# Velomobile aerodynamics
# – side wind effect and operation limits

*by Carl Georg Rasmussen*

*6th Seminar on Velomobile Design 16. - 17. October 2009*

**Abstract**

The wind and the speed of a velomobile cause aerodynamic forces on the fairing, which can be dangerous under extreme conditions. In order to ride in a safe way, it is important to know the operation limits.

The wind can also be helpful. The sail effect adds to the propulsion even in side wind, where there is a considerable head wind component.

Wind tunnel measurements on different types of fairings give more insight in this phenomena.

In velomobile design it is often necessary to make trade offs of ideal aerodynamics to obtain a practical function. E.g. some fairings use a partly open bottom in order to make better conditions for the cyclist to enter and to get out of the vehicle. How much does it mean to the aerodynamical drag?

This, and other design detailles were studied by measuring the drag on a Leitra velomobile in down hill experiments.

## Wind tunnel experiments

When riding a velomobile in the wind, it is not easy to measure the actual aerodynamical forces on a fairing. It is better to use wind tunnel experiments, where wind speed and forces can be measured under controlled conditions.

Since we have no access to make full scale wind tunnel experiments (a privilege for big car makers), it was necessary to use models in a smaller scale. We chose scale 1:5, which could fit into a 50 x 50 cm test section of a wind tunnel at the Technical University of Denmark (DTU).

In order to obtain the same Reynolds Number (Re) as in full scale experiments, the speed (U) was set as high as 32 m/sec (115 km/h). The models had a width (D) of 14 cm, which results in

$$Re = \frac{D \cdot U}{\nu} = \frac{0.14\ m\ 32\ m/sec}{15 \cdot 10^{-6}\ m^2/sec} = 3 \cdot 10^5$$

They were mounted in the test section on a thin steel rod, which could be rotated in the air stream to different angular positions. The steel rod was attached to a weight, which measures the horizontal or vertical force directly in N (Newton). Measurements were made in steps of 5 degrees, covering a range of +/– 45 degrees.

The results are shown in Fig. 2 and Fig. 3. The horizontal force (the direction of the air stream) and the vertical force are shown as a function of the angle of incidence $\theta$.

*Fig. 1 shows the three models used:*
*(1) a very slim and aerodynamical reference model, to the left.*
*(2) a model of the Leitra "sport" fairing with and without bottom, front right.*
*(3) a model of a Leitra "classic" small size fairing, back right.*

*Fig. 2. Forces on a 1:5 scale model of Leitra "Classic" small size at 32 m/sec. The right side shows drag and lateral force on the model at different angles of attack. The small curve covering only +/– 20 degrees is for the aerodynamical reference model.*

