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DESIGN AND DEVELOPMENT OF PAC car II

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Warning – Important safety notice

The information in this book represents a general summary of engineering principles involved in fuel economy vehicle design and construction. Some of these design practices may be dangerous unless undertaken and implemented by experienced people who are trained in vehicle engineering, design, and construction. The authors and publisher have endeavored to ensure the accuracy of this book. However, all information should be read with the potential risks of racing and vehicle modification in mind. Racing and vehicle design and construction are risky undertakings – both for yourself and for others. No book can teach all aspects of racing and vehicle design and construction. There is no substitute for appropriate engineering credentials and experience. For these reasons, the authors and publisher make no warranties, express or implied, that the information in this book is free of error, or that it will meet requirements for any particular application. The authors and publisher expressly disclaim the implied warranties of merchantability and of fitness for any particular purpose, even if the authors and publisher have been advised of a particular purpose, and even if a particular purpose is described in the book. The authors and publisher also disclaim all liability for direct, indirect, incidental, or consequential damages that result from any use of the examples, instructions, or other information in this book.

(Text based on the safety notice of Tamai [18])

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Preface

Created more than 20 years ago to promote fuel efficiency, the Shell Eco-marathon has embraced – and anticipated – the challenges raised by energy use in the transportation sector. Energy companies like Shell face these challenges daily in their business; by sharing them with students and their teachers as part of the Shell Eco-marathon project, we hope to help them prepare their careers as future engineers, technicians or scientists.

This opportunity to gain hands-on experience working on a project that is environmental, economic and social in nature is an invitation to contribute to sustainable mobility. This tripartite equation has several unknowns, including the future role that alternative energy sources will play in the transport sector. Hydrogen, used in fuel cells like the one used in the PAC-Car II, is one possible alternative response that would represent a major technological leap forward.

The capacity for innovation – the primary quality demanded of Shell Eco-marathon participants – is what drove the PAC-Car II project, managed by the Swiss Federal Institute of Technology (ETH) in Zurich. In 2005, their vehicle set a new race record at the Nogaro motor circuit in France: 3,836 km/l[*] with a fuel cell system driving an electric motor! Two months later, they confirmed and exceeded this accomplishment at the Michelin Technology Centre, setting a new record of 5,385 km/l[*].

The Shell Eco-marathon's reputation has been built largely on such legendary performances by the top performing teams, which are generally based on partnerships between teachers, students and industry – a key value of this event. The PAC-Car team demonstrated the heights that can be reached by such educational projects, and now they share their experience in another demonstration of team spirit, sportsmanship and openness.

This is the first time that a book has been published telling the steps taken for the development, construction and successful performance of a vehicle designed

[*] Distance that would have been covered with one litre of petrol, equivalent consumption calculated using the lower heating values of hydrogen and gasoline.

specifically for the Shell Eco-marathon. In general, the secrets of a winning and record-breaking vehicle are jealously guarded, but this exceptional team would like to make the findings of their adventure available to those who share an interest in developing a similar project. The spirit of the Shell Eco-marathon is one of innovation and creativity; by sharing their experience, the PAC-Car team provides experiments, results, models and ideas for comparison, which will stimulate further innovation by the next generation.

Bravo to this pan-European team, which is a perfect reflection of the Shell Eco-marathon's international scope. They deserve our warmest congratulations for having built the PAC-Car II, a fantastic vehicle that incites us to think about sustainable mobility and how to use the planet's precious energy resources. But, beyond the vehicle itself, we should also congratulate the team for putting this educational project together in order to achieve their ambition, for demonstrating real teamwork in doing so and for sharing the knowledge acquired.

I am certain that the experience acquired by all the team members will be very useful to them in their future careers and that the positive values that drove this project will continue to guide them in their search for innovative solutions in all fields.

Serge Giacomo
Director, European Shell Eco-marathon 2005.

Acknowledgments

As the initiator of, and coordinator for, the writing of this book, it gives me great pleasure to be able to thank all those who have contributed to its development.

Firstly, I would like to thank Professor Lino Guzzella, the Director of both the *Institut für Mess-und Regeltechnik* (Measurement and Control Laboratory) at the *Eidgenössische Technische Hochschule Zürich* (Swiss Federal Institute of Technology Zurich) and the PAC-Car projects, for having given us the freedom to write this book as we saw fit, and at the same time for making sure that we always had the means to complete the project in the best of conditions – his Golden Rule!

Next, I would like to thank the authors, in particular the five students at the heart of the PAC-Car II project: Dominik Isler, Pius Kobler, Florian Kolb, Nicolas Weidmann and Jérôme Bernard. It's true to say that after working on such a demanding project, we were all ready to turn the page; but the five of you found the energy to dive back in again by writing one or more chapters. Without your individual contributions, this book wouldn't have been complete.

My thanks also go to Mr. Serge Giacomo, the Director of the European Shell Eco-Marathon 2005, for agreeing to write the preface to this book.

