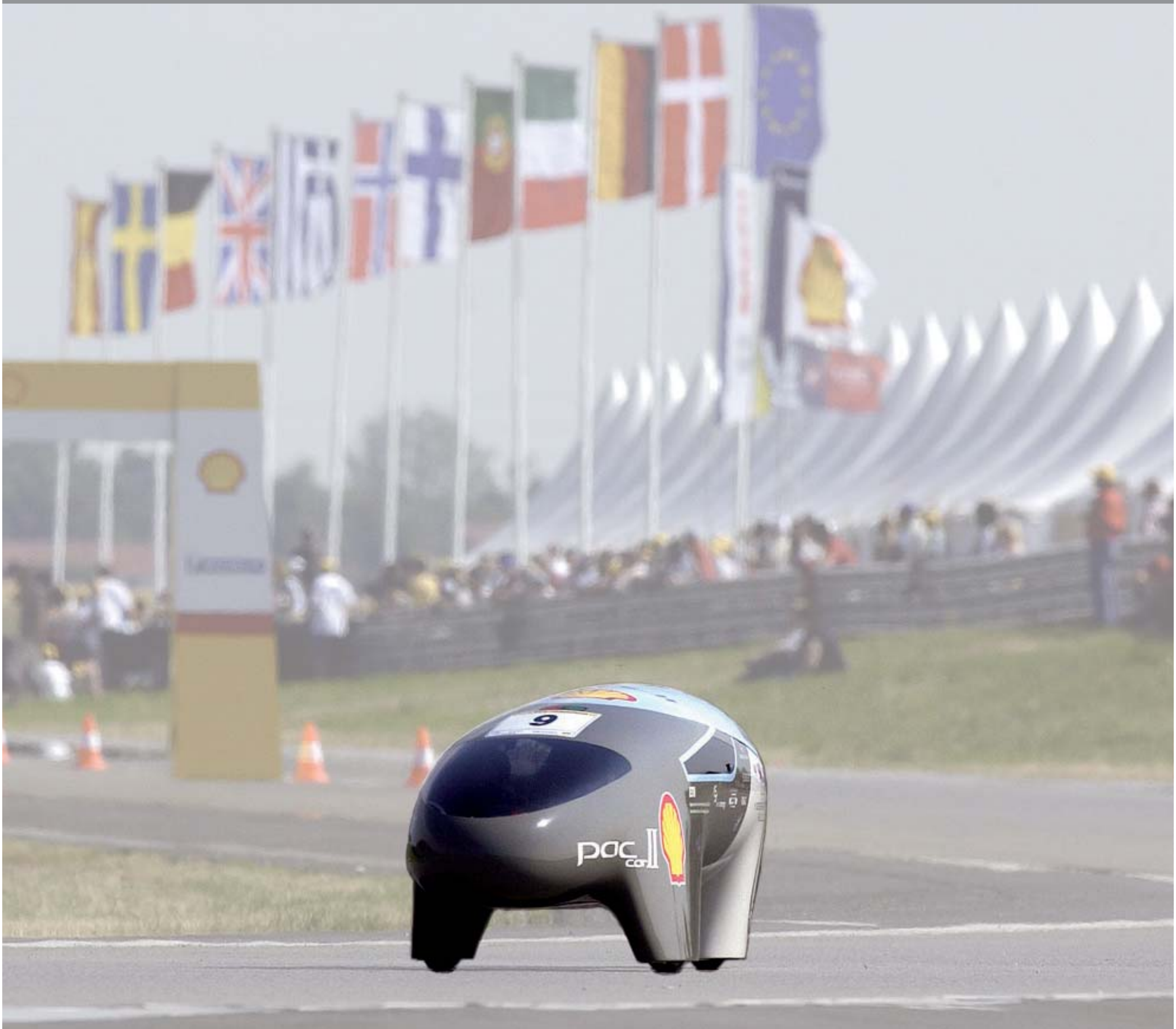
# THE WORLD'S MOST FUEL EFFICIENT VEHICLE

