to the global phenomenon of urbanization and suburban spread).

In order to attain such goals, it would be sufficient to have hybrid cars with an electrically driven range of 30 to 40 kilometres, which should not be out of our reach between now and 2010 or 2020. Of course, most battery recharging would go on at night, thanks to suitable off-peak tariffs, and this would enable electricity producers to make an old dream reality – smoothing out the fluctuations in daily demand curves. In this case, the smoothing would be achieved by storing electricity produced during demand off-peak periods in the batteries of cars that are off the road.

It is worth noting that in a country like France, whose installed electrical capacity is in the region of 100 gigawatts (that is, the equivalent of one hundred 1,000MW generating units), the "installed capacity" under the hoods of the private car fleet is in the region of 2,000 gigawatts (30 million 100HP cars or 73 kilowatts on average). The national car fleet thus represents a total power twenty times greater than the installed electricity generation infrastructure, but it "runs" on average less than 5% of the time during the year whereas the electricity generation infrastructure is "running" approximately 50% of the time. We have here a solution that would be very significantly more effective in smoothing electricity demand curves than the few pumped storage power plants that we can build.

In our chosen context, in which we have assumed a strong worldwide relaunch of nuclear power generation after 2020, it can be easily seen that this would be complemented to a remarkable degree by large-scale development of rechargeable hybrid vehicles.

The globalization of such hybrid solutions, consisting in the main of cars for use in towns, suburbs or, more simply, used only for short distances, makes it possible to look forward to a third or a quarter of the total energy consumption for the land transport sector to be sourced in electricity, beginning before 2050 for countries in the OECD category, and a little later for all fleets worldwide. This solution seems however to be destined to be restricted to private cars (excluding professionals habitually travelling long distances) and utility vehicles specializing in short journeys (50 to 100 km/day), to the exclusion of long-distance road travellers. Such vehicles, for which the "rechargeable hybrid" solution is on the face of it an attractive one, are likely to account for 70% to 80% of the global fleet in 20 or 30 years' time and approximately two-thirds of total energy consumption.

Summary and conclusions

Where transport is concerned, the year 2020 is tomorrow, and 2050 is the day after tomorrow. This is so because the sector is characterized, like the whole range of phenomena associated with energy, by a high degree of inertia, and therefore very great slowness to react when confronted with fundamental change.

This is due first and foremost to the inertia of existing transport resources: fifty or so years for aircraft and ships, a dozen years for road vehicles. But more particularly there is the inertia of transport infrastructures. The highways, railways, ports and airports we build today will still be in use in fifty years, and in most cases at the end of the century. The infrastructures for the distribution of energy to the various transport systems also involve long logistics chains that are costly and long-lived. In our vision of the future, they would not need to be modified. This is a substantial economic advantage compared with any other solution.

At a more fundamental level, the vision we have set out here stems from a conviction that the advantages of liquid hydrocarbons are so strong in technical and economic terms (ease of use, safety, high energy density, low cost) that they will continue to be unbeatable. Although hydrogen or all-electric vehicles are capable of occupying a few niches, more or less hybridized vehicles running on liquid hydrocarbons – natural or synthetic – would, in fact, on this view, continue to meet 80% or 90% of road transport requirements worldwide over the coming century.

Theoretically, the major drawback of this view of the future is the impossibility of sequestering CO_2 emissions in the vehicles themselves. But ongoing development of the sources for fuels of the types we have envisaged would enable a gradual reduction to be achieved in such emissions. The increasing concentration of carbon dioxide emissions in the transport sector has a strong underlying logic: it is in this sector that CO_2 emissions have the highest economic value. In other words, transport can pay the highest emission levies, just as transport bears the highest taxation today in the developed world without this constituting any real impediment to the development of automotive transport.

Furthermore, if the carbon emission costs were to become prohibitive, the "carbonization" of hydrogen using essentially nuclear power and biomass could offer a solution that deserves evaluation (biomass requirements would probably be somewhat less than those required for direct conversion into biofuels per TOE of fuel produced). This solution is backed by logic firstly insofar as the synthetic gas made from biomass has a structurally low hydrogen content (part of the hydrogen combines with oxygen in the biomass), and secondly, it is likely that in the future there will be stringent economic constraints obliging use for the production of synthetic gas of a source of carbon that does not emit CO_2 in terms of overall energy balances.