I would also like to thank the people whose participation so improved the quality of the final product: Jan Hailwood and Lisa Helen Spencer, for their English language work; the individuals and companies who gave permission for their illustrations to be used; Nicolas Weidmann, for all his work on the 307 figures found throughout the book.

More generally, I would like to thank all those who contributed in some way to the PAC-Car II project: this book would not exist had PAC-Car II not been such a great collective success.

And finally, my heartfelt thanks go to my colleagues, friends and family, and in particular, Karine, Léa and Luc, for their patience and support.

Jean-Jacques Santin

Introduction

"If you want to build a ship, don't herd people together to collect wood and don't assign them tasks and work, but rather teach them to long for the endless immensity of the sea."

Antoine de Saint-Exupéry

Why PAC-Car?

The PAC-Car project began in 2002 at the *Eidgenössische Technische Hochschule Zürich* (ETH Zurich, Swiss Federal Institute of Technology Zurich). At that time, our laboratory had been involved in research in the field of advanced vehicle propulsion systems for almost twenty years, working primarily to reduce the pollution emissions and improve the fuel economy of passenger cars. Amazing progress was made during this period: passenger car pollution emissions were reduced by two orders of magnitude and prototype IC engines and hybrid-electric propulsion systems with the potential to reduce fuel consumption by a factor of two were constructed. Low-temperature fuel cell systems were a "hot topic" at the time, and our laboratory acquired expertise in such systems by cooperating on a fuel cell vehicle and a fuel cell auxiliary power unit project.

Amazingly, despite these achievements, a somewhat melancholic feeling permeated the laboratory because the ongoing research projects did not constitute a really exciting challenge. As often happens, it was at that moment that serendipity struck: Gino Paganelli – at that time a post-doctoral associate in our lab – came into my office one day and told me about the Shell Eco-marathon. He wanted to check with the organizers to see if they would let us race with a fuel cell vehicle, and if so, would they allow us to participate in the next Shell Eco-marathon using a new fuel cell propulsion system embedded in an existing vehicle, built by the French *Université de Valenciennes* (UVHC – University of Valenciennes).

With the approval of the organizers of the Nogaro Shell Eco-marathon, the PAC-Car adventure began. Gino's idea immediately became a full-fledged serious project. From the very beginning, it was clear that a fuel cell driving an ultra-efficient vehicle would have the potential to achieve a level of fuel economy beyond all known limits. In the PAC-Car I project, an innovative fuel cell-based power train was developed to verify this potential, and this power train was tested in the UVHC vehicle on proving grounds and in several Shell Eco-marathons. The second phase of the PAC-Car project – the design and construction of a completely new vehicle – would prove even more exciting and challenging, calling for serious management skills and more ample resources. Luckily, we were able to persuade Jean-Jacques Santin from UVHC to lead this second phase, and the *Bundesamt für Energie* (BfE – Swiss Federal Office of Energy) and ETH Zurich were generous enough to provide the needed financial support. The results of this second phase are presented in this volume.

The students who worked on the PAC-Car II project, whether for a short or long period, were central to its success, and their names are listed on our website. All of them did a marvellous job, but four students played a special role: Dominik Isler, Pius Kobler, Florian Kolb and Nicolas Weidmann. Opting for a project-oriented major, these students organized their entire graduate curriculum around this project. I would guess that few mechanical engineering students ever learned the fundamentals of mechanical structures, control systems, composite materials and fluid dynamics in a more motivating environment. Many other people, too numerous to mention, contributed in some way or another to the project's successful completion. Among them, the following groups were instrumental in this success: the teams at RUAG Aerospace, Esoro and Tribecraft AG; the colleagues of the *Paul Scherrer Institut* (PSI); and the colleagues in the *Institut für Fluiddynamik* (Institute of Fluid Dynamics) and *Zentrum für Strukturtechnologien* (Centre of Structure Technologies) at ETH Zurich.

PAC-Car I and II have probed the actual limits of road vehicle fuel economy. They provided an excellent breadboard for testing and then integrating the latest developments in materials, aerodynamics, structures, systems, and many other disciplines into a single system. I am convinced that some of the ideas generated during this project will eventually show up on the road and, in accordance with our primary mission, will help to save fuel and reduce the harmful pollution emitted by passenger cars.

This said, I think that the most important reason why our team was captivated by this project from the very first moment is simply that we had a lot of fun working on it. For this reason, in the name of all the team members, I would like to express our gratitude to our sponsors, who made this adventure possible. My personal "thank you" goes out to all the members of the PAC-Car I and II teams. Without their enthusiasm, endurance and creativity, this adventure would not have been possible.

Professor Dr. Lino Guzzella
Head of the Institut für Mess-und Regeltechnik
(Measurement and Control Laboratory)
ETH Zürich

Contents

Chapter 1: Fuel economy competitions

By Jean-Jacques Santin.