*DESIGN AND DEVELOPMENT OF* PAC car II




J.J. Santin, C.H. Onder, J. Bernard, D. Isler, P. Kobler, F. Kolb, N. Weidmann, L. Guzzella

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Authors:

Dr. Jean-Jacques Santin
Dr. Christopher H. Onder
Jérôme Bernard
Dominik Isler
Pius Kobler
Florian Kolb
Nicolas Weidmann
Professor Dr. Lino Guzzella

ETH Zurich
Institut für Mess- und Regeltechnik
Sonneggstr. 3
8092 Zurich
Switzerland
Email: paccar@ethz.ch

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*Dear Reader,*

*What you hold in your hands is a small excerpt of the book*

# The World's Most Fuel Efficient Vehicle

## Design and Development of PAC-Car II

*to be published in July 2007. This excerpt offers you an impression of what you can expect from the book. It provides you with the Table of Contents and two samples from Chapter 5, Aerodynamics. We hope to stimulate your interest in the development of PAC-Car II which led to our record-breaking performance in 2005.*

*The PAC-Car Team*

## About PAC-Car II

PAC-Car was a joint project of ETH Zurich and partners from academia and industry. The goal was to build a vehicle powered by a fuel cell system that uses as little fuel as possible. PAC-Car II set a new world record in fuel efficient driving (5,385 km per liter of petrol equivalent) during the Shell Eco-marathon in Ladoux (France) on June 26, 2005.

## About the Book

This book is the first to summarize the design and construction issues of a vehicle for fuel economy contests. It deals with the adventure of developing this world-record vehicle and provides numerous specific technical tips. It will help anyone who is designing an ultra lightweight land vehicle, whatever its source of energy (thermal engine, human power, solar panels…), and/or those who are interested in fuel cell applications. The book addresses graduate students and teachers of engineering disciplines as well as other people interested in fuel economy contests.

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www.vdf.ethz.ch


## PAC-Car Team


ETH Zurich
Institut für Mess- und Regeltechnik
Sonneggstr. 3
CH-8092 Zurich
Switzerland
Email: paccar@ethz.ch
www.paccar.ch

## Table of Contents

# Chapter 5: Aerodynamics

*By Nicolas Weidmann.*

*The PAC-Car II's aerodynamic design won the ECARA AWARD from the European Car Aerodynamics Research Association in 2007.*

*The CAD file of the shape of PAC-Car II is available for educational purposes. Please visit www.paccar.ch for further information about the transfer of the CAD-data.*

In Chapter 2, aerodynamic drag was cited as being responsible for half of the power demand of a fuel economy vehicle cruising on a flat, level road. In light of this reality, high-quality aerodynamics are clearly essential to such a vehicle's success. This chapter describes the tremendous effort expended to improve the PAC-Car II's aerodynamics. The CAD modeling and body manufacturing processes employed once the most aerodynamic shape had been determined are discussed in the next chapter, since these two processes also play an important role in the success of the final product.

Section 5.1. of this chapter introduces the aerodynamics fundamentals relevant to the body design of a fuel economy vehicle, and Section 5.2 explains the PAC-Car II body design process in terms of these fundamentals. The vehicle's aerodynamic performance and the possibilities for improvement are presented in Section 5.3., while the experimental methods and simulation processes used to optimize the body's aerodynamics are described in Section 5.4. The chapter concludes with a short discussion of the aerodynamic study conducted for this project (Section 5.5).

## 5.2. Design process for the PAC-Car II body shape

A FEV body shape design is limited by certain qualitative and quantitative parameters summed up under the term, "design constraints". These constraints come from a variety of sources, including race regulations, ergonomics and aerodynamics. At the end of the preliminary design phase, which mainly consists of making choices about vehicle architecture and listing the design constraints, these constraints constitute the vehicle's "topological model". With this model as the starting point, a series of modifications are carried out during the aerodynamic design phase in order to improve the vehicle body's aerodynamic properties, using two complementary tools: Computational Fluid Dynamics (CFD) and wind tunnel experiments.

