

*First  
European Seminar  
on  
Velomobile  
Design*

*Technical University of Denmark  
July 8th 1993*

*Proceedings*

*The First European Seminar on Velomobile Design took place July 8th, 1993 at the Technical University of Denmark.*

*It was organized by HPV Klub Danmark, Danish Cyclist Federation, Rømersgade 7, DK-1362 Copenhagen K, and Institute for Engineering Design, Building 421, Technical University of Denmark, DK-2800 Lyngby.*

*This book, which contains the papers presented at the seminar, can be purchased from the Danish Cyclist Federation, telefax Nr +45 33 32 76 83.*

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## INTRODUCTION – A BRIEF HISTORICAL RETROSPECT

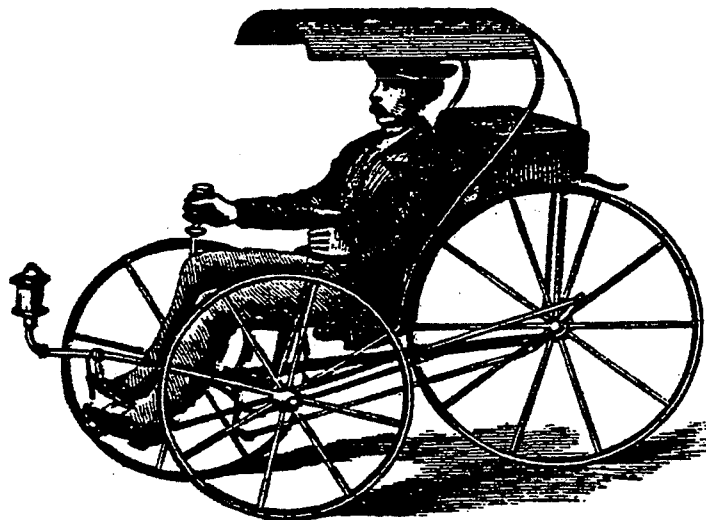
*by Carl Georg Rasmussen, LEITRA ApS*

It is a great pleasure to welcome so many people from so many countries to the First European Seminar on Velomobile Design.

I believe that most of us see the great potential of velomobiles as a future means of individual transportation.

They offer a higher degree of mobility and accessibility than the automobiles, need no gasoline, need no expensive equipment for pollution abatement, give the same kind of weather protection as the car and have a higher comfort, speed and safety than ordinary bicycles.

Although the basic concept of a velomobile is as old as the safety bike itself, there are still very few in actual use.



*An early British velomobile (1881). The basic concept is already there: recumbent seating, three wheels for stability, ergonomical steering system, place for luggage and a cover for protection against the sun/rain.*

The design of velomobiles has for many years been the domain of happy amateurs, who's main interest is racing. Speed-optimization has, therefore, had highest priority as design factor, and very few velomobiles have been developed to a stage, where they could be used in normal traffic.

Two early examples are shown on the following pages: a French model from the 20-ties and a Swedish model from the 40-ties. They have both been built in a relatively large number.

With the technology of that time it was not possible to build sufficiently light and strong structures. Before the space age single-seaters ranged from 35 to 50 kg. To-day, velomobile riders would hardly accept an empty weight above 30 kg.

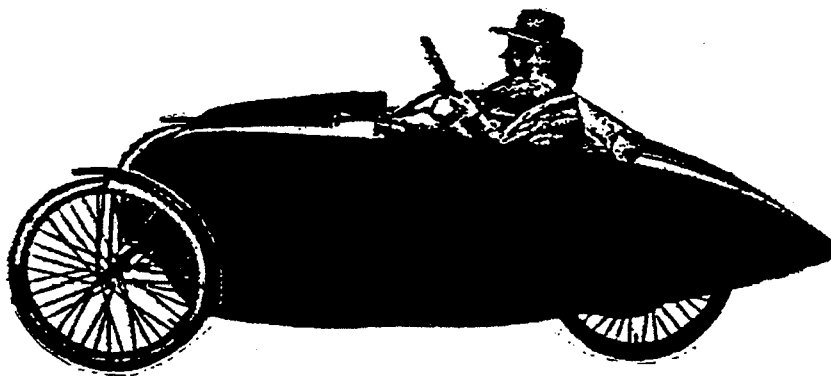
New materials, which first found applications in the aero-space industry, are now available to the velomobile designer. It has opened a lot of new opportunities, and the number of new creations has almost exploded in the 80-ties.

However, it is still not a simple task to design and produce a good velomobile to a popular price. The complexity is often underestimated -and so are the costs.

This seminar will expose some of the important problems, which we have to solve before the full potential of the velomobiles can be realized.

We must work systematically with new design concepts, materials and technologies.

In this work we need the support of university research to check ideas and theories, to tell us what is true and what is false, and to bring new inspiration to the design process.



**In the period 1920-40**, the velomobiles took a more aerodynamical form, and racing with faired recumbent bicycles and tricycles became a popular sport in Europe.

A number of practical vehicles were produced and sold for touring and commuting.

One example is the French VELOCAR. It became quite popular, and the reasons for this can be found in a brochure published in 1928. Let us quote (translated from French):

*The VELOCAR represents a new method of transportation for business, touring and sport.*

- Does not require a drivers licence
- Can be used without prior training
- Needs no gasoline
- Needs no registration number (tax)
- Travels at speeds from 10 to 50 km/h

The VELOCAR is a light vehicle on four wheels, with two seats side by side. It is moved by it's users by the aid of pedals, just like an ordinary bicycle, but the pedals are placed in front, which offers the user the most efficient position of all, the recumbent position. In this position it is possible to generate maximum power due to the support of the back by the seat.

It's three speeds enables the user to climb any hill without excessive effort. Two strong persons can drive the VELOCAR more easily than one, but it is quite easy to ride it single.

The chassis is made of steel tubes without soldering and with aluminium joints, bronzed to avoid oxydation.

The weight is around 60 kg.

The dimensions: 1.30 x 2.50 x 0.95 meters.

Besides the automobile, which is relatively expensive to buy and to maintain, there is no better means of transportation than the bicycle. That is why our VELOCAR is designed on basis of bicycle techniques.

By simple modifications it has been possible to make further improvements:



Racing in the streets of Paris, Champs-Élysées, 1930. Perhaps the French HPV-Association will take up this tradition again.

Notice the grave and determined faces of the drivers!

- The seating position of a cyclist could be more favourable for the respiration. The bicyclist arches his back. The velocarist expands his chest.
- The saddle of a bicycle is rather hard and does not give ideal support, in particular not for the ladies. The VELOCAR has a comfortable seat !
- Stability is a problem by stop and go. The cyclist must put a foot on the ground. The velocarist can always sit relaxed with the feeds on the pedals, ready to start.
- The working position could be made better. In order to put extra power in the pedals, the bicyclist must pull the handlebars, which is very tiring.

The velocarist can press the back against the seat.

- The air-resistance is a serious obstruction for higher speeds. Without air-resistance a bicyclist could easily reach speeds of about 100 km/h.

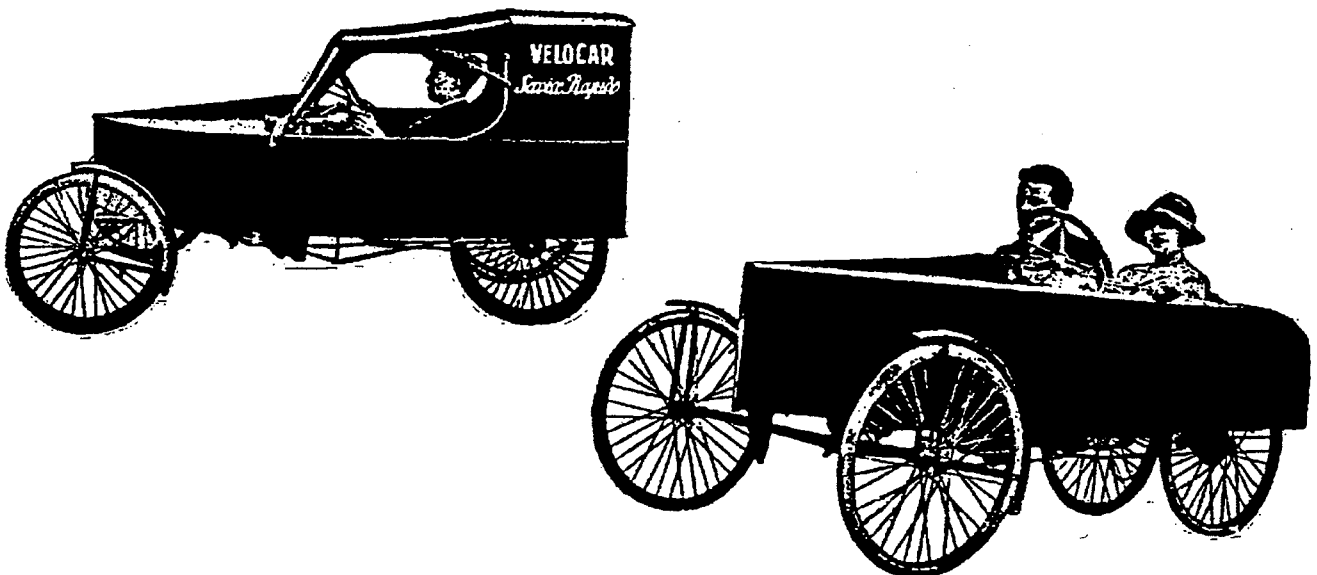
Therefore, the cyclist should sit in a position, which favours penetration of the air, and he should be enclosed by a fairing, just like an aviation pilot, in order to obtain better aerodynamics.