This chapter introduces the fuel economy competitions and should provide useful information to the reader who has not yet encountered this specific kind of race. Section 1.1 presents the principles and spirit of these fuel economy challenges and describes the growth of these events around the world over the last several years. Section 1.2 focuses on fuel consumption measurement practices and the calculations that allow an overall ranking of the participating vehicles, whatever the fuel that they use. Like for all car races, the regulations are of primary importance. They define what is technically feasible and guarantee fairness and safety. The key aspects of the regulations that stipulate vehicle design for the European Shell Eco-marathon 2006 are summarized in Section 1.3. Section 1.4 provides a short history of the world records in fuel-efficiency and offers guidance and recommendations for obtaining official recognition of such records. Last but not least, Section 1.5 deals with the pilots and the necessary piloting skills.

1.1. The philosophy behind a fuel economy competition

1.1.1. The basic principles

The goal of fuel economy competitions is to develop and race a vehicle that consumes the least possible amount of fuel. The vehicle's performance is evaluated at a minimum average speed of about 30 km/h for a run of twenty or so kilometers. In general, the vehicles start from full stop and complete the 20-km run alone. The final vehicle ranking is determined by calculating the equivalent gasoline consumption, regardless of the fuel actually used. This calculation is performed using the lower heating value (LHV) of both fuels, and the results are expressed in kilometers per liter. Thus, for example, the fuel consumption in a hydrogen fuel cell vehicle is measured either by using a mass flow meter or by weighing the hydrogen storage system before and after the run. Then this consumption is converted in gasoline consumption as described above. At the time that these lines were written (2006), the record, set by our hydrogen fuel cell vehicle, is a theoretical distance of 5,385 km covered with the equivalent of one liter of gasoline.

1.1.2. The spirit of the competitions

These challenge competitions are open principally to students from a whole range of educational levels (e.g., middle schools, secondary schools, technical colleges, universities and engineering schools) from all around the world. Whatever the level, the challenge for the students and their teachers is to design and produce a vehicle that has the lowest possible fuel consumption and complies with the race regulations, while using only their own means.

Figure 1-1: Family photo taken during the Shell Eco-marathon in 2004. (Courtesy of Shell)

Participating in a fuel economy event is a perfect occasion for students to learn to manage a long-term 1-year project from A to Z. This project touches on a large variety of subjects, ranging from the obvious design and manufacturing, to the less obvious management, communications, and finance. Participation provides a unique opportunity in the context of the school curriculum for students to work on team project that has a firm deadline (the date of the event), a real budget (often quite small), and a chance to compete internationally with other students. The search for technical partners and financial sponsors offers them an excellent initiation into the world of business, which can lead to useful professional contacts.

The project also introduces students to two of the primary topical concerns of the automotive industry: safety and environmental sustainability.

1.1.3. History of fuel economy races in Europe

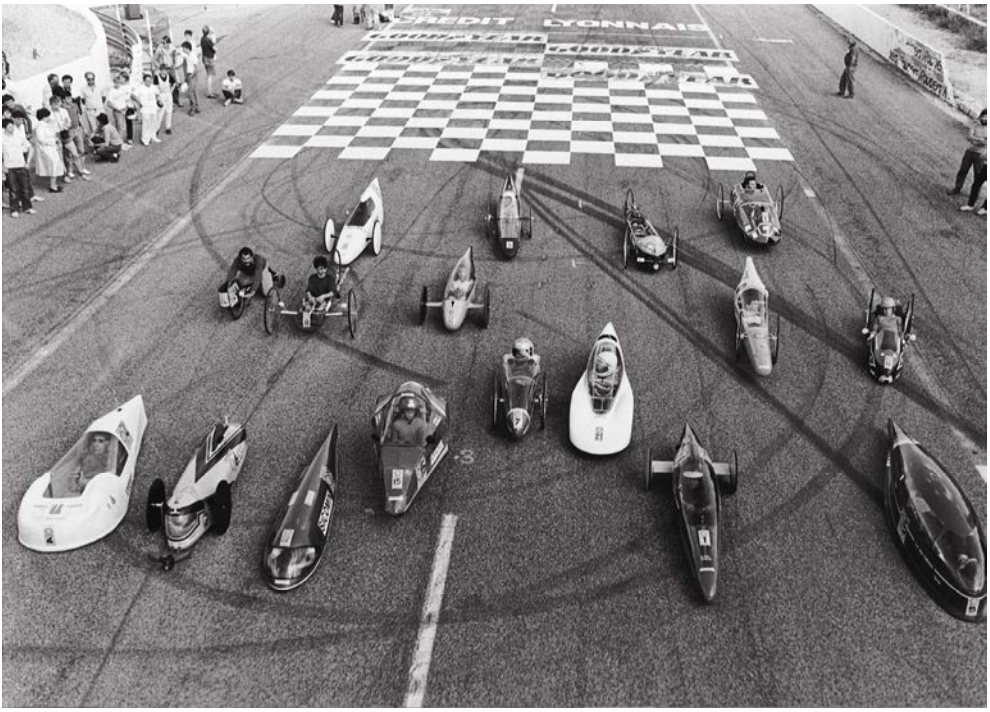

Figure 1-2: Family photo taken during the French Shell Eco-marathon in 1985. (Courtesy of Shell)