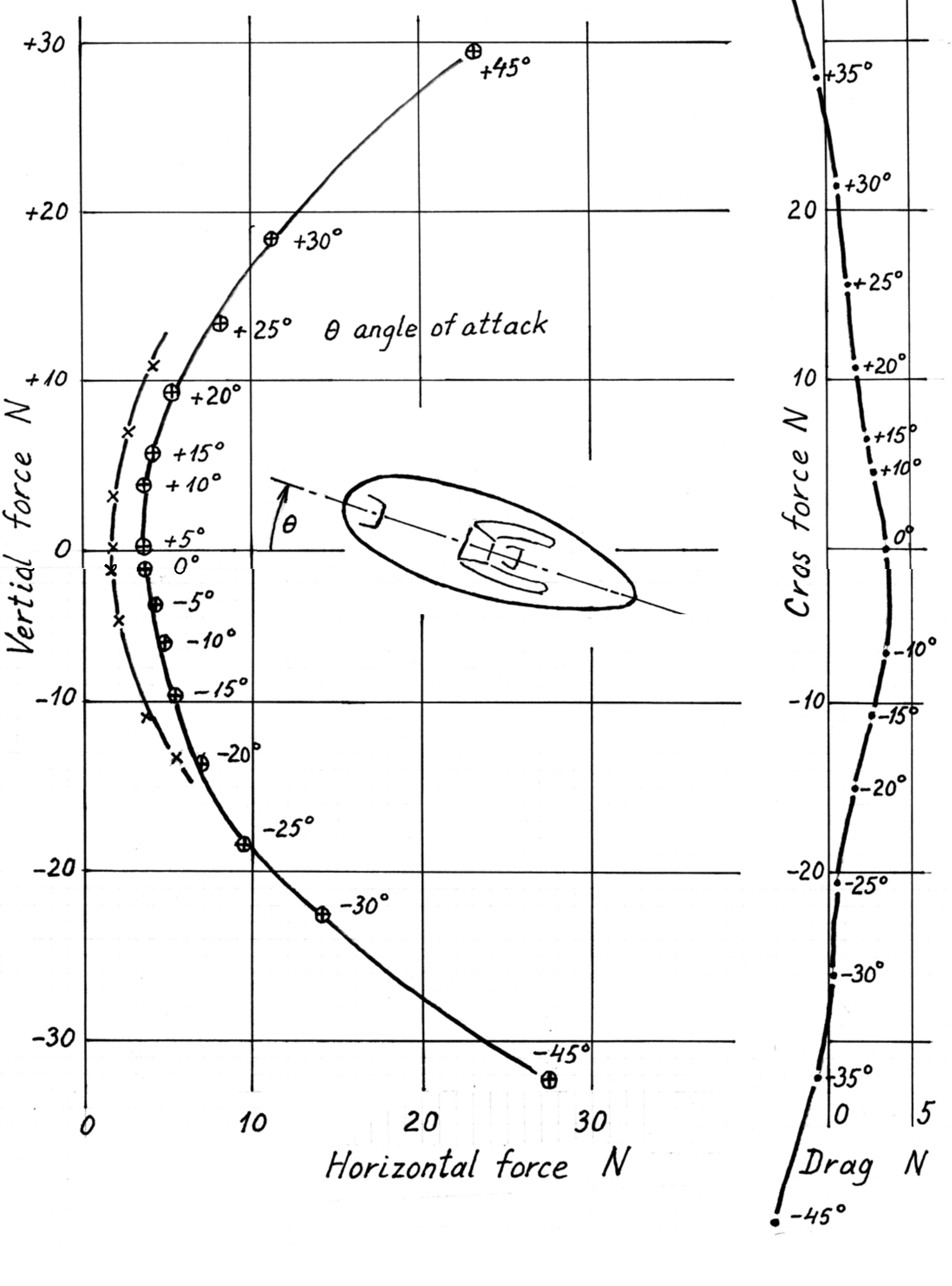
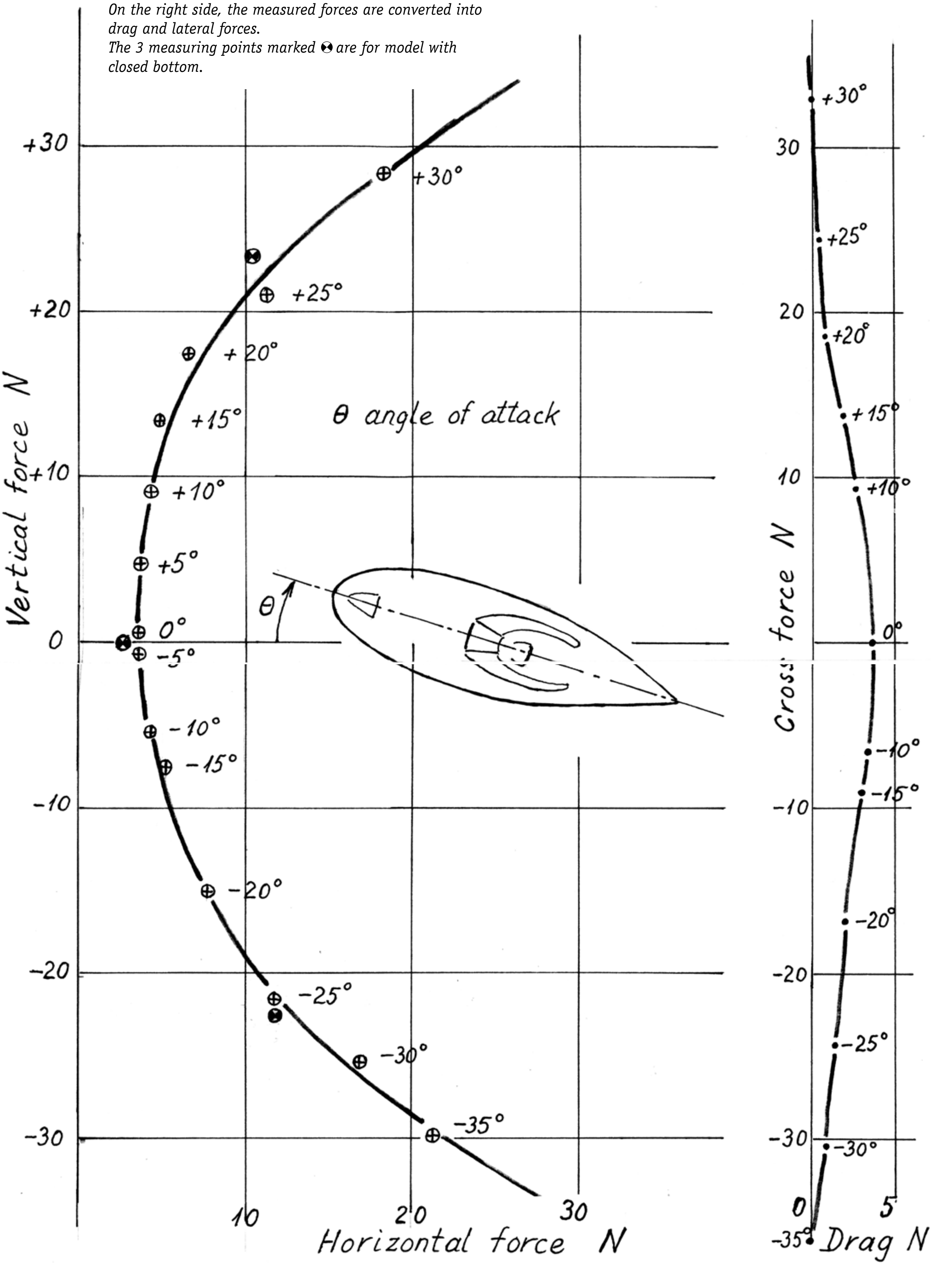
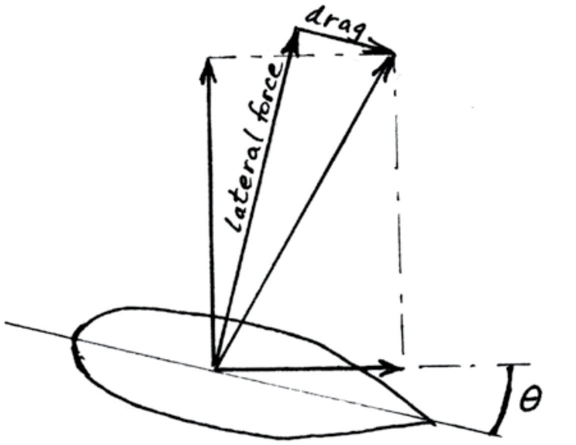