This is the case of the velocarist !

So the VELOCAR is the ideal cycle. It's formidable success in Paris, which is seen by the large number of VELOCARs in operation, permits us to conclude, that it is the definite solution to cycling.

In order to convince potential buyers, the brochure brings a number of testimonies from happy users. They show that tours of several hundred kilometers in a VELOCAR, with man and wife, were quite common.

The designer of the VELOCAR, M. Charles St. Queen, certainly had good reasons for being proud of his invention.

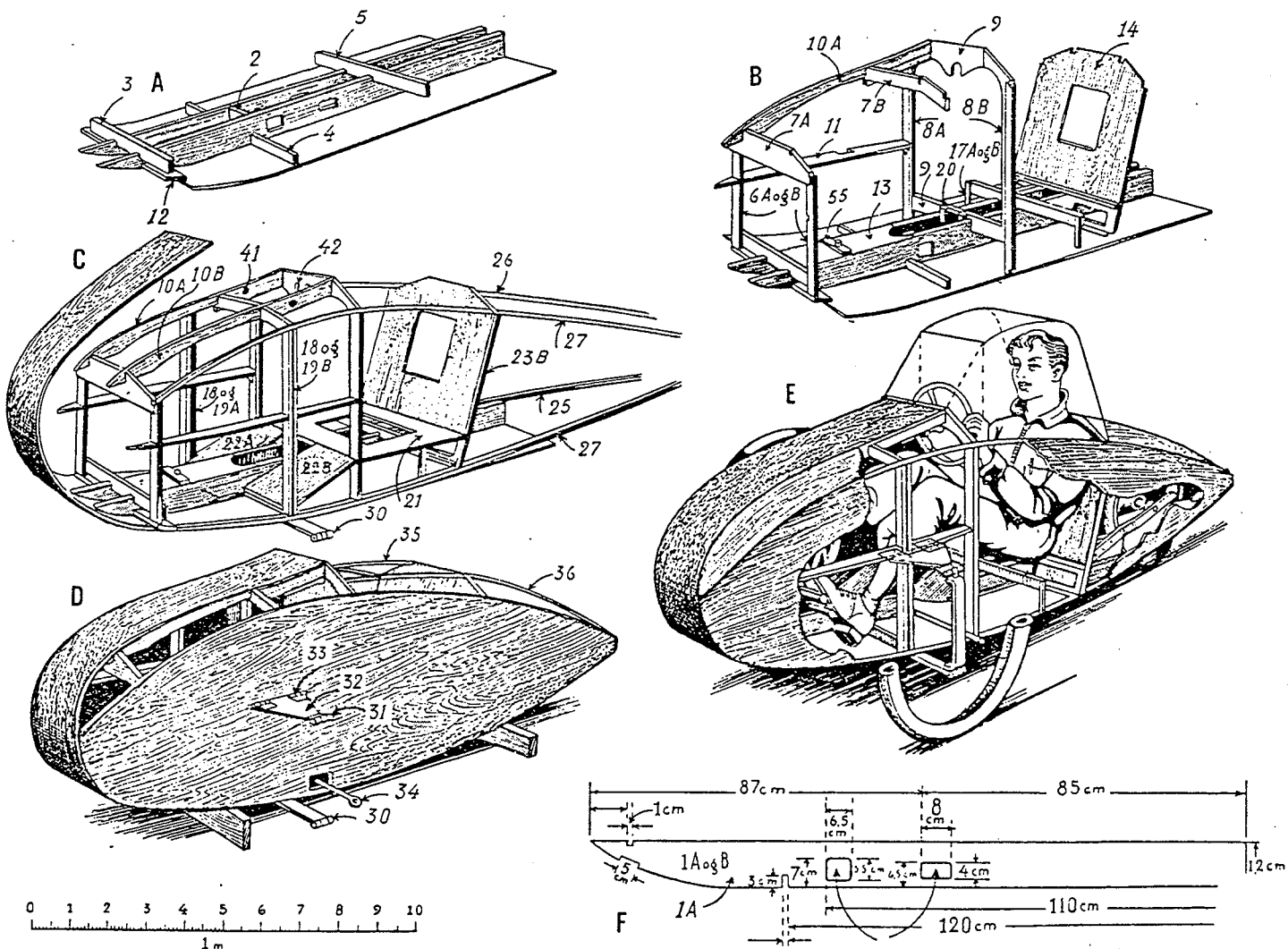


In the period 1935-50 economical crises and wars gave rise to a wider use of velomobiles for distribution of goods in the towns, for taxis and for private transport.

Some of the designs were very successful, e.g. the Swedish monocoque shown below. It was developed by Ulf Cronberg and was built by many people in Scandinavia – including myself. The drawings were published in hobby books and magazines with detailed instruction, so that even teen-agers could build their own velomobile.

I built one in 1950-51 and used it several years, mainly for touring. The monocoque structure was constructed by wood-lists and thin plywood, glued together. All three wheels were 20 inch. The front wheels were suspended by a single leaf spring of steel, which was mounted under the monocoque. It had rear-wheel-drive and front-wheel-steering.

From the experience with my first velomobile I learned to appreciate the complete weather protection and the extra speed due to the aerodynamical monocoque, but the vehicle was rather heavy, about 42 kg, and had a poor gearing system.



The Ulf Cronberg velomobile, 1945. (Scandinavians can read a full do-it-yourself instruction in the *Politikens Hobbybog* 1946).

After leaving school I gave up the velomobile construction and concentrated on my other fascination: flying and the design and construction of gliders and light aircrafts.

**In the period 1970-80** the first and second energy crises gave new inspiration to look at the potential of the velomobile as a low-energy-vehicle for individual transport.

When I build the first LEITRA ( = Light Individual Transport) in 1978/79 I still had the qualities and drawbacks of the Cronberg-design in mind.

I discarded the monocoque concept, because it gives no flexibility to adapt the vehicle for different applications and for different size of the user, and it usually results in a heavier structure, but I adopted the concept with two front wheels and a chain transmission to the rear wheel.

That is what it is all about in design work: you take the best concept developed so far and add your own ideas.