According to its UK website, the Shell Eco-marathon “originated at Shell’s research lab in Illinois (USA) with friendly wagers between fellow scientists to see who could get the most miles per gallon from their vehicles. From these humble origins, where the winner scarcely achieved 50 MPG, more organized competitions evolved. In 1977, Shell organized the first competition at Mallory Park, essentially for student teams. In 1978 the competition grew further, and an open class was introduced.” The Finnish Mileage Marathon Club’s website, on the other hand, claims to have organized its thirtieth race in 2005, which would mean that the Finns started a bit earlier. The first Shell Eco-marathon event in France was not held until 1985, with a record of 680 km on a liter of gasoline.

1.1.4. Fuel economy races around the world

Several fuel economy challenges are held around the world, in countries like Finland, France, Japan, Scotland, the United Kingdom and the United States of America. Still others have taken place in other places. The various events all differ in terms of their tracks and their regulations, which have evolved over the years.

Undoubtedly, the best place to break a fuel economy record is the Shell Eco-marathon UK, an annual competition organized by Shell Global Solutions on the tremendous Rockingham Motor Speedway in Corby, Northamptonshire (UK). The principle reasons for this being the best place include: a ring track with large curvature radii (about 200 m), one of the lowest minimum average speeds allowed (24.1 km/h), and no minimum mandatory weight for the pilot.

1.1.5. Technical innovation

A fuel economy race is a propitious environment for technical innovation. Unfortunately, the majority of the teams do not have a strong enough connection to the worlds of research and industry – particularly the automotive or cycling industries – and have very limited financial support. These are the two primary obstacles to the development of true technical innovations. Still, at least three major automobile manufacturers, namely Ford, Honda, and Mercedes-Benz, have participated in these competitions in the past, so there is hope that the links to industry can be encouraged. Honda also organize from several years some fuel economy competitions called Honda Econo Power in countries like Japan, China and Thailand.

The most remarkable and long-lasting of the innovations for fuel-efficient vehicles is probably the so-called "stop-and-go" strategy. This strategy consists of switching off the engine when drive power is not required, and using it when it is most efficient, for example, when the vehicle is going uphill. On one hand, the stop-and-go strategy is becoming widespread, as is proved by the launching on the market of the Citroën "Stop & Start" system or the BMW "Auto Start/Stop" system. On the other hand, using the engine at its most efficient operating point is now possible in hybrid vehicles, thanks to the reversibility of the electric drive motor. A scientific discussion about these ideas can be found in [1].

1.2. Measuring fuel consumption

In this section, two kinds of fuel are considered separately. First (1.2.1), we present the so-called "conventional fuels", which have been used for many years in fuel economy contests, and for which the fuel consumption measurement protocol is well-established and well known. Then (1.2.2), we move on to the less well-known case of hydrogen, which is typical in fuel cell powered vehicles. The other fuels are not considered. The next sub-section (1.2.3) explains how the equivalent gasoline consumption is calculated for several kinds of fuel, and the last sub-section (1.2.4) explains how and why the final figure is displayed as the number of kilometers covered per liter of gasoline.

1.2.1. Conventional fuels

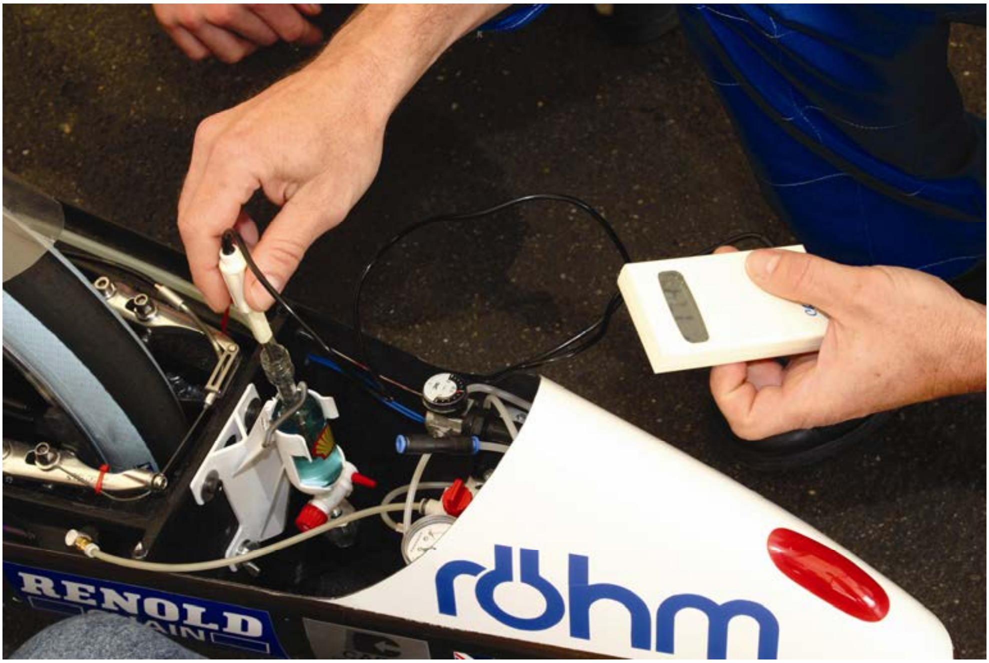

Figure 1-3: Measurement of the fuel temperature after the tank has been refilled, part of the measuring procedure by volume of the fuel consumption during the European Shell Eco-marathon. (Courtesy of Shell)