In the course of the future developments we have envisaged here, fuels and drive systems would continue to evolve just as they have over recent decades. This means that by 2020 or 2030 automotive diesel and gasoline fuels might converge in response to the possible convergence of controlled ignition engine systems and those based on self-ignition. Such fuels of the future may have predetermined molecular compositions or they might even perhaps become "monomolecular".

In the event that this latter solution were to win out, it would be only logical to use the hydrocarbon with the least carbon content, or the one with the greatest hydrogen content, and which was a liquid stable under ordinary conditions of temperature and pressure, and which corresponded to the requirements of the engine systems current at the time. These objectives will naturally raise some problems for fuel manufacture, as well as for the various types of synthetic fuel and for those that would still be derived from natural liquid hydrocarbons: the refining industry would in this case become a true synthesizing industry very similar to the petrochemical sector.

Where synthetic fuels as such are concerned, their relative importance would tend to change over time.

This would mean that initially, the first half of the 21st century, for the sake of argument, biofuels and Fischer-Tropsch fuels based on natural gas or coal would be dominant as a source of synthetic fuels. It would then be the turn of "nuclear hydrogen carbonized at source", an environmentally friendly variant of the Fischer-Tropsch process, to take over gradually, becoming the dominant source of synthetic fuel in the period beyond 2050.

And lastly, electricity, thanks to the hybridization of the majority of vehicles in the form of rechargeable hybrids, would become in turn a major source of energy for land transport (with hybridization of virtually all private vehicles and a percentage of utility vehicles: those specializing in short journeys).

The respective market shares of these various sources of energy will depend in any given period on movements in their respective costs, including the costs linked to their greenhouse gas emissions and all the other costs linked to political decisions.

At this stage in our analysis, it is tempting to quantify the relative importance of the various energy sources which by the end of the 21st century would be combining to meet the needs of mobility on land. Naturally, this would be a quite illusory exercise, given the sheer number of parameters open to change in the future, shifting the cursor along the scale in determining the equilibrium between the major technological and economic factors: what quantities of natural liquid hydrocarbons will actually be available around 2100? What in the long term will be the costs linked to carbon emissions? What in the long term will be the costs linked to nuclear waste? What will be the costs for the large-scale production of biomass? What technological advances will come along that we are incapable of imagining today?

But despite its illusory character, such an exercise is beneficial, because it provides an illustration of the fact that the sustainable development of transport systems based essentially on liquid hydrocarbons is feasible over the century to come, despite the foreseeable decline in world oil production. If we accept that the only virtue of such figures is to describe one possible future, and that they have no claim to forecasting the actual future, we would suggest a breakdown of the energy sources used towards the end of the 21st century in the transport sector into four more or less equal quarters:

(a) one-quarter "natural" liquid hydrocarbons,
(b) one-quarter conventional synthetic fuels,
(c) one-quarter carbonized hydrogen,
(d) one-quarter electricity.

This vision of the future is shown in two graphs in figures 13 and 14.

Figure 13 shows what might be the share of oil production available for use by the transport sector.

Figure 14 indicates how the different sources of synthetic hydrocarbons might combine, and the penetration of electricity into the automotive transport sector. This simplistic analysis of the future in terms of four equal quarters must of course be interpreted by including, for each of the four energy sources considered, the margin of error, which must be ± 0.5bn TOE/year, and possibly even higher for some sources.

It will be noticed that the "final reserves" for the above graphics would represent some 4,000 billion barrels (3,000 for conventional and non-conventional crude oils, including tar sands, plus 1,000 for oil shales).