*Fig. 3. Forces on a 1:5 scale model of the Leitra "Sport" at 32 m/sec.*
*On the right side, the measured forces are converted into drag and lateral forces.*
*The 3 measuring points marked ⊗ are for model with closed bottom.*






The diagram with direct measurements can be transformed into an other diagram, which shows the forces as drag and lateral force at different angles of incidence, see right side of Fig. 2 and Fig. 3.

The drag is seen to decrease, when the model turns away from the flow direction, and at approximately +/– 33 degrees the drag disappears, and at larger angles of attack it becomes negative, i.e. the model gets a push forward.

This observation is confirmed when riding a Leitra velomobile in side wind. In a head/side wind,

coming from 60 degrees, and at a speed of 10 m/sec, the drag is not noticable, and in direct cross wind you feel a light push. You do not get full advantage of the sail effect, because at the same time the rolling resistance will increase, since you have to steer against the cross wind, which causes higher friction between wheels and road.

Other velomobile designers have tried to optimize the sail effect. The company Birkenstock in Switzerland made similar wind tunnel experiments with a ”Butterfly” model, and they found the shift from drag to push to occur at a slightly smaller angle. Data from a diploma thesis by J. R. E. Diener indicate 25-30 degrees as the angle of attack, where the shift in drag occurs. The model of the ”Butterfly” is more slim, has a higher tail section, and the shape is more like a vertical air foil.

From the measurements we can calculate the drag coefficient $C_D$ of the models. All measurements were made at 32 m/sec, which gives a dynamic pressure of

$$P = \tfrac{1}{2}\rho \cdot U^2 = \tfrac{1}{2} \cdot 1.2\ \mathrm{kg/m^3} \cdot (32\ \mathrm{m/sec})^2 = 614\ \mathrm{N/m^2}$$

and with the cross section A and the drag at angle of incidence $\theta = 0$, we get:

| | **Drag F** | **F/P = $C_D$ A** | **A** | **$C_D$** |
|---|---|---|---|---|
| Model 1 | 1.5 N | $2.44 \cdot 10^{-3}$ m² | $1.60 \cdot 10^{-2}$ m² | 0.15 |
| Model 2 + bottom | 2.6 N | $4.23 \cdot 10^{-3}$ m² | $2.28 \cdot 10^{-2}$ m² | 0.19 |
| Model 2 – bottom | 3.2 N | $5.21 \cdot 10^{-3}$ m² | $2.17 \cdot 10^{-2}$ m² | 0.24 |
| Model 3 | 3.4 N | $5.54 \cdot 10^{-3}$ m² | $2.17 \cdot 10^{-2}$ m² | 0.25 |

The model experiments indicate, that closing the bottom of the fairing could give as much as 20% reduction of the drag. The reduction is much less, when the model has a small angle of attack.