The "conventional" fuels include gasoline, diesel fuel, and Liquefied Petroleum Gas (LPG). The consumption of liquid fuels like gasoline and diesel are measured either by volume or by weight. The consumption of LPG, on the other hand, is only be measured by weight.

Measurement by volume

Measurement by volume is the standard measuring system used in the competitions. The vehicles used in the competitions are all equipped with a special glass tank, which has a visible marker on its side, allowing it to always be filled to the same level. A few minutes before departure, the tank is filled to the level of that marker by a race steward. After the run, a steward using a precisely graduated pipette again fills the tank up to that same mark. The quantity of fuel added by the steward is the quantity of fuel used during the run. The temperature of the fuel is also measured, before and after the run, making it possible to take the fuel's thermal expansion into account, and to convert the volume consumed into the actual mass consumed.

Measurement by weight

Measurement by weight is reserved for the top teams. This technique is much more precise, but is a complex procedure that takes much longer. First, the entire fuel supply system – the tank, the flexible gasoline pipe and the injector – is dismantled. The system is then filled, carefully bled of all air bubbles, weighed and then reassembled in the vehicle. After the run, it is again dismantled and weighed. The difference in weight is the weight of fuel consumed. The scales used in this procedure are precise to one hundredth of a gram. Calibrated on the spot, they are used in an air-conditioned room on an anti-vibratory table.

1.2.2. Hydrogen fuel

There are two procedures currently in use for measuring hydrogen fuel consumption. One relies on an embedded flowmeter to measure the mass flow of hydrogen, and the other weighs the hydrogen tank. They are sometimes used together in order to verify the coherence of the results.

Measurement by flowmeter

A flowmeter is a measuring instrument installed in the hydrogen circuit, at the outlet of the pressure regulator situated downstream from the tank. It measures the instantaneous mass flow of hydrogen and calculates the total amount consumed during the entire run. Several sensor technologies that are more or less appropriate for this specific application are available on the market. Sometimes, the flowmeter has a display, allowing a direct reading of the measurement, and a basic keyboard for resetting the display to zero. Alternatively, these operations can be carried out via a computer link and dedicated software.

However, the intrinsic accuracy of such a device is around 5% (full scale), which is insufficient for ranking high-performance teams. Moreover, certain flow levels are not detected, such as those that are too slight or too short and high. For example, the diffusion of hydrogen through the membranes when the stack is pressurized but no electric power is delivered can lead to a very slight flow, around 3 Sl (Standard liter) of hydrogen per hour and per square meter of active surface of the membrane.

On the other hand, purging the hydrogen circuit can generate a very short flow peak, equal to around 3 Sl of hydrogen per second during a tenth of a second. Of course, those two figures are fairly approximative as they both depend on many parameters, such as, in case of the hydrogen diffusion flow rate, the type of membrane or the differential pressure on both sides of the membrane. For all these reasons, weighing the tank is preferable to using a flowmeter.

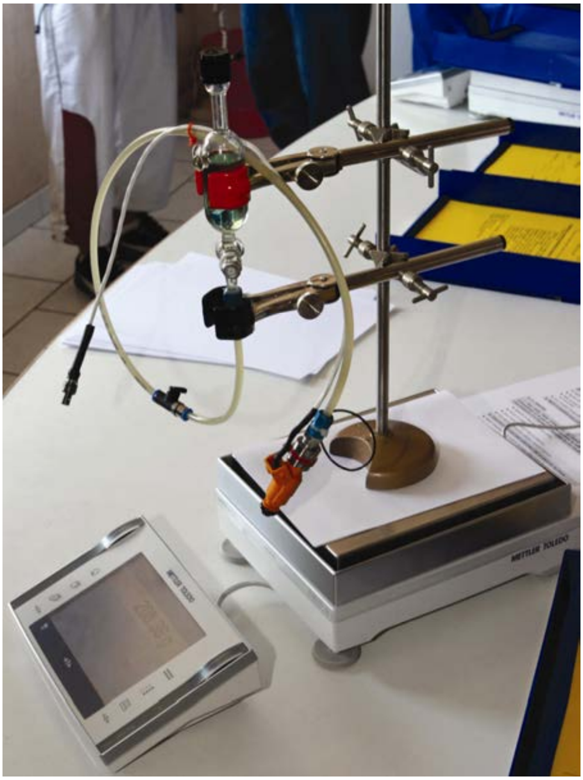

Figure 1-4: Measurement by weight of the fuel consumption during the European Shell Eco-marathon. The entire fueling system has been put on the scale.
(Courtesy of Shell)

Measurement by weight

In principle, the procedure for measuring hydrogen consumption by weight is nearly identical to the one used for the standard fuels (Section 1.2.1). Still, some differences do exist, and they are described below.