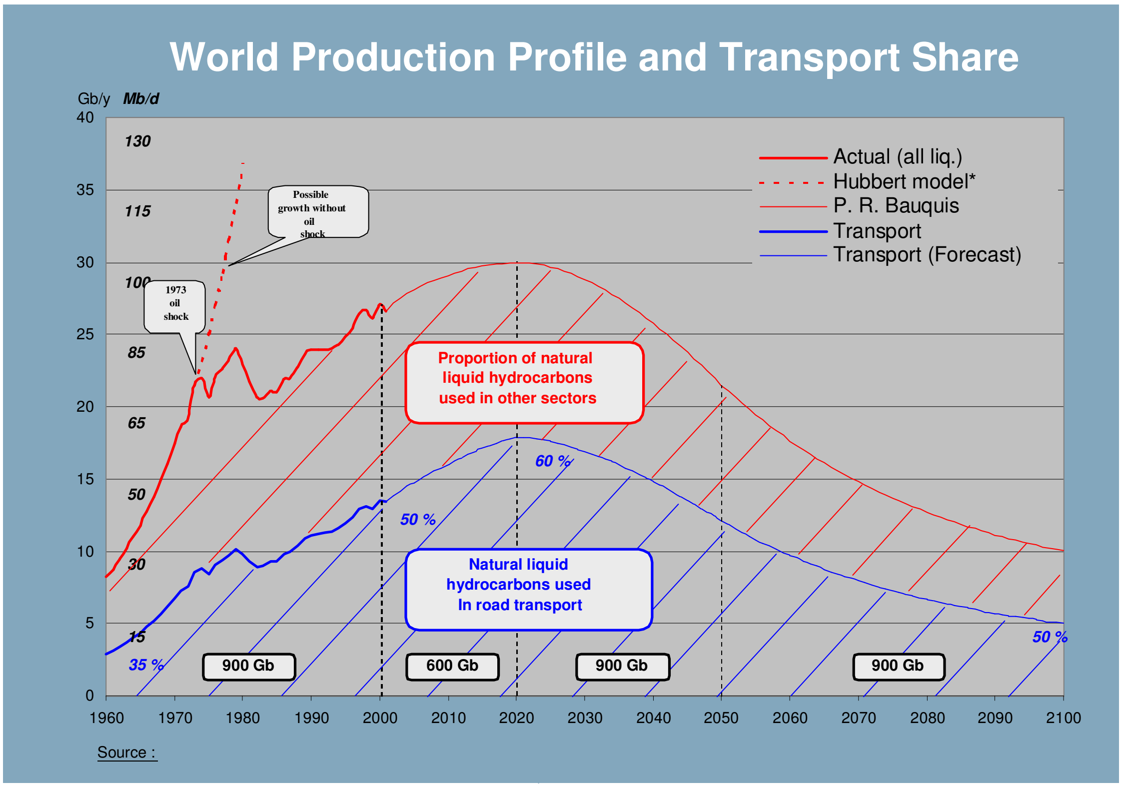

World Production Profile and Transport Share
Gb/y
Mb/d
40
35
30
25
20
15
10
5
0
130
115
100
85
65
50
30
15
Actual (all liq.)
Hubbert model*
P. R. Bauquis
Transport
Transport (Forecast)
Possible growth without oil shock
1973 oil shock
Proportion of natural liquid hydrocarbons used in other sectors
Natural liquid hydrocarbons used In road transport
60 %
50 %
35 %
50 %
900 Gb
600 Gb
900 Gb
900 Gb
1960
1970
1980
1990
2000
2010
2020
2030
2040
2050
2060
2070
2080
2090
2100
Source :