This section provides a brief summary of the design constraints for the PAC-Car II project, followed by a more detailed description of the model iterations that occurred during the project's aerodynamic design phase. Figure 5-12 shows a top-down view of the design process of the body shape of PAC-Car II.

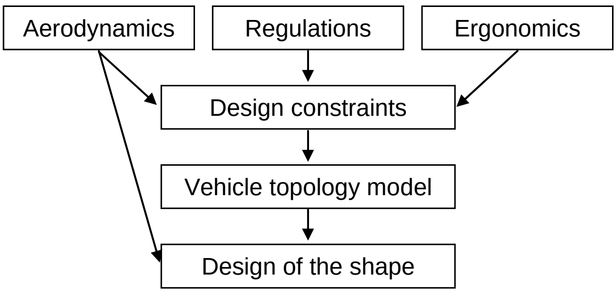



*Figure 5-12: Overview of the PAC-Car II body shape design process.*

### 5.2.1. Sources of the design constraints

Three design constraint sources were taken into account when designing PAC-Car II: race regulations, ergonomics and aerodynamics. Other constraints could also have been considered, such as the rigidity, strength or manufacturability of the vehicle body. However, we decided that, if our goal was to obtain the best aerodynamic shape inside which a pilot would be able to lie down, these other constraints were secondary compared to the three already mentioned. Once the shape had been decided upon, we could determine how make it more rigid and how to build it.

## Race regulations

The race regulations are designed to insure the fairness, safety and spirit of the competition. All participating vehicles have to abide by these rules in order to be admitted to the competition. For example, the maximum height measured at the top of the cockpit must be less than the dimension imposed by the regulations. Chapter 1 discusses these rules in more detail.

## Ergonomics

When designing the vehicle, it was very important to pay special attention to ergonomics and such natural boundary conditions as the pilot’s physical dimensions. The pilot needs to feel safe in the vehicle as well as comfortable enough to drive the vehicle without needing to maintain excessive concentration throughout the run. Intensive experiments about the ergonomics of the vehicle design were conducted, and the result contributed decisively to PAC-Car II’s success. Figure 5-13 and Figure 5-14 depict the driving position and visibility tests. Numerous wheel positions (Figure 5-15) were tested and evaluated according to a variety of ergonomic and technical criteria, such as the pilot’s field of vision, in order to define the best driving position.

## Vehicle topological model

Once the design constraints had been evaluated, a vehicle topological model, including the pilot, was created using computer-aided design (CAD) software (Figure 5-16). This CAD model was fully parametric so that changes could be made as required. The final PAC-Car II shape design was based on this model.

## Aerodynamics – the preliminary design

Since the body shape design and its resulting aerodynamics are based on the vehicle topology, aerodynamic principles had to be considered early in the design process. As mentioned in Section 5.1, a vehicle’s aerodynamic qualities depend on its drag coefficient $c_X$ and its frontal area $A$, with the drag area of a vehicle (i.e., $c_X \times A$) being minimized to achieve the least possible amount of air drag.

Based on the vehicle's topological model, sketches and drawings of the vehicle’s hard points were done by hand (Figure 5-17). In the preliminary design, streamlined airfoils (e.g., Natural Laminar Flow (NLF) profiles) were used for the top and side views. NLF profiles are specially designed for estimating laminar

*Figure 5-13: Driving position and visibility tests. Overview of the experimental apparatus, with the mock-up chassis model in the foreground and the labels used to quantify the pilot's field of vision in the background.*

*Figure 5-14: Driving position and visibility tests. Measurement of the minimal height of the vehicle body.*