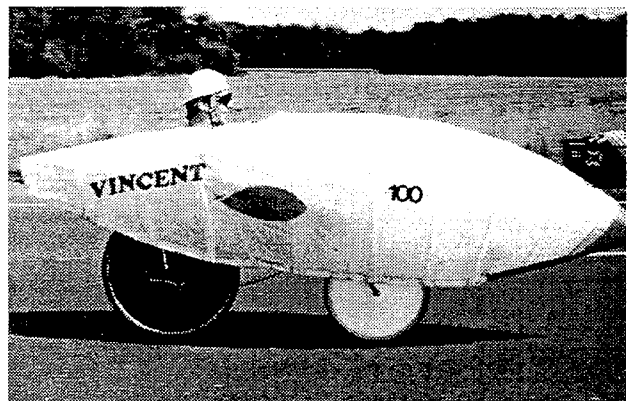
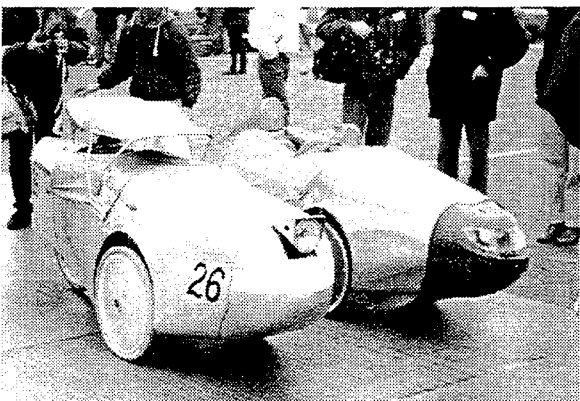
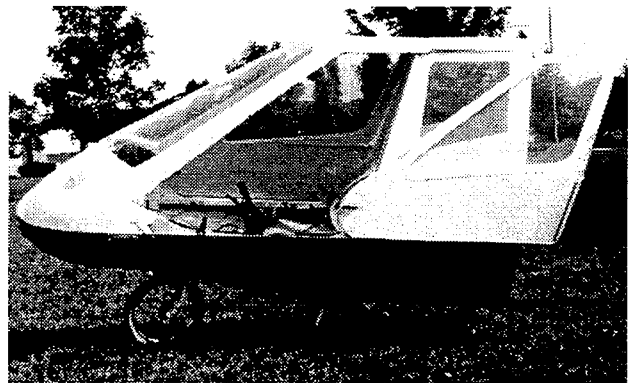
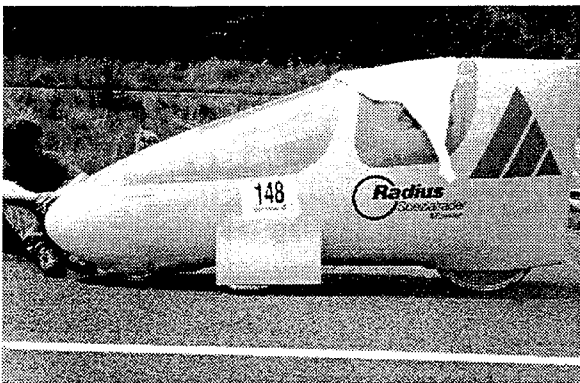
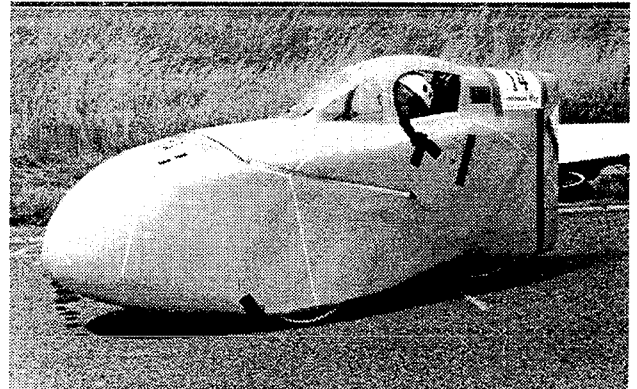
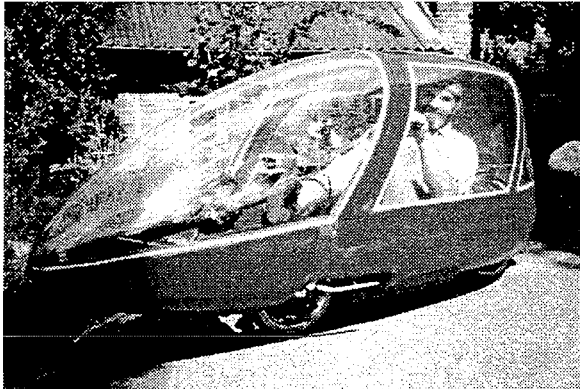
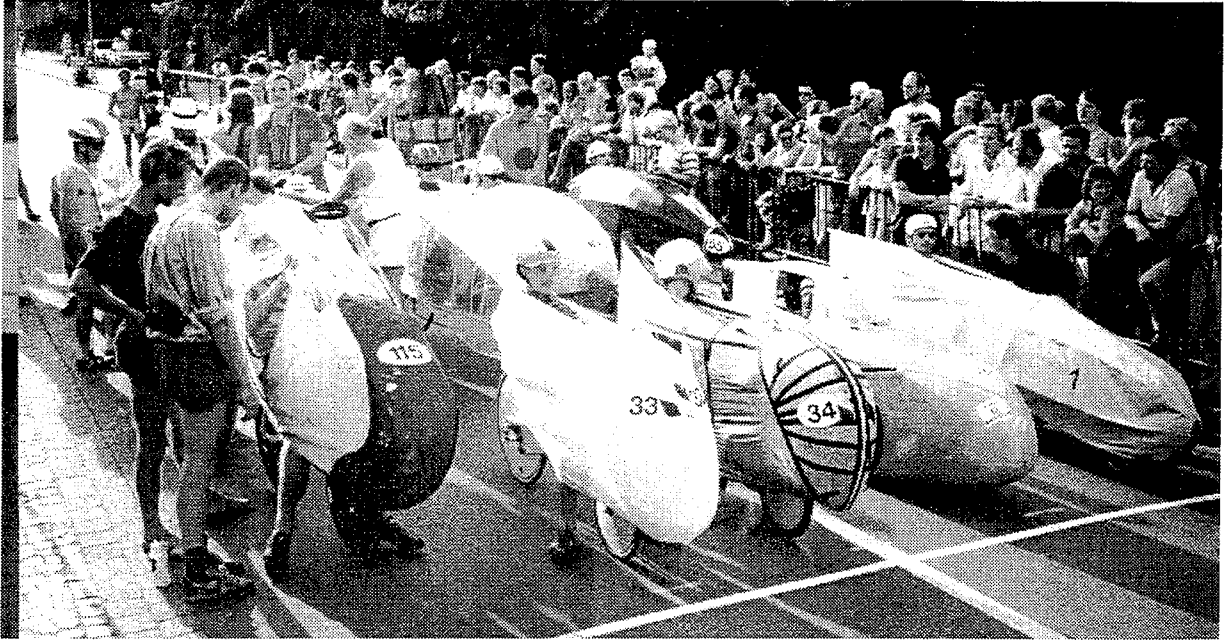
*Celebration of production number 100 of the LEITRA velomobile, Langwedel, Germany in Spring 1993.*

*(Photo: Jürgen Eick).*

**In the period 1980-90** the creativity has flourished like never before, and the design activity has been high all over the world.

The rapid development has been stimulated by a large number of races, in particular since 1985, organized by national and international HPV-organizations. In Europe such organizations exist in Germany, Switzerland, France, United Kingdom, Belgium, The Netherlands, Denmark and in the Baltic countries and Russia.

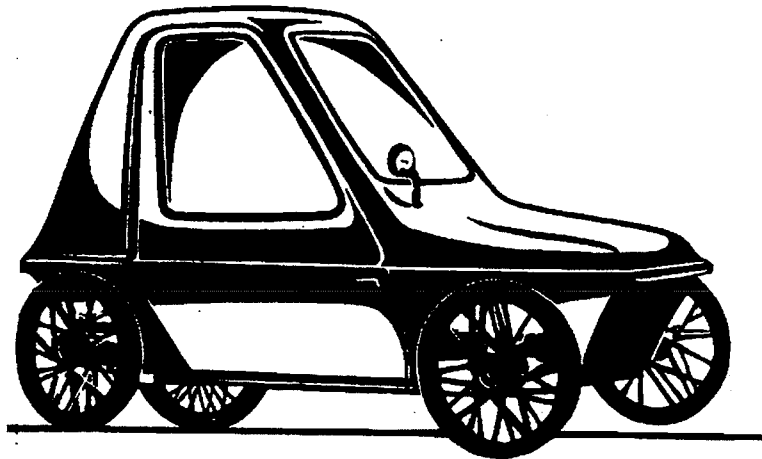
We are all looking forward to see what the period 1990-2000 will bring, and we ask ourselves: Will the next century be ready for a wide spread use of velomobiles?



## VELOMOBILES

*V. Dovydėnas, Vilnius Technical University*

The prototype of the first modern human powered vehicle (HPV), R.Bundschuch's "Pedicar", was designed in 1970. In 1979 the information about HPV was sufficient to write my small book "Velomobiles" in Lithuanian. It was not expected that there would be any interest expressed by the public press – but the contrary proved to be true: articles referring to this book appeared in Russian and German newspapers. Also the author received many letters showing interest in this book.



*R. Bundschuch's "Pedicar", USA 1970.*

### **Trends for new towns**

After the war-and-peace problem, the environment is the next most important problem of mankind. Hypodynamia is a very acute problem in developed countries. Electrocars may take over, but they do not solve the traffic jam problems. Energy problems are also very accute.

Well, these main problems can be solved in towns by HPVs or "velomobiles", as we say. And this is not all.

The practical transport velocity (now about 10-12 km/h in public transport) can be increased by velomobiles by a factor of 2 or 3, because these devices can be used for door-to-door transport and improve capacity of traffic. This enables the user to enjoy a high level of comfort and safety, and furnishes relaxation while riding on clean streets.

Now we have all the scientifically based reasons to speak about a new type of town – the recreational type, a resort-town. This new town, called ECOPOLIS, is a highly desirable alternative to the present type of town, and is totally practicable in the nearest future.

We can and must liquidate “autoholism” in our towns !

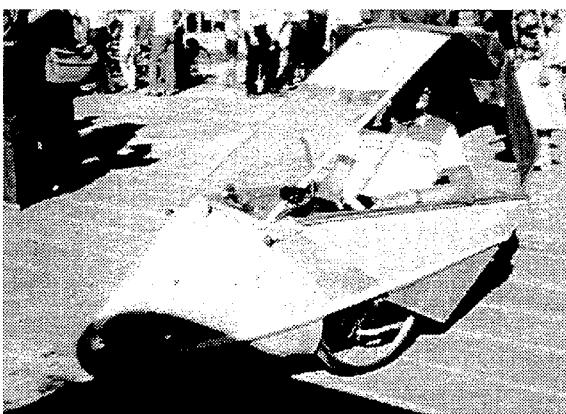
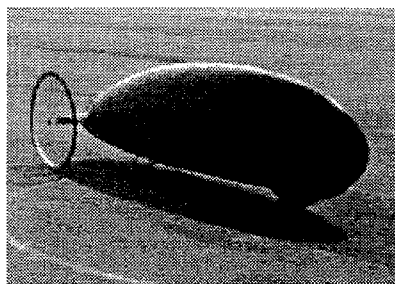
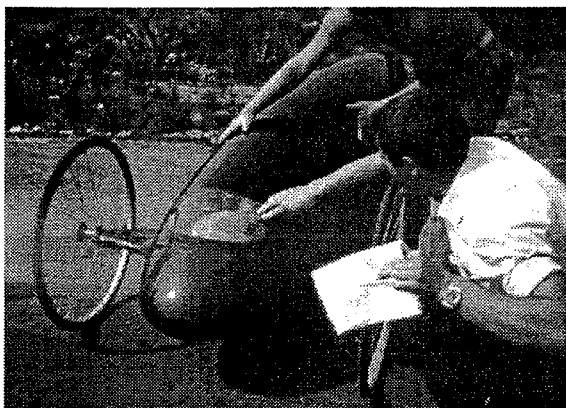
The classics of modern urbanism – O.Niemeyer and K.Linch consider automobile towns as unmodern towns. The trend to a clean, green and silent town is obvious, and the roads and streets in towns are perfect for velomobiles.