Figure 13

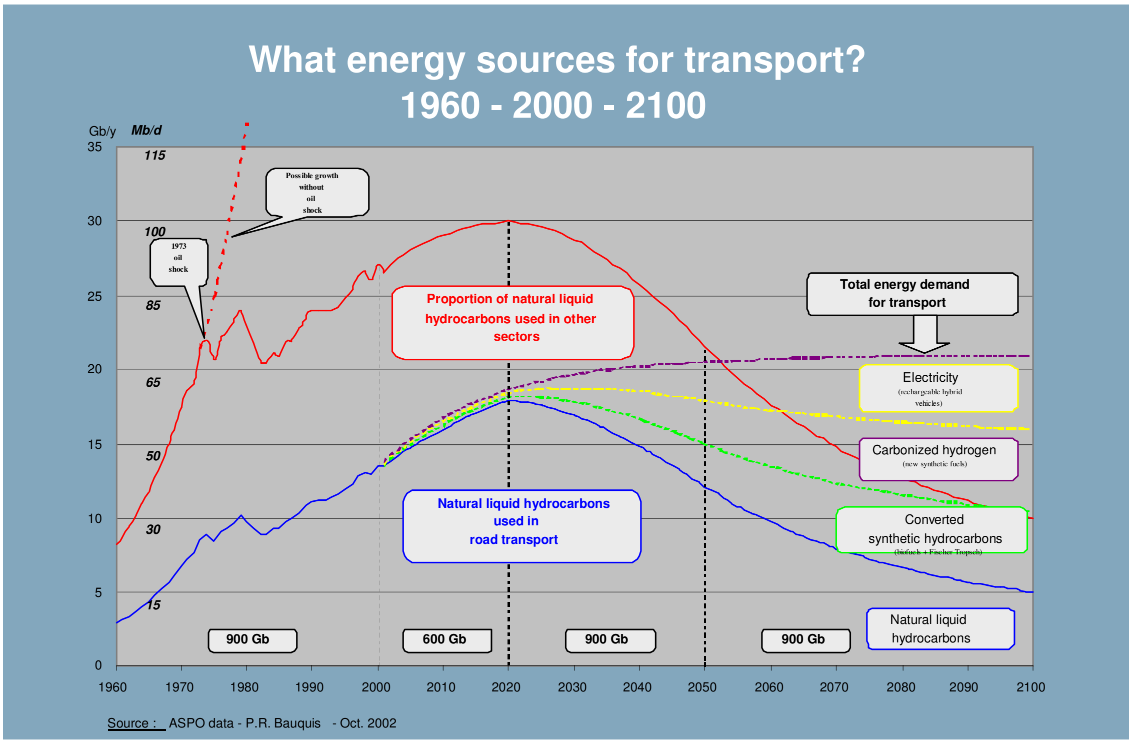


Figure 14

Another way of seeing this future would involve saying that 1.5bn TOE/year would come from fossil energy sources: the entirety of (a) and half of (b), over 1.5bn TOE/year would come from nuclear power, the entirety of (d) and over half of (c) — while less than 1bn TOE/year would be provided by renewable energy sources, half of (b) and less than half of (c) from biomass.

The long-term vision of the energy sources used in the transport sector that transpires from the present article has one drawback, to which we have already drawn attention: the decentralized emission of carbon dioxide, which cannot therefore be sequestered. We consider that this handicap, as expressed in economic terms, would remain very much below the extra cost inherent in vision of the future of "all-hydrogen" types (with or without fuel cells).

And lastly, the gradual linking up of sources of liquid hydrocarbons used with declining emissions of CO_2 as we move from one synthetic fuel to another, and as electricity begins to penetrate the market (thanks to rechargeable hybrids), enables a sustainable system to achieved in the end. It is in fact the case that calculation of global CO_2 emissions from land transport as a whole reveals a curve which rises until around 2030-2040, with a peak at about 10GT CO_2/year, and then declines before levelling out below 8GT CO_2/year after 2060 (cf. figure 18).

Figure 19 shows what the global profile would be for $C0_2$ emissions linked to energy consumption from 2000 to 2100 (choosing the view of future world energy consumption shown in figure 15) and the proportion that would be generated by land transport.

Epilogue

The reader will perhaps be surprised to find nothing in this article on LPG or CNG vehicles, which are mentioned only in passing in our introduction. The reason for this is that these are "energy niches" whose potential for development will remain very limited due to a whole raft of technological and economic reasons. Specifically, this is due to the fact that in the case of compressed gas vehicles we can see, as for all-electric vehicles, an extreme slowness in technological development and therefore in the development of the characteristics of such vehicles. The compressed gas tanks of Sulzer automobiles at the beginning of the century had virtually identical characteristics (pressure, weight, volume) as the gas tanks on CNG vehicles in the 1980s (it is only recently that they have developed further, with tanks in composite materials pressurized to 300 bars or more replacing 200-bar metal types).

The reader will perhaps be even more surprised to have found nothing here on the future of fuel cells, mentioned only briefly in the introduction.

This omission reflects a point of view according to which the future success or failure of fuel cells in the automotive sector will not modify in any fundamental sense the issues associated with the requirements and sources of energy over the long term in this sector. Fuel cells are no more than energy converters. Vehicles running on fuel cells will need to be supplied either with hydrocarbons or similar materials (alcohols, esters, etc.) if they are to produce hydrogen on board, or they must be supplied directly with hydrogen.

The real problems are therefore in fact those we set out to analyse: what energy sources will power the vehicles of tomorrow and the day after tomorrow?

It can be seen that the sustainable solution we have envisioned, sustainable because it can be extended well beyond the end of the 21st century, entails a high degree of symbiosis between two energy sectors that are quite separate today: the hydrocarbons industry and the nuclear industry.

And here we come to the reason for which we dedicated this exercise in futurology to James Lovelock (1) and to that minority of ecologists who, like him, consider that there can be no sustainable development without the widespread use of nuclear power.

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(1) **Author's note**: James Lovelock, a world-renowned British scientist, was, in the 1960s, one of the founding fathers of ecology. His favourable position on the development of nuclear power set him apart from the majority of conservationists.