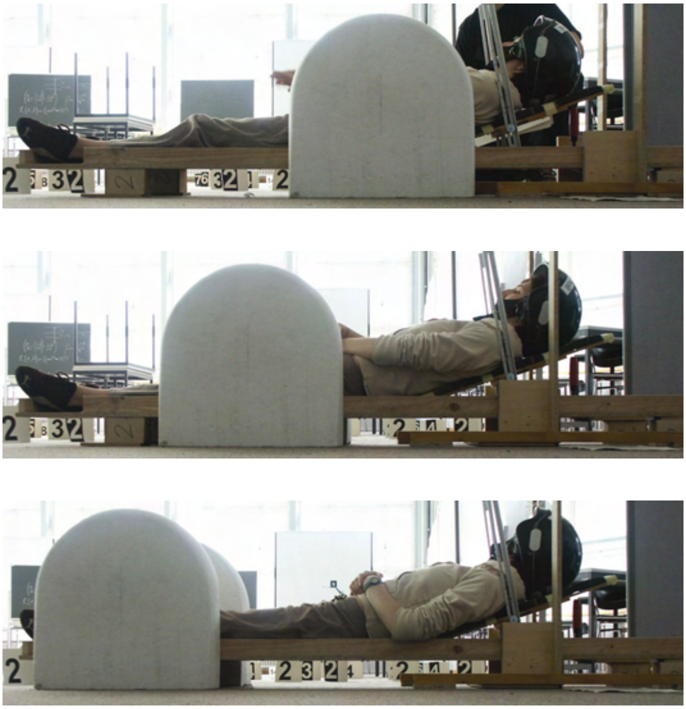
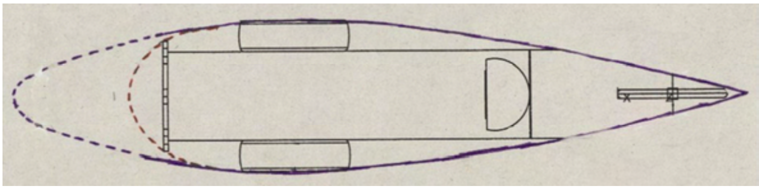


*Figure 5-15: Driving position and visibility tests. The three front wheel positions.*

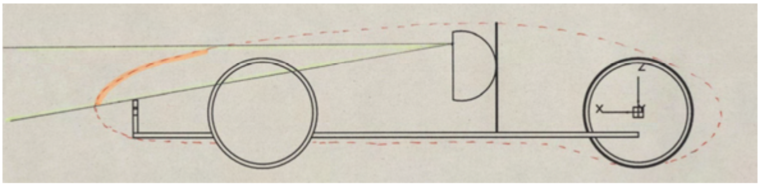
*Figure 5-16: Vehicle topological model in CAD.*

airflow over the length of the airfoil, allowing the qualities of a 3D wing at a certain aspect ratio to be estimated from the 2D airfoil data. However, since the PAC-Car II is shaped like a "torpedo" rather than a wing, it was difficult to judge the benefit of accurately converting the NLF profiles from 2D to 3D. Therefore, in the PAC-Car II design phase, these profiles were used qualitatively to help us deal with the dimensional constraints.

Consider, for example, the design of the vehicle’s nose. As shown in Figure 5-17, the vehicle would have been much longer if the original NLF airfoil had been used, which would have led to additional friction drag and additional weight. Since it was also not clear if applying the NLF airfoils in 3D would produce the same good quality laminar airflow as in the 2D version, the PAC-Car team decided to modify the shape of the profile a little.



*(a) Top view*



*(b) Side view*

*Figure 5-17: Application of NLF profiles on a simplified topological model.*

An important element considered during the preliminary design phase was the windshield. According to the theory of optics, the more perpendicular the windscreen is to the pilot’s line of sight, the better the pilot’s vision will be, as the effects of reflections and surface defects will be minimized. This theory had to be kept in mind when we were designing the windshield.