### Contests in East Europe

Some words about our work which started in 1975. Only “Pedicar” was known to us, a pioneer, but a slow and bulky machine. Theoretical analysis shows that such machines can be faster than a normal bicycle. It was demonstrated by the velomobile “Vilnius-82” in 1982.

In 1980 we had a succesful racing under winter conditions, and in the Lithuanian town Siauliai we began in 1982 traditional USSR velomobile contests and racing, perhaps the most numerous in the world (about 100 different models in 1989).

Over 100 different velomobile models are designed in Lithuania, while there are more than 1000 models in the world.



Not all of them are high tech, but almost all have interesting details. A broad spectrum of velomobiles, amphibias, velobuses, velocarts and succesful touring machines participated in the event. One of them toured to Siauliai from Joshkar-Ola (2300 km.) and won the first prize in street racing. The high practical value of velomobiles became obvious.

A velomobile is a simple machine. But the requirements for its succesful use are very high. For example, minimum mass requirements are as strict as for a space vehicle.

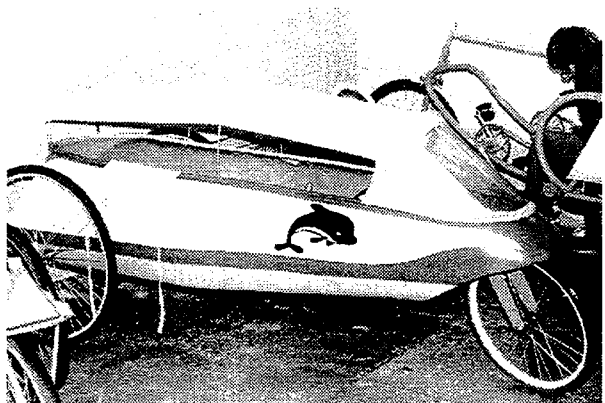
A velomobile is a HPV for good roads with better aerodynamics and speed than those of a bicycle, a more convenient sitting position and protection from bad weather.

In order to make a modern velomobile, we must not only learn from record vehicles, but analyse much more aspects. Different branches of science and technology must be considered.

Let me suggest the following topics:

*Biology.* It is necessary to underline the highest standards of the live Nature. For example, the modern technology cannot create a robot with transport characteristics of a man. Bio-transport vehicles must have the highest standards or they will be naive. We must use bio-nics or patents of the Nature.

*Antropology (Antropometria).* Two or three sizes of velomobiles must be produced for adults and two or three – for children.



*Biomechanics.* A maximum of muscles must be in operation. This is not only for obtaining higher power output, but for comfort as well. Today the pedalling is usually used in HPVs. It can realize all power of a man limited by oxygen consumption during long time. More effective and comfortable is a rowing type motion, especially when the seat does not move, but hands and legs move. This type of motion was very successfully used by Kolb in 1980, but... disapproved by rowing federation, because in racing it was incomparable.

*Physiology.* Sitting position of a racing bicyclist is not good, especially for women. Face-beneath laying position is also not suitable for a practical velomobile. Difficult breathing and headache are characteristic for this position.

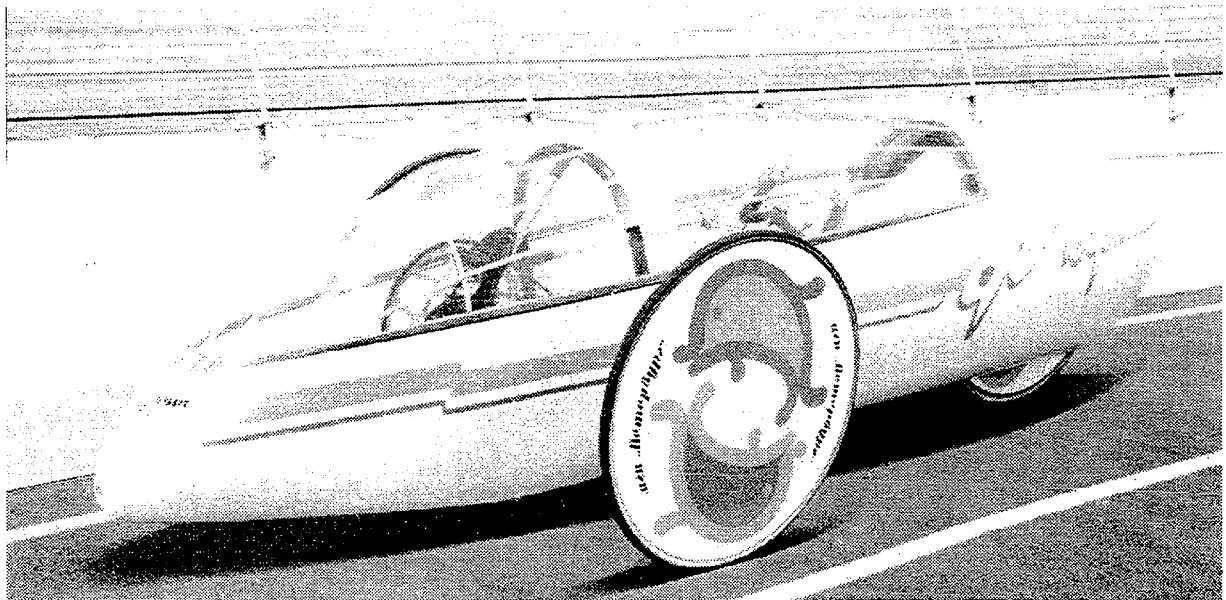
*Ergonomics.* The maximum power for 10 seconds can be as high as 1.5 kW, but for long time transport we have only 70-100 W available. Ergonomics considers such power as light work which does not require a shower-bath after.

The best position of a body is similar to that of an aviation passenger.

An aviation chair is very suitable for our velomobiles, but it must be made smaller. In modern clothing you can drive with comfort in winter, but rain is a problem in an open vehicle. Steering can be performed by one hand or leg, but only two-hand steering is practical.

The velomobile fairing is the most difficult problem for a designer. It should not cover the whole driver all the time. Noise and bad visibility, isolation from Nature beauty are inevitable characteristics of all car bodies. This should be avoided in velomobiles. The idea of a quickly removable fairing is the best; open in fair weather, protecting in rain. The design should be of an original and high standard, aircraft and car analogies can not be directly applied.

*Aerodynamics.* Only fully faired record vehicles can be calculated theoretically. Partly-covered vehicles must be designed using experimental aerodynamics.



The front covering is useful all the time and it also must protect partially against rain. The fairing must be of a round form in every section, which is significant for riding in strong side wind. It is possible to make the position of the fairing adjustable to meet a side wind.

*Psychology.* Advertising biotransports environmental and hygienic factors as well as super-pleasant driving must be underlined. It can be done by making reference to the idea of ECO-POLIS. The best way is to offer everybody a ride in a special foolproof velomobile for five minutes. Perhaps resorts are the best places for this.

### **Technologies and design characteristics**

The car is a bad example for the designer to follow. The power requirements of a car with only one or two (average statistics is 1,2 to 1,7) passengers are as high as those of a whale, whose mass is hundred times bigger than man's. Characteristics of a car are not acceptable for Nature and of course, for biotransport.

Academic articles are written on bicycles mechanics but mathematical calculations are not precise because a human body is very complicated. For this reason HPV design must be based on experiments rather than on theoretical calculations.

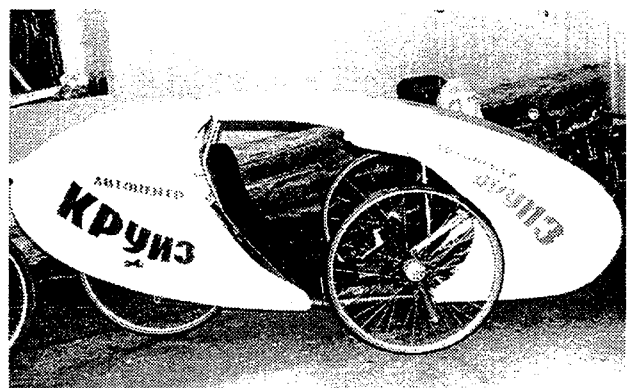
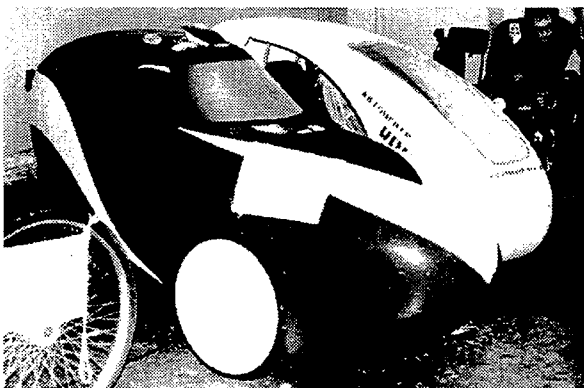
An experiment is cheaper than a complicated theory.