Figure 1-5: Measurement by weight of the hydrogen consumption of PAC-Car II during the Shell Eco-marathon at the Michelin Technology Center in 2005.

Unlike a conventional fuel engine, the fueling system of a FCS cannot be separated the hydrogen circuit is constituted of many inter-connected components, including the stack. Therefore, the tank itself must be dismounted in order to weigh it. The consequences of this reality are two-fold:

- the tank must be equipped with a double-end shutoff connector, which makes possible to disconnect the tank from the hydrogen circuit without a pressure drop on both sides, and without any hydrogen leaking. However, before connecting the full tank after weighing, the hydrogen circuit must first be pressurized at the same pressure as the full tank, using a separate bottle;

- the tank must not weigh more than the maximal load of the scale, which is generally a few hundred grams. If the tanks exceeds this maximal weight, it is impossible to obtain the necessary accuracy (i.e., at least one hundredth of a gram) for measuring the consumption of only a few grams of hydrogen. For this reason, we strongly recommend contacting the organizers of the competition at an early date to find out the exact type of scale that will be used.

1.2.3. Calculating the equivalent gasoline consumption

Since 2004, regardless of the fuel really used, the overall ranking of the competitors in the Shell Eco-marathon in France is based on the equivalent consumption of Shell Unleaded 95 gasoline. This regulation was made inevitable by the growing diversity of fuels used for the competition. Up to that point, gasoline consumption was compared to LPG consumption, for example, without even considering whether the two fuels had the same energy value! This kind of inapt comparison, which is widespread among the general public (After all, who has not compared the consumption of a gasoline vehicle with a diesel vehicle?), was brought into question when the competition began to register vehicles using a fuel that, whatever its pressure, can only be in a gaseous state at the ambient temperature: hydrogen.

Beginning in 2004, the calculations of equivalent gasoline consumption has been based on the lower heating value (LHV, also known as “net calorific value”) of the different fuels. The LHV, expressed in MJ/kg, represents the quantity of heat given off by the complete combustion of 1 kg of this fuel in air, under certain well-defined initial and final conditions of temperature, pressure and state of byproducts. This value provides an index of the energy content of different fuels. The following table collects the LHV and the densities of the most generally used fuels.

Table 1-1: Lower heating value (LHV) and density values for a few fuels.

Fuel	LHV [kJ/g] [2]	density [g/ml] [3]
Shell Unleaded 95 gasoline	42.9	0.730…0.780
LPG “Gepel-Butagaz”	46.0	0.54
Diesel “Shell Formula Diesel Plus”	42.6	0.815…0.855
Rapeseed methyl ester	37.7	
Dimethyl ether	28.43	
Ethanol	26.9	0.79
Hydrogen	119.93	

To provide a concrete application of the above information, consider the PAC-Car II performance. The PAC-Car II consumed 1.02 grams of hydrogen during its run for the Shell Eco-marathon at the Michelin Technology Center in

Ladoux, France, on 26 June 2005. The following formula can be used to convert this amount of fuel into the equivalent volume of gasoline, $v_{gas\ eq.}$:

$$v_{gas\ eq.} = \frac{119.93 \times 1.02}{42.9 \times 0.74262} = 3.8397 \text{ ml} \tag{1.1}$$

1.2.4. Expressing of the final result

Usually, the fuel consumption of a ground transport vehicle is expressed as the number of liters consumed to cover a distance of 100 km under standardized conditions (i.e., speed profiles called driving cycles). However, in the fuel economy competitions, the final result is expressed as the number of kilometers covered per liter of gasoline. This commonly causes confusion among the general public, who assume that the vehicles have really covered the distance indicated. Still, in deciding to express the results in this way, the organizers of the event made a deliberate choice since they felt that a result in liters consumed per 100 km wasn't meaningful enough for the average person. Certainly, 5,385 km per liter is more evocative than 0.01857 l per 100 km! Furthermore, expressing the results in liters per hundred kilometers would make the difference between the best vehicles appear to be narrow and insignificant.

In reality, for example, the PAC-Car II covered 20.678 km using an amount of fuel equivalent to 3.8398 ml of gasoline. Given that real consumption, the pro rata distance that would have been covered if one liter of fuel had really been consumed can be calculated as follows:

$$d_{1\ litre} = \frac{20.678}{3.8398} 1{,}000 = 5{,}385 \text{ km} \tag{1.2}$$

1.3. A brief summary of the Shell Eco-marathon rules and regulations

The information given below is taken from the regulations of the European Shell Eco-marathon 2006 (prototype group). This is partial summary designed to provide general guidance. This section reviews some of the rules related to the vehicles, but the rules governing the organization or the traffic on the track, for example, have not been mentioned. Please remember that this is a summary, and that only the official regulations are valid!