### 5.2.2. The body shape design

The body shape design was the result of several progressive steps (Figure 5-18). Once the preliminary design described above had been established, several model iterations based on that design were developed and tested using wind tunnel trials and CFD analysis. The results of these tests were taken into account in subsequent iterations of the body shape design. After numerous model iterations, the final shape of PAC-Car II was defined.

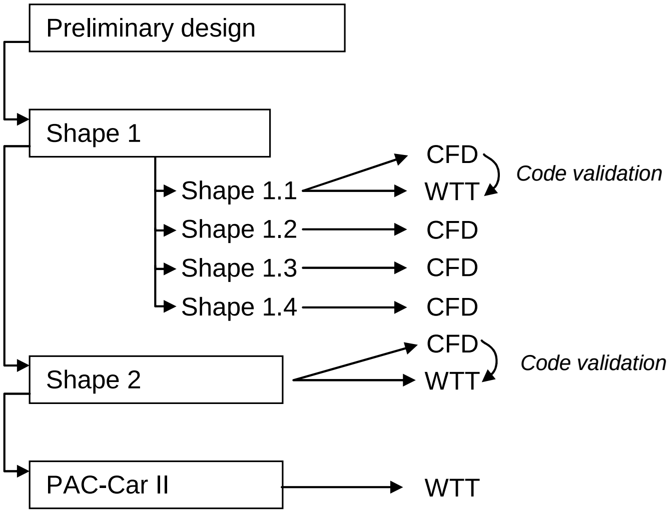



*Figure 5-18: Steps of the PAC-Car II aerodynamic design process. (CFD: Computational Fluid Dynamics, WTT: Wind Tunnel Test)*

#### Model iterations

Five model iterations were created during the PAC-Car II design process. These iterations can be divided into two types: Type 1 had non-tilted front wheels (Shape 1.x), and Type 2 had tilted front wheels (Shape 2). Because the various aspects of the vehicle were researched and developed in parallel, the results of the rolling resistance tests with tilted front wheels were not available at the beginning of the design process for Shape 1.x; thus, these results were only applied to Shape 2.

#### Shape 1.1

The results of the preliminary design phase (Section 5.2.1) were imported into a CAD application in order to draw a first shape: Shape 1.1 (Figure 5-19). Streamlined profiles were used for the wheel fairings (i.e., wheel covers). The frontal area of Shape 1.1, which measures 0.3 $m^2$, bulges slightly more than necessary on the sides, in order to guarantee enough space for the front wheels. Though this bulge clearly increases the frontal area, it also makes for a more rounded, smoother shape at the intersection of the vehicle's roof and side wall. Such a smooth shape can be expected to perform better aerodynamically in cross winds, since the risk of flow separation is lower. The challenge is to find the best trade-off between a small frontal area and a smooth shape with sufficiently good cross wind aerodynamics.

In this shape, the junctions between the wheel fairings and the main vehicle body are smooth in order to reduce interference drag to a minimum. Though the frontal area increases with the radius of these junctions, the interference drag is decreased. Thus, in order to obtain the lowest over-all aerodynamic drag, a trade-off is also necessary here.

Our wind tunnel trials and CFD analysis showed that the wheel fairing design has a great impact on the aerodynamic quality of the overall shape of the vehicle. The wheel fairings in Shape 1.1 have certain flaws, such as concavities on the outer sides of the body surface, mostly due to CAD design errors. In the wind tunnel, large separation bubbles – visible at an angle of attack between 10° and 15° – occurred near these concavities on the lee side of the vehicle. Since CFD simulations confirmed these observations, the wheel fairings had to be improved in subsequent model iterations.

### Shape 1.2

Since the wheel fairings of Shape 1.1 were not optimal, the team decided to perform two additional model iterations, modifying only the fairings. The first of these iterations, Shape 1.2 (Figure 5-19), has the same basic body form as Shape 1.1, but the wheel fairings have no concavities and are thicker and more symmetrical than in Shape 1.1. The effect of these modifications was calculated in CFD; as expected, the critical zones of separation were smaller than for Shape 1.1. Though these modifications did increase the frontal area (by less than 1%) the drag coefficient $c_X$ was reduced, which compensated for the increased size.