However, the model was placed in the free air stream, far from walls, which could simulate ground effect from the road. Therefore, further studies of the effect of closed bottom will be made on the road under full scale conditions.

## Stability and operation limits

The Leitra is a tadpole trike with a relatively short wheel base and a wide track. This is to obtain high manoeuvrebility and high turn over stability. The configuration is shown in Fig. 4.

The seat is a little higher, and not as recumbent as many other recumbent trikes. This is to provide a good overview and easy visual communication in traffic.

Let us first consider the stability by manoeuvring, in particular by sharp cornering. This is determined by the level of the centre of gravity over the ground and the minimum horizontal distance between the centre of gravity and the line of turn over.

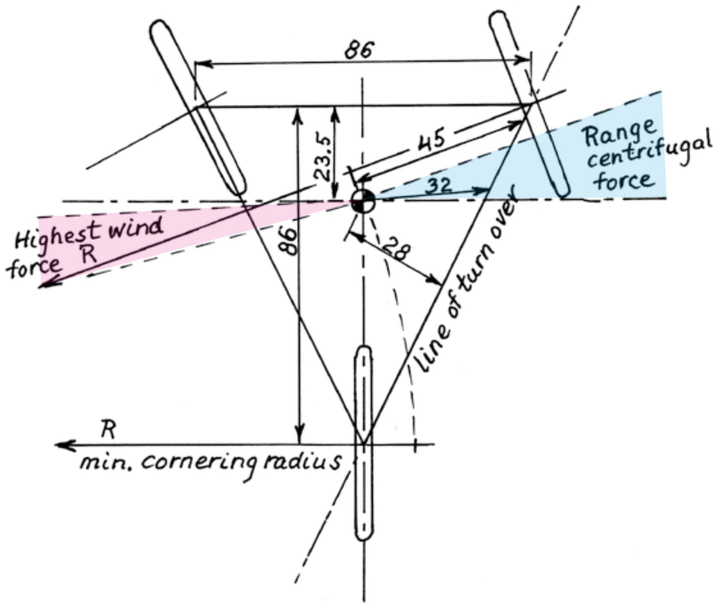



*Fig. 4. Wheel configuration of a Leitra velomobile, with centre og gravity (velomobile + rider + no luggage).*

An empty Leitra ”Sport” with full fairing, including aerodynamical front wheel fairings and heavy duty tires, has the centre of gravity 36 cm over the ground, and a rider (180 cm/70 kg) has centre of gravity approx. at a level of 52 cm. With a mass distribution of 34.5 kg for the velomobile and 70 kg for the rider (total 104,5 kg), we get a common centre of gravity at a level of 47 cm.

The horizontal position og the centre is shown in Fig. 4, and we see, that the critical moment for turn over is:

$$M \cdot g \cdot 0.28\ \text{m} = M \cdot 2.75\ \text{m}^2/\text{sec}^2 \qquad [1]$$

where M is the mass and g is the gravity accelleration. By steep cornering (R = 2 m) the centrifugal force will turn forward towards the front wheel, resulting in a longer moment arm and a critical turn over moment of:

$$\frac{M \cdot U^2}{R} \ \frac{28}{45} \cdot 0.47\ \text{m} = \frac{M \cdot U^2}{R} \cdot 0.292\ \text{m} \qquad [2]$$

From [1] and [2] we see, that with a cornering radius of R = 2m and a speed of 4.34 m/sec, or 15.6 km/h we reach the condition for turn over.

From this we learn: Never exceed a speed of 15 km/h in steep turns.

For larger cornering radius the speed limit will be $U \leq 2.6\ \text{sec}^{-1} \sqrt{R\ \text{m}}$

With heavy load in the rear luggage box, perhaps a child in special fairing with child seat, the critical cornering speed is even lower. On the other hand, heavy luggage under the seat will make the velomobile more stable.

Stability in the wind is another important factor for safe riding. While the centrifugal forces by manoeuvring never will take the direction most sensitive to turn over, the wind can take any direction.