*Aviation and space technologies.* L.Colanis (Germany) and A.Voigt (USA) created velomobiles based on aviation-space concept, but they can only be taken as good design examples, not as practical vehicles because of their price. The "Vector" is sold for 10.000 US dollars (1986). Mass production is not developed in aero-space industry.

The velomobile industry is mostly interested in superlight composite materials, but cheap technologies for mass production must first be developed.

*Materials.* Reinforced plastics such as glass fiber or carbon fiber plastic have the best strength-weight ratio. The whole fairing of a velomobile may have the weight of only 6 kg or less. Fiberglass plastic has about 4 times less specific weight compared with steel, but its rigidity is also about 4 times less.

An ideal material is carbon fiber plastic, which has not only the strength, but also the



rigidity of steel. Its specific weight is about 5 times less than that of steel. But it costs about 35 US dollars per kilogram. It is possible to use fiberglass with fibercarbon, making a cheaper combination.

The classic construction for a bicycle of light steel tube is for general purpose good enough. Good standard welding carbon steel can be used, because not the strength, but the rigidity is the criterium for velomobile construction.

The rigidity of the best special and the usual steel is almost the same.

Usual steel was used for such supermachines as "Vector". Special details can be made of titanium and other light alloys. A perfect material for vibration and shock isolation is polyurethane foam.

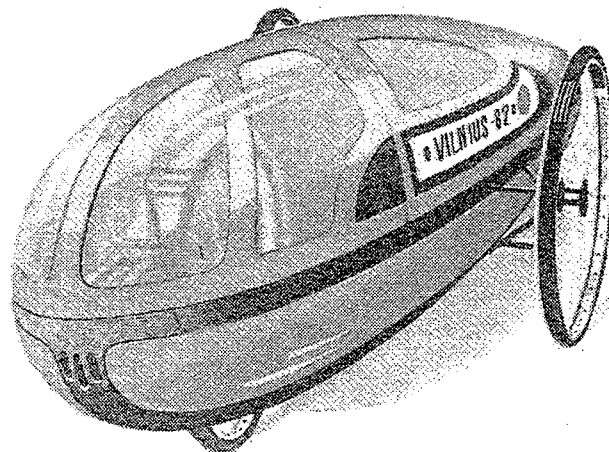
*Stability.* Dynamic stability is guarantied by a 4 wheel scheme, but it is not rational for a velomobile. A three-wheeler of full dynamic stability must have the width of approximately 1.8m.

The low sitting position on a two-wheeler velomobile gives a much better stability than that of a bicycle, especially on a slippery road. You can effectively increase stability by touching the ground with your feet and use the feet as auxiliary brake.

*Vibration and shock isolation.* In a car the isolated and not isolated mass ratio is about 4-5. Mass ratio of a man and a velomobile is the same. For this reason the wheels of a velomobile are usually not suspended with a spring construction. Only high pressure (0.5-0.7 MPa) tires are recommended for velomobiles.

Even in this case a simple construction of the seat, using light polyurethan, is possibly. It can isolate sharp shocks and a smooth riding is guarantied on good roads.

*Body design.* A smooth and round form without sharp edges is recommended. Big, transparent fairings, such as on the "Vector" or the "Dolphin", are not practical. It is not durable (gets scratches), and the sun converts the transparent fairing into a hot green house. Exceptionally bright colours and contrast painting is recommended for velomobiles, which are small and fast.



### General conclusion.

A universal velomobile has not been designed yet. But there are no principal difficulties. A velomobile is an industrial product of medium sophistication and mass production can be organized in a few years. From our point of view G.Martin's record velomobile "Easy Racer" is a good prototype for it. But the fairing must be more practical.

In May 1988 we produced 2 "Easy Racers"(without fairing) for experiment and practice in town conditions. Good shock isolation and ergonomics was achieved with the mass of 15 kg.

We can list the following advantages in comparison with the best classic bicycles:

- 1) Driving is easier energetically (better aerodynamics),
- 2) Better safety, especially on a slippery road,
- 3) Comfortable sitting position,
- 4) Possibility of making stops without dismounting,
- 5) Extraordinary good braking action (with the feet in emergency cases),
- 6) Possibility to ride with big luggage (the centre of mass is at a lower height).
- 7) The possibility of a partial fairing for rain protection.

The disadvantages are the following:

- The vehicle is longer,
- The visibility is less for other road users.

By careful design, the length can be minimized to that of a bicycle.

Visibility may be improved using bright colours of clothes and by other means, such as a small flag on a high pole.

The author has a 5 years practice of riding "Easy Racer". It is easy to ride 20-30 km per day with average speed of about 20 km/h.

A front fairing increases the speed about 10-15%. It also protects the lower part of a rider against rain and dirt.

However, only an all-weather vehicle is capable of being a rival of the car in towns. We think that "Easy Racer" can be made an all-weather vehicle, as it is more aerodynamical and stable than a normal bicycle.

The history of bicycles shows, that two-wheeled vehicles are more practical, especially on bad roads. So three-wheelers, even of the highest quality, will be used for good roads or for special purposes only.

The all-weather two-wheeled velomobile with a partial fairing and with transformable rain protection has good chances to be the main transport vehicle in future towns.

**Supplement 1***Velomobiles*

<i>Facts</i>	<i>Year</i>
R.Bundschuh "Pedicar"	1971
First international race	1975
Speed record 71.9 km/h, (exceeding that of normal racing bikes)	1976
Standard velomobile race (Japan)	1976
Velomobile for sport in Lithuania (Vilnius)	1976
First book	1979
Sixth international race (USA)	1980
Winter race (Vilnius)	1980
Velodrome velomobile, velocart	1983
Record of F.Markham 105.375 km/h	1986

**Prognoses:**

Roads for velomobiles (with bicycles) in towns	1995
Town transport systems	2000
Velomobiles outnumber bicycles	2010
Basic individual town transport vehicle (American experts prognosis)	2020

**References**

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## OPPORTUNITIES BETWEEN MICHAULINES AND LIMOUSINES

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### 1. INTRODUCTION

#### 1.1 Scope of Paper

As a tribute to a forgotten symbiosis between two- and four-wheelers, I have chosen this title. Not out of nostalgia, but because the subject becomes topical again.

Indeed, before the advent of hydrocarbons, Michaulines and Limousines co-existed around 1850-1885, when Pierre Michaux and Charles Jeantaud built their non-polluting vehicles. If the 20th century was that of oil-euphoria, the next one may become the oil weaning trauma.

This paper is therefore exposing the gap between today's two-wheelers and their dominating four-wheeled cousins. It is divided into three sections: Technicalities, Humanities and Semi-Fiction, during which I shall present my personal commuter concept, as well as a solution conceived in the USA.

#### 1.2 Rearview Mirror

Soon after Michaux & Co had blessed the townsfolk with muscle-powered mobility, distilled crude became the object of numerous inventions. 100 years ago Carl Benz gave his name to a vehicle and its propellant, the 'benzine'. Two decades later, the Wright brothers wrote aviation history with hydrocarbons. Our grandparents entered the 'oil plus' era. The pace was hectic and nations depending on the new energy source were increasingly ready, willing and able to wage war over the black liquid. I.e. 7 wars in 90 years, with increasing agility.

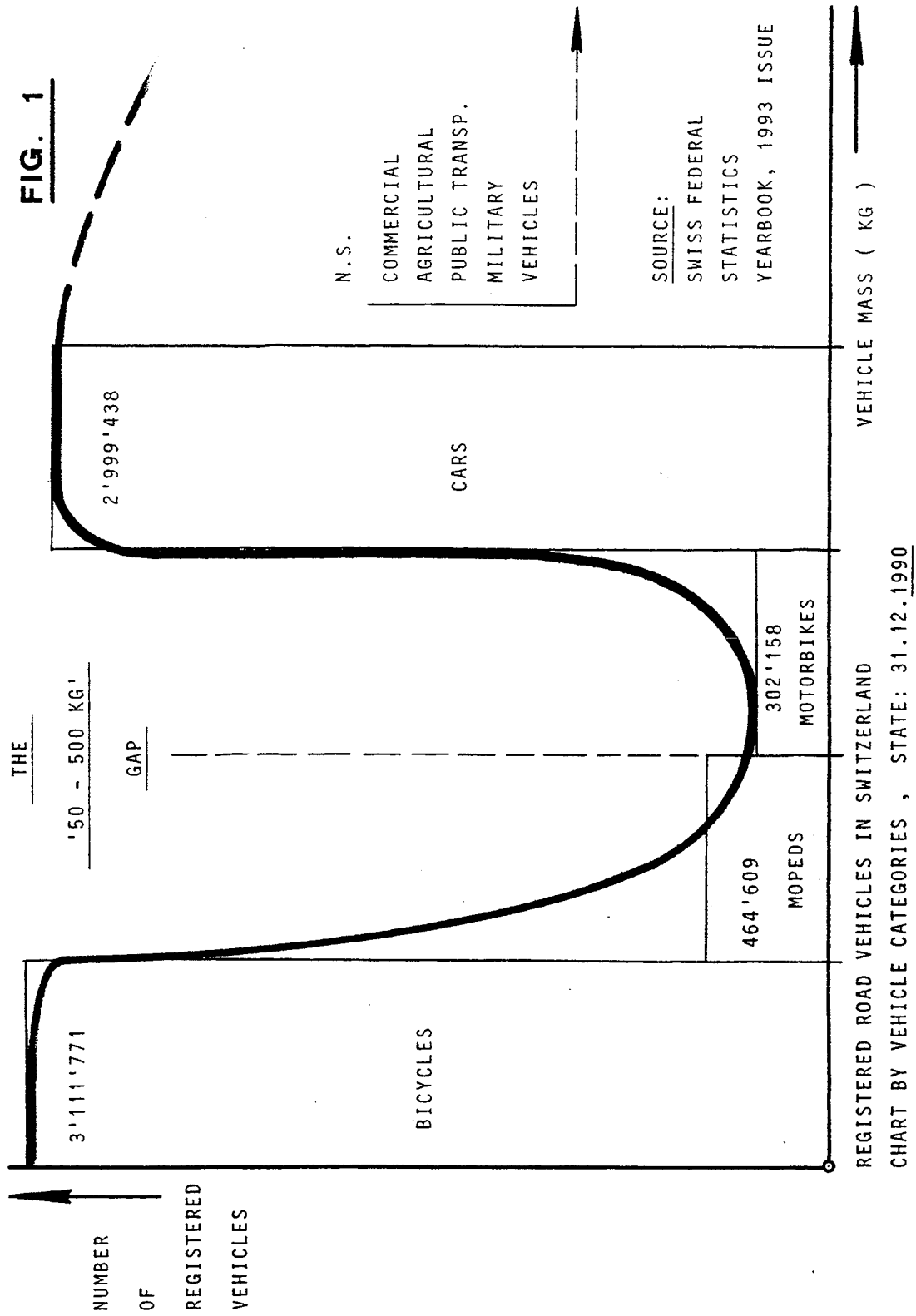
Technical trends in Europe and in the USA must be seen in historic context:

- first, the original cars and planes were based on cycle technology prevailing at that time
- then, cycle efficiency was lost and vehicle weights increased, as more powerful engines emerged. E.g. today DAIMLER-BENZ builds cars 10 times heavier than its first Benz, propelled by 300 kW, which is roughly 1000 times more than the Velo-BENZ
- finally, during the 20th century, bicycles stagnated mainly because oil became cheaper and the UNION CYCLISTE INTERNATIONALE (UCI) froze their shape by a set of banning rules, for running competitions amongst athletes with identical machines only

#### 1.3 Status Quo

Whoever cares to investigate national registration data and transport performance statistics of various road vehicle categories<sup>(1)</sup>, will invariably find a pronounced rift in the plotted curve, caused by vehicles whose mass is roughly between 50 and 500 kg.

Not only is the number of registrations therein very low, the corresponding transport performance too. This is due to motorbikes, for loss of function as transport tools. Today, they are leisure instruments and are left in the garage over Winter. As Fig. 1 shows, bicycles and cars are kept in a state of apartheid.



### 1.4 Forward Periscope

If today the situation begins to budge, it is the result of several cumulative effects:

manmade pollution spans and degrades our ecosphere  
+  
ecological consciousness is increasing  
+  
energy is appreciating  
+  
we are officially forewarned of the coming 'oil minus' era

The dormant 50-500 bracket will be topical again, what with the calamities of pre-programmed oil wars, higher fiscal loads and the next environmental Job's post. Can there be more exciting challenges for our young, creative talents, than to address the vehicular problems besetting tomorrow's generation ?

In practical terms: What can be done **NOW**, to conserve oil and environment simultaneously ? Our immediate goal may be re-defined as stretching oil thinly. Part of it will be the social and physical upgrading of cycle-related technologies, while at the same time weaning fast ovens on wheels from burning non-renewables. Those who attribute to the term 'cycle-related' a negative connotation, must recall that our cars and planes all took off from bicycles of yore. Today, at the 'oil minus' threshold, we are in a similar situation, except that we can presently draw from many other disciplines, including bionics and wholistic bio-cybernetic methods, as advocated by Prof.Dr. Frederic Vester<sup>(2)</sup>.

Unfortunately, 'experts' at both ends of the spectrum tend to pursue a simple-minded technical approach. 'Makers' often forget that people have to change too, otherwise the formation of a critical mass, indispensable for setting our destiny on a new course, will never materialize.

### 1.5 Pitfalls

Typical delusions nurtured by 'busy' promoters:

( of a cycle world )	( of a car world )
- cycle lanes is the answer to all hanging problems	- traffic collapse can only be avoided by more motorways
- streamlining means speed/sport for easier product acceptance	- catalytic converters eradicate hyper-mobility loads on nature
- the stronger the brake-calliper force, the safer the stopping	- heavier cars are safer
- the lower the centre of gravity, the better the bike's balance	- fat tires offer better vehicle handling properties
	- 'PROMETHEUS' and other guidance systems guarantee free traffic
	- Formula racing is needed to solve future mobility problems

Traditional fossil-powered vehicles dominate the scene, with worsening pollution trends in agglomerations, in spite of better combustion efficiencies ( at least on test-benches ).

E.g. If the German Ministry of Transport plans to reduce CO<sub>2</sub> emissions by 10 % till the year 2005, other ministries will have to perform miracles, because, if present trends continue, West Germany will produce 28,7 % more traffic pollutants and former East Germany 155,4 % more<sup>(3)</sup>.

Causal is the propulsive power war on German Autobahns. The directives of the 1992 Rio Environmental Summit (UNCED) remain empty words, in the face of escalations on all fronts<sup>(4)</sup>:

in 1960 German cars had an average installed power of 25 kW( 34HP)  
 by 1988 German cars had an average installed power of 58 kW( 79HP)  
 in 1989 newly registred German cars averaged around 63 kW( 85HP)  
 by 1992 ministerial cars escalated from 118 kW('87)to180 kW(245HP)

The same up-beat curve emerges, if one analyses other car parameters, such as: weight, acceleration, speed, number of servo-motors, loudspeakers, or other paraphernalia in the service of luxury cravings. As the exponential figures evidence, politicians are unwilling to state examples. Whoever tries to offer zero emission vehicles (ZEVs) in this context, soon realises how difficult this market is, mainly because of underrated oil prices.

I shall attempt to formulate in the following chapter my commuter concept, hoping not to sound like the ticking of a certain popular Swiss watch, trying desperately to grow wheels.

## 2. TECHNICALITIES

### 2.1 Grappling with Specifications

Early in 1986 a well-meaning US sponsor sent pages of vehicle specifications to Max Horlacher, the Swiss solar car pioneer. After digesting them, Max observed wearily:

"If on top of it, we shove a broom up the colon of the driver, he might as well sweep the road with it !"

Since the art lays in self-restraint, let me begin at the base.

### 2.2 Pushbike Improvements

#### 2.2.1 Climate

Weather protection is first. No matter which configuration is applied, it is bound to cause cross-wind stability problems. This in turn calls for 3-wheeled solutions, imposing weight penalties which, for reasons of cost, can not always be compensated with lightweight materials

If one opts for 2-wheels on account of simplicity, low weight and price, R+D funds may best be directed towards new fibres and clothing, rather than on bike fairings.

#### 2.2.2 Payload

To carry the daily necessities of life is second. In addition to the rider's weight, a sensible pedalbike should be able to carry 18-20 kg, corresponding to the weight of a 4 year old child, or the equivalent in shopping bags. The stiffest challenge comes from the bulk of a standard beverage crate, namely 30 x 40 x 38 cm (i.e. a volume of 45,6 litres). To lodge such a bulking item is generally less of a problem in 3-wheelers. Reasonably priced bicycles have so far failed to solve this problem, except by trailer, turning the lot into a 3-4 wheel convoy. Commendable exceptions are the LONG JOHN and the German ERGO RAD.

#### 2.2.3 Streamlining

Since classical uprights resemble windmills and absorb precious knee-wax, my third concern is to reduce aerodynamic drag. This can be realized by reduced areas of man plus machine, accompanied by lowest aerodynamic form coefficients. The latter can be obtained only with a fully closed fairing, which is justified in two cases:

record-performance vehicles	( $C_w$ 0,01 - 0,02 )
cold-climate commuters	( $C_w$ 0,2 - 0,4 )

Since each wheel creates turbulence, bi-cycles are out-slipping tri-cycles, which is confirmed by the last few world speed records, culminating in 110,6 Km/h<sup>(5)</sup>.

The recumbent riding position helps in reducing aerodynamic drag. However, for commuting this advantage must be carefully weighed against several negative factors:

- if the eye-level drops below 135 cm, then visibility and perceptibility are critical in **TODAY'S** traffic
- if the centre of gravity is too low, riders may experience balancing problems at low speeds, in case of single-track machines
- because recumbent cyclists push against a backrest, this must be rigidly integrated to a stiff frame, otherwise energy gets lost. Structural stiffness via high-tech composite materials is justifiable only if they are easily separable for correct recycling.