### Shape 1.3

The second of the wheel fairing model iterations, Shape 1.3 (Figure 5-19), again has the same body form as Shape 1.1, but this time the wheel fairings are thinner than in the previous shapes. As a result of this modification, the size of the frontal area is reduced. Compared to the flow separation produced by Shape 1.2 in the critical areas on the lee side of the wheel fairings, the separation bubbles produced by Shape 1.3 are significantly smaller. This difference can be explained by the smaller trailing-edge angle at the rear edge of the wheel fairings, leading to lower pressure gradients along the streamlines.

### Shape 1.4

Shape 1.4 examined the effect of modifications to the vehicle's pitch angle. As has been mentioned previously, Shape 1.1 generates lift even at 0° Yaw. However, according to the literature, there is no advantage in creating lift or downforce in FEV. Thus, the PAC-Car II team decided to investigate how changing the pitch angle would influence lift or downforce. Shape 1.4 has exactly the same body form and wheel fairings as Shape 1.1, but the vehicle is turned around its y-axis by a pitch angle of −1°. The results of the CFD analysis showed that this pitch angle modification could decrease the lift by 50 % for 0° Yaw.

### Shape 2

Based on the results of the wind tunnel trials and the CFD analysis, as well as the results of our rolling resistance experiments, we completely redesigned the vehicle. The front wheels of Shape 2 (Figure 5-19) were tilted 8°, which changed the shape of the body significantly. The frontal area was reduced to 0.254 $m^2$, and the cross flow qualities were improved considerably. The wetted area was also reduced by 7.1%, which had a direct impact on the level of friction drag and on the drag coefficient $c_X$. Table 5-1 provides a comparison of the basic numbers for Shape 1.1 and Shape 2.

*Table 5-1: Comparison of Shape 1.1 and Shape 2 (Scale 1:1).*

| | Shape 1.1 | Shape 2 | |
|---|---|---|---|
| $c_X$ | 0.08 | 0.07 | - |
| Frontal area | 0.292 | 0.254 | $m^2$ |
| Drag area | 0.02336 | 0.01778 | $m^2$ |
| Wetted area | 4.2 | 3.9 | $m^2$ |

### From Shape 2 to PAC-Car II

Given the satisfactory aerodynamic qualities of Shape 2, the team decided to use this shape for PAC-Car II. Only small millimetric changes (e.g., slight modifications of the surface curvature to influence the lines of reflection) were made. These changes had no significant effect on the aerodynamic quality of PAC-Car II.

| *Shape number* | *Perspective* |
|---|---|
| *1.1* |  |
| *1.2* |  |
| *1.3* |  |
| *2* |  |

*Figure 5-19: Comparison of the body shapes at various stages of the design process.*

| *Front view* | *Side view* |
|---|---|
|  |  |
|  |  |
|  |  |
|  |  |

*Figure 5-19 (continued).*

# 5.3. Aerodynamics of the PAC-Car II

This section provides a general overview of PAC-Car II's aerodynamic characteristics (Sections 5.3.1). Specific design elements are explained in detail in Sections 5.3.2, 5.3.3 and 5.3.4, and some wind tunnel trial [5] results are reported and compared with those produced with the wind tunnel model. The additional PAC-Car II aerodynamic improvements, and their benefits as shown by the wind tunnel trials, are discussed in Section 5.3.5.

## 5.3.1. Overview

As mentioned in Section 5.2.1, PAC-Car II is streamlined in order to achieve the best aerodynamic properties. Seen from above (Figure 5-20), the vehicle looks like a tear drop.

*Figure 5-20: Top view of PAC-Car II.*
*(Courtesy of Tribecraft AG)*

As recommended in Section 5.1.3, the sides of PAC-Car II are slightly cambered to achieve zero-lift properties (Figure 5-21).