However, as we have seen from the wind tunnel experiments, the wind force shifts quickly to a dominating lateral force, as the angle of attack increases beyond 10 – 15 degrees.

When riding in strong side wind, you will tend to reduce the driving speed for safety reasons.

The wind speed Uw will then be the determining component of the relative air velocity, and we may disregard the driving speed.The level (h) of the aerodynamical pressure centre is estimated to be 55 cm above the ground, and the area of the fairing seen from the side is 1.81 m².

Unfortunately, the wind tunnel measurements did not cover angles of attack beyond 45 degrees.

Therefore, the maximum lateral force is not known exactly, but if we assume a lateral $C_D = 1.0$, we can estimate the turn over moment of the wind:

$$\tfrac{1}{2}\rho \cdot U_w^2 \cdot C_D \cdot A \cdot \tfrac{28}{32} h =$$

$$\tfrac{1}{2} \cdot 1.2\ \text{kg/m}^3 \cdot U_w^2 \cdot 1.0 \cdot 1.81\ \text{m}^2 \cdot \tfrac{28}{32} \cdot 0.55\ \text{m} =$$

$$U_w^2 \cdot 0.52\ \text{kg}$$

If we put the wind moment equal to the critical over turn moment

$$U_w^2 \cdot 0.52\ \text{kg} = M \cdot 2.75\ \text{m}^2/\text{sec}^2$$

we can find the wind speed, where an over turn may occur

$U_w = \sqrt{M\ 5.3\ \text{kg}^{-1}}\ \text{m/sec}$,
with M = 104.5 kg,
we get a critical wind speed $U_w = 23.5$ m/s

I weigh only 59 kg, so my personal limit is slightly lower. To be on the safe side, I set my personal limit at 20 m/sec.

When riding in strong side wind, the velomobile tends to make small jumps sidewards, and you have to keep against the wind with the steering.

If the wind causes an over turn, you slide on the side and may even find yourself in a rolling velomobile. I have been swept off the road a few times in gusts at 25 –30 m/sec in my 30 years as velomobile rider.

Perhaps I should come up with one more warning. If the side wind is strong, but not strong enough

*Fig. 5. Leitra "Sport" side view with centre og pressure and centre of gravity.*

to cause an over turn by itself, you manoeuvring is critical. You should never make fast and steep turns against a strong side wind. In this case you will have centrifugal and wind forces working same way.

It is better to turn away from the wind, if this is possible.

The stability can, of course, be improved by more load in the luggage compartments under the seat. Therefore, I prefer to ride an electrical version of the Leitra under extreme wind conditions. It has the batteries placed low under the seat.

When the vehicle is parked empty, it may well fly away with the wind, if it isn't moored properly.

And a final hint: Always open the fairing against the wind.

## Aerodynamical drag measured full scale

The step from wind tunnel measurements in the laboratory, on small scale models, to full scale experiments under more realistic conditions may lead to a number of possible disturbances.

In order to obtain a reasonable accuracy, it is necessary to select the free air conditions carefully.

The effect of wind, other traffic, road conditions, tire pressure etc. should be kept at a minimum.

As test stretch we found a road with a 4.23 % slope, fairly constant over a distance of 1 km.

The best time to perform the experiments –with least traffic – is a sunday morning, and if the weather happens to be dry with little or no wind, your patience has been rewarded, and you can start the down hill coasting experiments.

The vehicle is accelerated to an initial speed, in these experiments around 35 km/h, and at time zero logging of the speed (U) starts while free wheeling downhill. The run is repeated several times to improve accuracy. The accelleration downhill dU/dt , which can be measured from the U versus time recording, is given by

$$dU/dt = (a - C_R)\cdot g - \tfrac{1}{2}\rho\ (U + U_w)^2\ C_D\ A/M$$

where a is the slope, $C_R$ is the coefficient of rolling resistance, $C_D$ the drag coefficient, A the frontal area of the velomobile and M is the mass of vehicle + rider. From the above formula we find:

$$C_R = a - \frac{dU/dt}{g} - \frac{\tfrac{1}{2}\rho\ C_D\ A\ (U + U_w)^2}{M\ g}$$

and

$$C_D = \frac{(a - C_R)\ M\ g - M\ dU/dt}{\tfrac{1}{2}\rho\ A\ (U + U_w)^2}$$

$C_R$ can be found from measurements, where the speed, and thereby the aerodynamical drag, is low.

$C_D$ can then be calculated from recordings at higher speed, where rolling resistance is small compared to the aerodynamical drag.

Let us first find the $C_R$ coefficient from coasting downhill a weak slope of only 0.013.