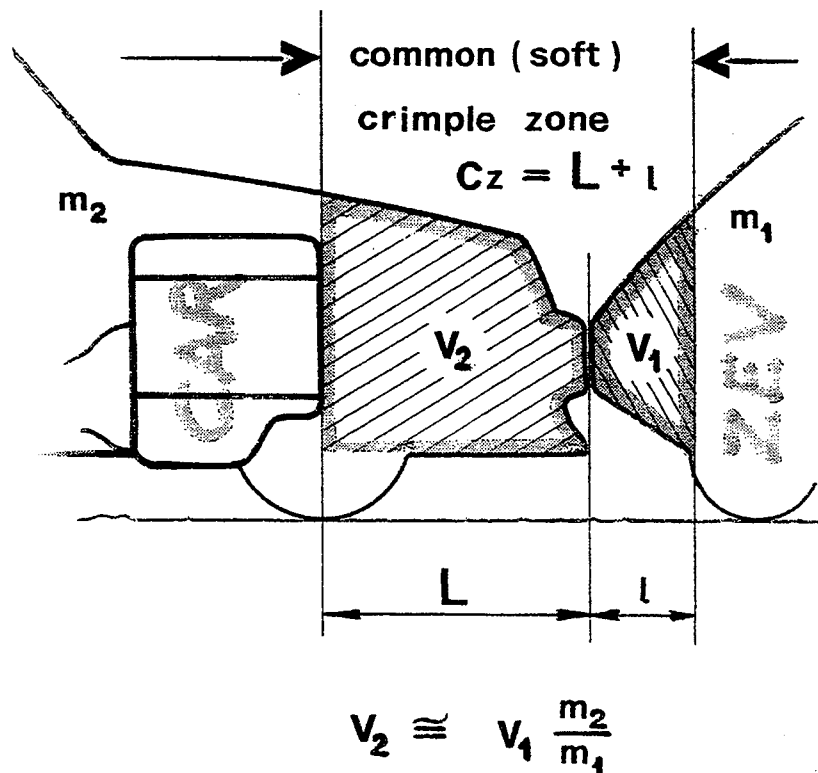
N.B.

There is no ethic in compelling battery-, fridge-, electronic-hardware makers to take back their spent items, while carmakers run scot-free. Any vehicle leaving the factory must be compensated by an old one entering the back door. This will drive home the lost sense for energies and car makers will stop shipping new and old products half way around the world, which is doubly senseless, since oil tankers already do that pollutingly.

#### 2.2.4 Safety

Last but not least safety. This type of human-propelled vehicle can not bear bolsters to increase passive safety. These must logically be worn by the big polluters. I.e. soft shoulders on limousines must become mandatory in proportion to their mass, the principle of which is intimated in Fig.2

**FIG. 2**



However, active safety features are a must and pay dividends:

e.g:

- the centre of gravity must be moved as far back as possible, in order to avoid forward-tipping during emergency stops
- in downhill curves 3-wheelers are safer, if twin wheels are up front, for hard braking
- multitrack vehicles should have a low centre of gravity, unless they have leaning capability in bends
- soft suspensions reduce strain on vehicle structures and on riders and may be used for leaning-geometries
- should the rider's head not be visible above car roofs (presently 140 cm high), then a 160-180 cm high flag should be carried.

### 2.2.5 Size

If the length surpasses 200 cm, then crossparking becomes critical and 'stand-up' parking may be an alternative. Should the maximum width be less than 80 cm, bikes will go through any standard door. Finally vehicles up to 75 cm wide are admitted on cycling lanes in Holland and possibly also in a few other cycle-minded countries.

The USA is not one of them, but the UNITED STATES CYCLING FEDERATION (USCF) has confirmed to the INTERNATIONAL HUMAN POWERED VEHICLE ASSOCIATION (IHPVA) that in future their US-organized cycle-races may also admit human powered vehicles of non-UCI-standards, provided:

- lengths and widths do not exceed 200x75 cm
- the vehicle is not found to be unsafe <sup>(6)</sup>

### 2.3 General Velomobile Specifications

If 100% weather protection has to be achieved, we enter into the category of velomobiles, which in human powered form weigh anything between 20-60 kg. These are mostly 3-wheelers, exceptionally 4-wheelers and rarer still 2-wheelers with a pair of retractable support wheels. Preliminary considerations:

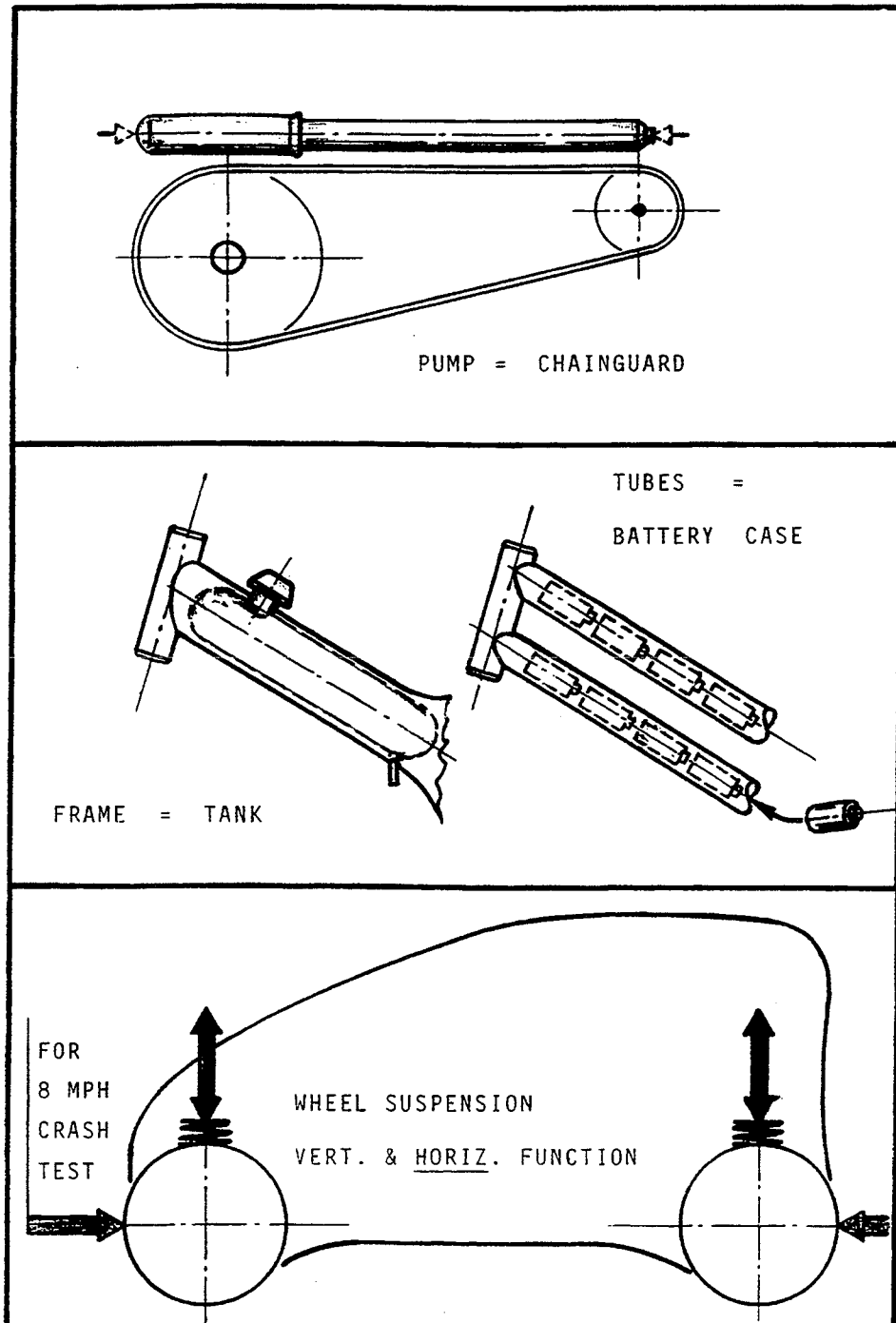
- national vehicle registration bodies may, for dimensional reasons, disallow the cycle status.
- closed tops, safety glass, windshield wipers, etc....may add critical weight, calling for auxiliary power
- since there may be no appropriate homologation niche, the design may be subjected to motorbike-, or even car regulations

Irrespective of \$-hurdles, time has come to shed automotive tunnel views. Let us start with an open mind for true innovation, as practised by Max Horklacher in 1983, when he built Switzerland's first human powered aircraft. After a flight of some 2 Km he observed: "Had I graduated from an aeronautics college, that knowledge would probably have inhibited this job".

Efficiency on land, water and in the air can be improved dramatically by weight reduction: Unconventional approaches have to be tried. A retiring German car executive <sup>(7)</sup> admitted that lightness is the key to a number of problem eradication. Unfortunately, his successors in Stuttgart did not bother and their future 'ecological' city car <sup>(8)</sup> is grazing the 1-tonne limit, putting the alibi-effort back to square one. Typically, the new MERCEDES 180 is 200 kg heavier than the old 'baby'-Benz, model 190.