*Figure 5-21: Side view of PAC-Car II.*
*(Courtesy of Tribecraft AG)*

In keeping with aerodynamic principles, the overall surface of PAC-Car II is very smooth to reduce the effect of side winds.

The overall aerodynamic characteristics of PAC-Car II are given in the table below:

*Table 5-2: The aerodynamic characteristics of the PAC-Car II.*

| | | |
|---|---|---|
| Frontal area (from Shape 2, scale 1:1) | 0.254 | $m^2$ |
| $c_X$ (from PAC-Car II wind tunnel trials) | 0.075 | - |
| Cruising speed | 30 | km/h |
| Vehicle length | 2.8 | m |
| $Re_L$ | $1.6 \cdot 10^6$ | - |

### 5.3.2. Wheel fairings

As explained in Chapter 7, wheels have considerable influence on a vehicle's overall aerodynamic quality, making it worthwhile to pay special attention to this element. As recommended by Tamai [1] and Carroll [2], the wheels of PAC-Car II are covered by wheel fairings, the light-weight drag-reducing pieces covering the gaps and spaces created by the wheels. The wheel fairings used in PAC-Car II can, from an aerodynamics point of view, be compared to airplane wings. These wheel fairings are described more in detail below.

#### Junctions

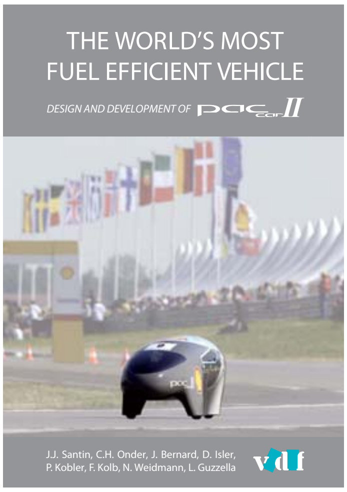
Figure 5-22 shows the junctions between the wheel fairing and main vehicle body. These junctions are smooth, in order to reduce the interference drag caused by the gap between the two parts. In addition, the radii of the rounded junctions are fairly small, in order to avoid increasing the frontal area too much.

#### Cross-sections

The cross-sections of the wheel fairings, perpendicular to the wheel's plane of symmetry, are streamlined for the same reasons as the main vehicle body. There is a round nose and a sharp closing edge where the air streaming around the profile meets again. The angle $\Phi$ between the direction of the incident airflow and the tangent of the profile's rear end should not be too large; otherwise, the pressure gradients become too high, especially in the event of side winds, and the risk of flow separation increases. Figure 5-23 shows the angle $\Phi$ for an airfoil.

For PAC-Car II, these wheel fairing profiles are symmetric because the wind direction distribution during the race is symmetric. According to the CFD results, making the wheel fairings symmetric was probably not the best choice for two reasons:

- A small separation area occurs behind the rear edges of the front wheel fairings, even at a 0° yaw angle. Figure 5-24 shows the velocity distribution in the x-

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## PAC-Car Team

ETH Zurich
Institut für Mess- und Regeltechnik
Sonneggstr. 3
CH-8092 Zurich
Switzerland
Email: paccar@ethz.ch
www.paccar.ch

ETH
Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

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**PAC-Car Team**
ETH Zurich
Institut für Mess- und Regeltechnik
Sonneggstr. 3
CH-8092 Zurich
Switzerland
Email: paccar@ethz.ch
www.paccar.ch

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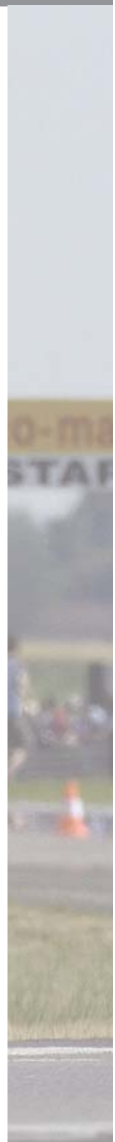

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