The recordings are shown in Fig. 6.

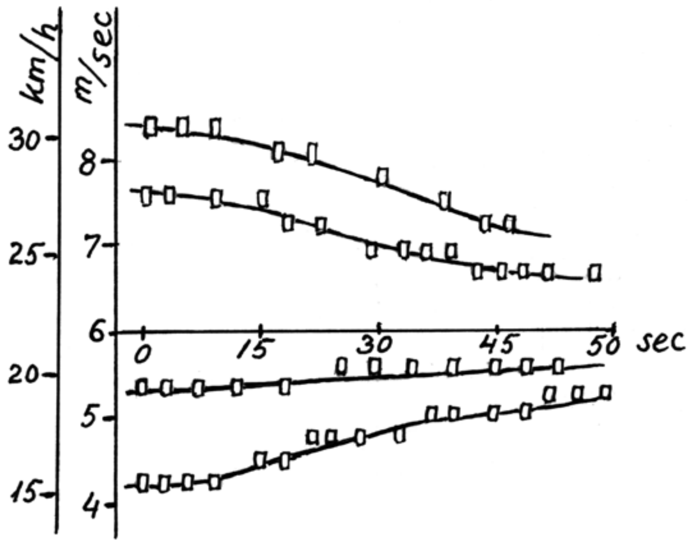



*Fig. 6. Recording of speed as a function of time, measured by coasting down a 1.3 % slope on rough asfalt with Schwalbe Maraton + tyres at 5 bar. No wind.*

With an initial speed of 30 km/h the vehicle slows down, and at a lower initial speed, 15 km/h, it accelerates. From the recordings we can measure dU/dt at a given speed, and if we set

$C_D\ A = 0.2\cdot 0.61\ m^2 = 0.122\ m^2$, $M\ g = 920$ N,
and $U_w = 0$, we can calculate the $C_R$ from the four runs in Fig. 6

| Run | M dU/dt | U | $C_R$ |
|---|---|---|---|
| 1 | – 2.6 N | 7.78 m/sec | 0.011 |
| 2 | – 1.9 N | 6.95 m/sec | 0.011 |
| 3 | + 0.43 N | 5.55 m/sec | 0.010 |
| 4 | + 1.9 N | 4.72 m/sec | 0.009 |
| | | Mean value | 0.010 |

We then move to the steeper slope a = 0.0423 and start coasting at time zero with an initial speed around 36 km/h (10 m/sec). The speed is recorded over a period of 50 seconds, and the rider then pedals slowly uphill for a new run. The results are shown in Fig. 7 and Fig. 8.