The rules of the competition have been established with the dual purpose of maintaining safety and fairness, with the two ideas sometimes overlapping. Some of the rules pertaining to safety are presented in Section 1.3.1. A fuel economy competition is just like any car race, with its attendant risks of collision or leaving the track. If there have been no accidents or major incidents since the start of these competitions, it is definitely due to the safety regulations, the relatively low vehicle velocity, and the small amount of fuel taken on board. Section 1.3.2 introduces some of the rules designed to make the competitions fair, offering the same chance of success to everyone, while at the same time preventing cheating.

1.3.1. Safety

In the automotive industry, safety systems are divided into three main categories:

- Primary (or active) safety systems, which focus on both the vehicle and its environment, are intended to avoid accidents;
- Secondary (or passive) safety systems focus on the vehicle itself, and are designed to prevent serious injuries to the pilots during a crash;
- Tertiary safety systems also target the vehicle, but they are intended to facilitate the intervention of the rescue teams after an accident.

These three levels of safety can be found in the rules of the competition, and this summary follows that organization.

Primary safety

- Three or four running wheels must be in continuous contact with the road.
- The minimum track width between the two outermost wheels is 50 cm (110 cm at the most).
- The wheelbase must be at least 1m.
- The maximum height measured at the top of the pilots' compartment must be less than 1.25 times the maximum track width.
- Pilots must have direct forward visibility. They must be able to turn their heads 90° on each side of the longitudinal axis of the vehicle. This field of vision must be achieved without help of any optical devices, such as mirrors, prisms, periscopes, etc.
- The vehicle must be equipped with a side-view mirror with a minimum surface area of 25 cm^2 on each side of the vehicle.
- The cockpit must be properly ventilated and equipped with a sunscreen windscreen.

- The vehicle must be equipped with at least two independent braking devices such that the failure of any one system does not render the other(s) inoperative. Hydraulically-controlled braking systems or disc brakes are required. The effectiveness of each brake systems is tested as follows: the vehicle must remain immobile when it is placed on a 20% incline.

- The vehicle must be equipped with a loud automotive-type horn, which must be used before passing any vehicle.

- The whole fueling system, from the tank to the engine, must be placed in a compartment completely separated from the cockpit. It must be properly ventilated with fresh air drawn from outside the vehicle and then expelled directly from the vehicle. For hydrogen-powered vehicles, this compartment must have a ventilation window measuring 1 cm^2 situated at the highest point of the compartment.

Secondary safety

- The headfirst driving position is prohibited.

- The pilots must wear a helmet (lightweight motorbike type).

- Synthetic pilots clothing are forbidden.

- Driving barefoot or in socks is prohibited.

- The pilots' seat must be equipped with a four-point safety belt.

- The sides of the cockpit must be sufficiently reinforced to protect the pilots from possible lateral shocks.

- The cockpit must be equipped with an effective roll bar, extending beyond the width of the pilots' shoulders. This bar must be at least 5 cm above the top of the pilots' helmet and must be capable of withstanding a 700 daN static load applied to its center without bending.

- A minimum distance of 10 cm is required between the pilots' feet and the internal front bodywork.

Tertiary safety

- An extinguisher must be placed in the cockpit within the pilots' reach.

- Pilots must be able to vacate their vehicles at any time without assistance. The vehicle must be equipped with a sufficiently large opening for the cockpit.

- The fuel cell system must be equipped with an emergency shutdown valve, easily accessible from the exterior via an opening in the bodywork or an access hatch that can be easily opened or broken.

1.3.2. Fairness

- Mobile aerodynamics appendages are forbidden.

- Stored electrical or pneumatic energy that is not replaced by the engine during the competition may only be used for the self-starter, the ignition and injection systems, and the instrumentation and metering units. Auxiliary energy sources (e.g., solar, chemical) are not permitted.

- For fuel cell vehicles: the use of non-replaced oxygen or compressed air reserves is not authorized.

- The wheels located inside the bodywork must not be accessible to the pilots.

- A bulkhead must be mounted between the engine compartment and the cockpit, preventing any manual access to the engine compartment by the driver.

1.4. World records

1.4.1. A brief history

Given the differences between the race circuits, the regulations and the fuels allowed in the various competitions organized throughout the world, it is very difficult to compare the results obtained. The 2004 introduction of an equivalent gasoline consumption calculation for all fuels (described in Section 1.2.3) has made comparing results less complicated, but it is not likely to become any easier soon.

The background information related to the fuel economy world record presented in Figure 1-6 was reconstructed by gathering together and examining the information available on the Internet: the official results published by the Guinness World Records[2], the official results appearing on the competition websites, and the results

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[2] www.guinnessworldrecords.com

posted by the individual teams. Vehicles with Internal Combustion Engines (ICE), running on gasoline, are shown in blue, and vehicles powered by fuel cells, which run on hydrogen, in green.