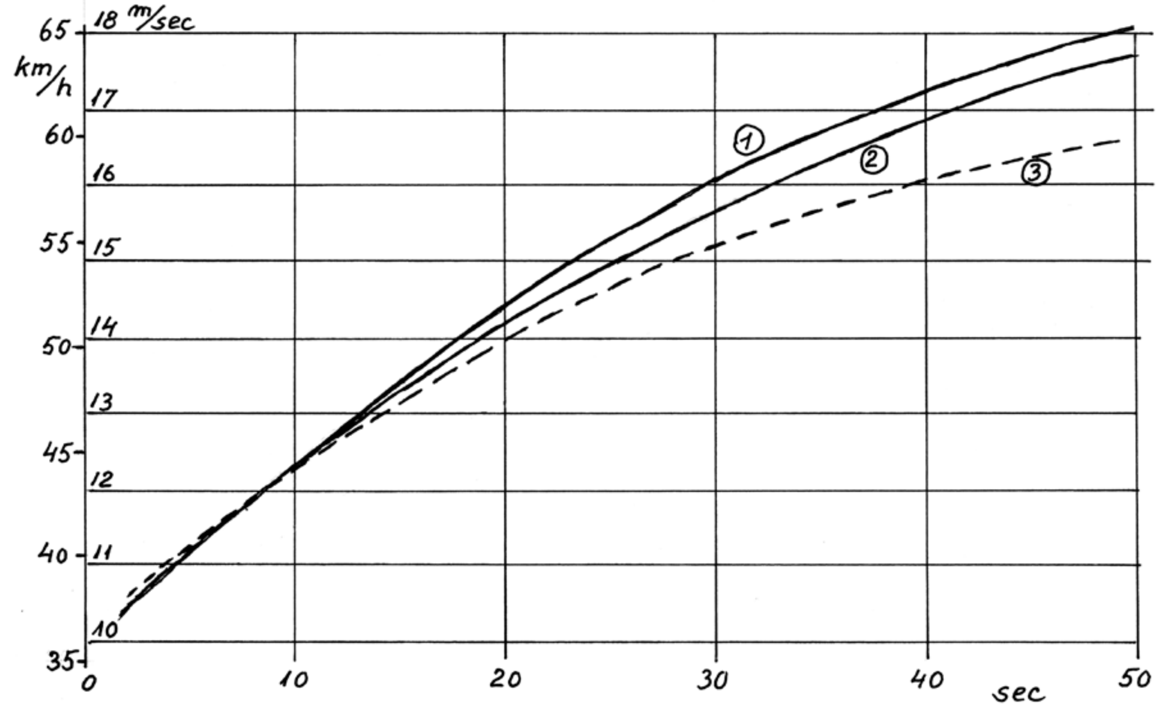



*Fig. 7. Downhill coasting on a 4,23 % slope with Leitra "Sport" fairing, open bottom.*

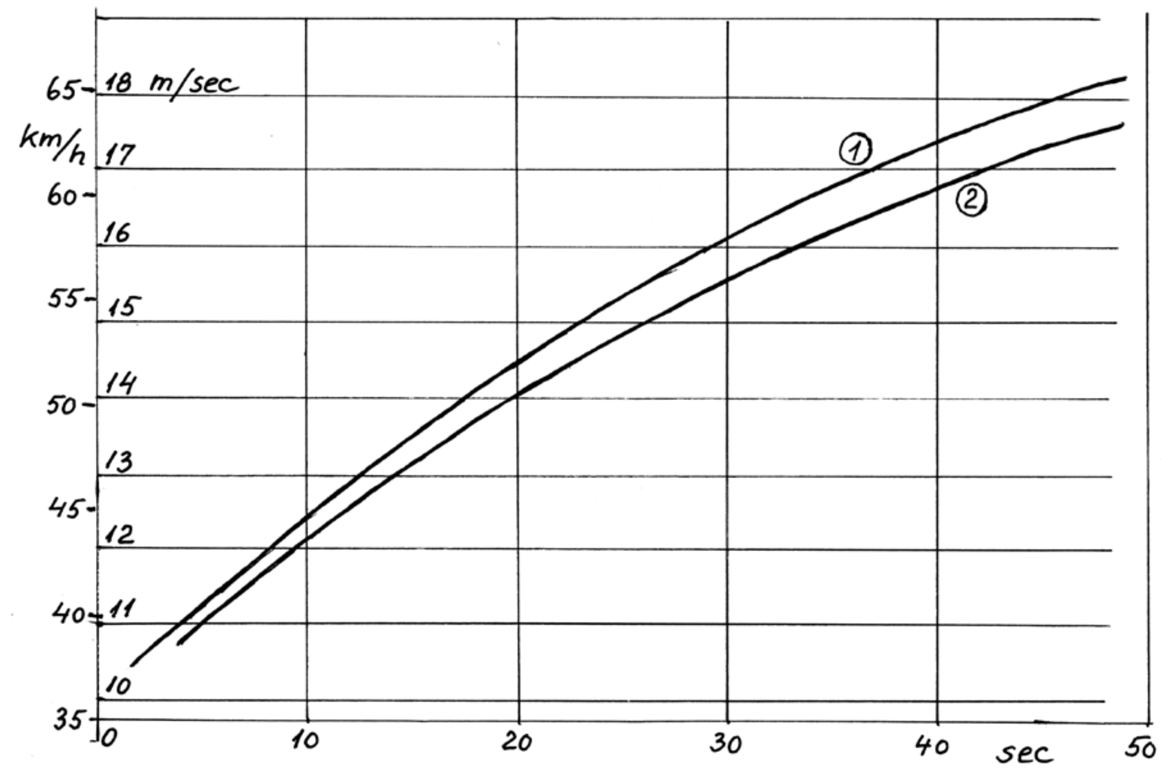



*Fig. 8. Downhill coasting on a 4.23 % slope with Leitra "Sport" fairing, closed bottom.*

From the two recordings 1 and 2 in Fig. 7 we can calculate the $C_D$ at different speeds.

The average values are found to be: $C_D$ = 0.178 +/– 0.011 and $C_D$ = 0.175 +/- 0.008 respectively.

In the run ③ the aerodynamical fairings on the front wheels were removed.

This resulted in a $C_D$ = 0.216 +/– 0.005, or an increase of 21-23 % of the drag.

Wheel fairings are, therefore, essential for low aerodynamical drag on a velomobile, which has the wheels outside the front fairing.

Another question, which has often been discussed, is how much an open bottom may add to the drag. Coasting experiments offer an opportunity to make direct comparisons.

The bottom of the Leitra "Sport" fairing was closed with a plate covering the whole bottom from the nose to the rear wheel, see Fig. 9

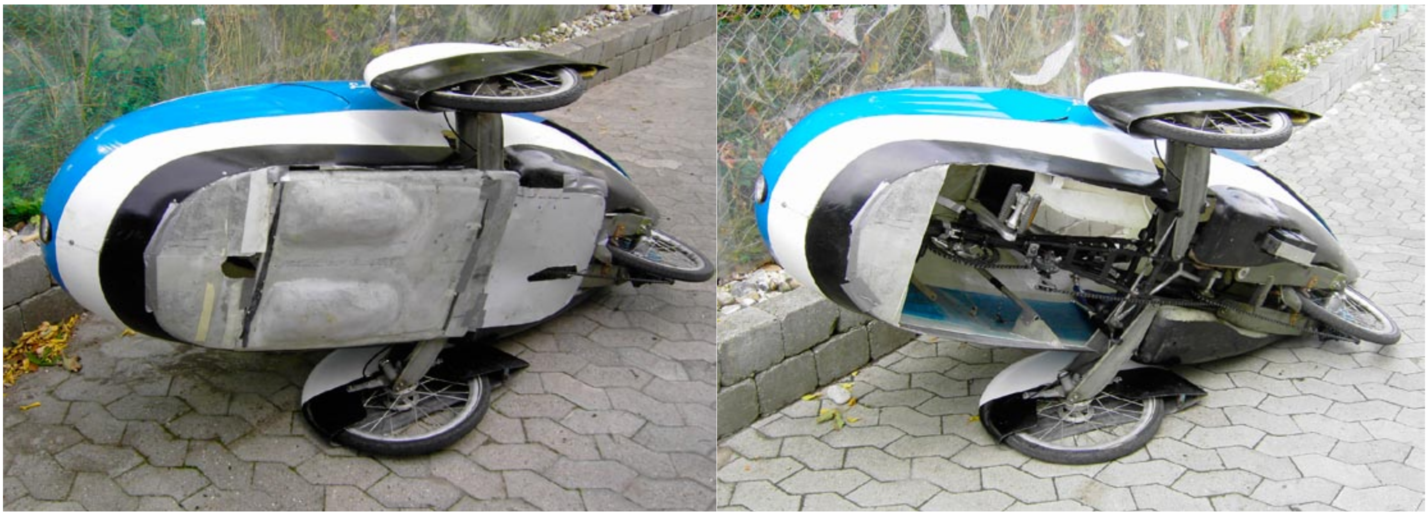


*Fig. 9. Leitra "Sport" fairing with and without closed bottom.*

From the recording ① of velocity as a function of time, shown in Fig. 8, we find $C_D = 0.161$ +/− 0.008. A completely closed bottom has in this experiment reduced $C_D$ by 9%.

The second run ② with closed bottom shows a significant anomali, with $C_D = 0.194$ +/− 0.008.

The reason was found to be an oversight by the rider. He forgot to close the air inlets on the sides of the fairing after a hot uphill return ride. The result was a 20 % increase of the $C_D$.

If you want to race with a Leitra "Sport", it is recommended to close the air inlets completely.

## Tools and accuracy

With the rather primitive instrumentation used in these experiments, one can not expect an accuracy better than 5%. The speed of the velomobile was recorded with a normal cycle computer, showing km/h in steps of 1 km/h. A speed of, say 30 km/h, can, therefore, not be detected with an accuracy better than 3%. Also the time of the reading of the speed has an uncertainty, say 1 second.

From Fig. 6 one can get an impression of the uncertainty of the individual measuring points.

In order to obtain higher accuracy, recording of the speed must be done with a resolution of 0.1 km/h. Also the sampling frequency must be higher, with an uncertainty of a fraction of a second.

With such tools, it would be possible to study aerodynamical effects of minor modifications in the design.


## Acknowledgment

The wind tunnel experiments were performed at the Technical University of Denmark, Section of Fluid Mechanics. I am thankful for the help and assistance I received from ass. prof. Robert Mikkelsen.

From Dr. Andreas Fuchs I received a copy of the thesis by Jan R. E. Diener, who made wind tunnel studies of the Birkenstock "Butterfly" velomobile. It offered an opportunity to make interesting comparisons.


## References:


Diploma thesis EPFL, Jan Raino Eerik Diener, 20.02.99

http://www.speedbikes.ch