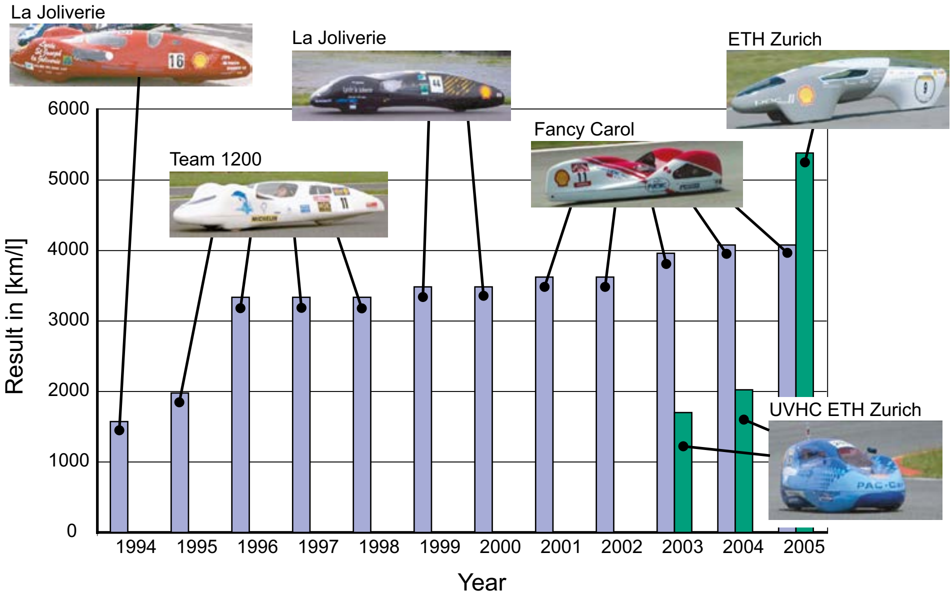

Figure 1-6: History of the world record for the fuel economy vehicle, based on our own investigations.
(Photo of Fancy Carol courtesy of Fancy Carol)
(Photo of PAC-Car I courtesy of Gérard Dechenaud)
(Photo of PAC-Car II courtesy of Dieter Wanke)

The year 1996 appears to have been a turning-point: the world record went from about 2,000 km/liter to 3,000 km/liter. This significant step forward might have been the result of the use of radial-ply tires specifically designed for such a competition instead of cross-ply tires, but this cannot be affirmed categorically. In any case, from 1996 to 2005, the results obtained by gasoline vehicles improved steadily, going from about 3,300 km/l to 4,100 km/l. The first vehicle powered by a hydrogen fuel cell, the PAC-Car I developed by ETH Zurich and University of Valenciennes, appeared in 2003. In 2005, the PAC-Car II, developed solely by ETH Zurich, outclassed the ICE-powered vehicles, improving the fuel economy performance to 5,385 km/l.

1.4.2. Obtaining an official world record

If your ultimate goal is to break the world record of fuel economy, it is necessary to get your result recognized by an official organization, which requires serious preparation. In fact, obtaining official recognition of a performance after the fact is almost always impossible, so one of your team members should be assigned exclusively to this task, beginning some months before the record-breaking attempt.

The recognition procedure may not be free of charge. For instance, the Guinness World Records (GWR) offers a free standard procedure, but the paying procedure offers additional services and dramatically speeds up the feedback and email exchanges, so we strongly suggest using it. Keep in mind that GWR receives hundreds of thousands of record proposals each year! If you want an adjudicator to attend the event, which is generally not necessary, you may have to pay costs, including traveling expenses, accommodation and a daily attendance fee. Though the original certificate is free, any copies requested may accrue additional charges.

The main tasks that you must accomplish include:

Before the attempt

- contact the organization that will register your record;
- prepare all the requested material (e.g., official forms, witness' letters, log books);
- contact the people who might help you get your record recognized (e.g., adjudicators, witnesses, reporters, photographers) and inform them of the role you would like them to play;
- prepare for the arrival of those you have invited (e.g., arranging for their transportation and accommodation).

During the attempt

- accompany your guests and keep them informed about what is going on;
- make sure that the requested information is being properly gathered.

After the attempt

- collect all the requested material (e.g., authentication statements, forms, log books, photographs, videos, newspaper and magazine clippings)

- prepare the material to send to the recording organization;
- update your claim;
- inform your team members and partners that the official record has been obtained and then… celebrate!

Figure 1-7: The PAC-Car II team during the award ceremony of the Shell Eco-marathon at the Michelin Technology Center, on 26 June 2005.

1.5. The pilot

This book deals almost exclusively with technical ideas. As technical experts, our natural tendency is to forget about the human beings involved. Nonetheless, the pilot is one of the key elements of the success of such a project, and as such has a place in this book. We estimate that the difference between a talented and an inept pilot can influence the final result by about 30%. Unfortunately, fuel economy races are so different from speed races that even a talented speed race pilot may not have the necessary skills for a fuel economy competition. So, what then constitutes a talented pilot?