Nobody asks to turn the wheel of time back, but we urge automotive technocrats to study nature more intimately. E.g. insects offer valuable insights for improving vehicle structures. Since aviation emulates insects, this technology certainly holds opportunities for saving weight. Luckily, we don't have to make our systems redundant with double/treble safeties. On the contrary, we on the ground can go the other way by adhering, whenever possible, to the weightsaving principle illustrated in Fig. 3 and termed:

" ONE COMPONENT - SEVERAL FUNCTIONS "

**FIG. 3**

When I developed this approach in a paper presented at a Korean car manufacturer's seminar in Seoul (9), it was met with reluctance and the murmurings went round in small circles. These rounds reflected the seating arrangements for members of distinct engineering sub-sections. Their heads would eventually voice their concern. True, in their hierarchy, each sub-section deals with a specific sub-assembly of the car. Such compartmented approaches are never conducive to wholistic thinking. E.g. chassis specialists jealously refuse to yield terrain to tank specialists and vice-versa. The lot seems cemented by rigid organigrams and section-heads who fear for their position.

So, meanwhile 'design-by-sub-delegation' products keep putting on fat. The average weight of 23 of the most popular cars in the early 60's was 510 kg. Today, this is doubled and cars in the 1-tonne-mass-market range possess e.g. servo-motors, whose nominal ratings surpass the tractive power needed for moving solar-electric cars.

AUDI nowadays try to counteract obesity by prescribing aluminium instead of steel for their top range. Ecology remains vile, as long as the car concept has not been fully re-appraised and the product still scales around 1,6 tonnes, with lots of grey energy wasted by the aluminium.

As the examples show, the answer is not wonder materials. Sustainable personal transport must be re-examined from scratch. The diet must not be limited to resources, but must also involve minds and hearts. The main question is: How much energy do we actually need to go from A to B ? Different people give different answers. Henry Ford is reputed to have said: "save shoes, buy cars". While Ho Chi Minh was convinced: "one bicycle and a bowl of rice is enough!" Compare the values in Fig.4:

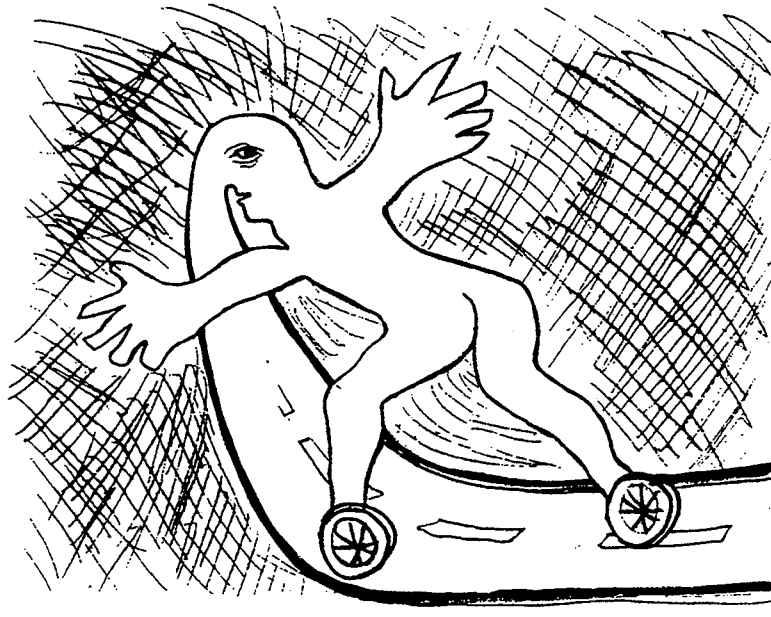
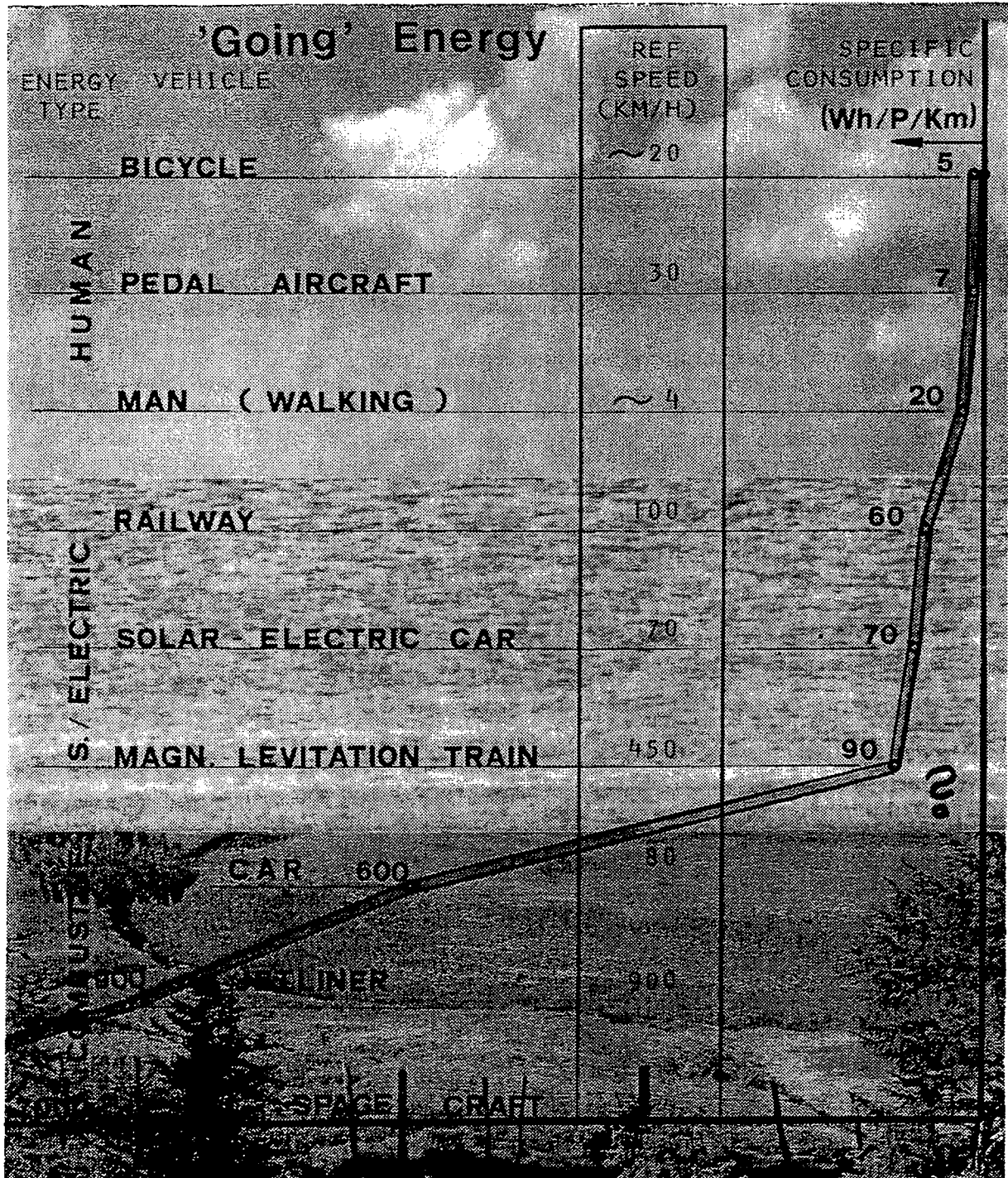


FIG. 4



From Fig. 4, we may easily detect that there can be NO GLOBAL specification for velomobiles. Too much depends on cultural and climatic backgrounds, historic acceptance and topographic and buying power factors. I therefore want Table (I) to be understood as a vernacular example:

**Table (I) SAMPLE VELOMOBILE SPECIFICATIONS**

	human powered only:		human + assist powered:	
vehicle mass	20	kg*	35	kg*
length overall	200	cm	220	cm
width	75	cm	80	cm
height	approx. 110	cm*	155	cm*
eye level	min. 135	cm*	138	cm*
body/cockpit top	open		closed	
crash helmet(compulsion)	yes		( ? )	
tractive wheels	1		1+	
differential	-		-	
total number of wheels	(2)	3	3	
wheel suspension	(yes)		yes	
fairing type	solid-soft		solid	
weather protection degree	85	%	100	%
payload, occupant(s)	75	kg	90	kg
payload, number of persons	1		1 + 1	child
payload, cargo	1	crate	15kg	crate
	or 15	kg	+ cargo 15	kg
<hr/>				
payload, total	90	kg	120	kg
total weight (laden)	110	kg	155	kg
<hr/>				
max. road speed	35	Km/h	50	Km/h
power assist	-		yes	
power assist, energy source	-		C.N.G / L.P.G	
			hydrocarbons	
			solar/electric	
power assist, max. boost power	-		440 W	

\* may be reduced in future, as motorcar predominance recedes

## 2.4 Personal HPV Project

My goals for 'THE UNWINDER' design are situated somewhere between the left and right column of the aforementioned specifications, as I try to wrap two functions in one:

- ultralight 3-wheeled commuter, basic pedal-powered model
- upgradable by assist-power kit, without modifying frame

The latter requires drive integration to a wheel. Since this adds mass to the unsprung parts of the vehicle, the maximum speed is limited to 40 Km/h, as a small compromise. Anyhow, no sports ambitions are claimed, other than the abolition of the motorist's rush to the expensive and superfluous fitness studio.

Since NASA's bio-data<sup>(10)</sup> suggest healthy men can sustain 220 W of pedal power input during 30 minutes, this means 8-10 flat commuting Km. Those who feel the road to be too hilly, or wish to tackle longer distances, or have an urge to peak constantly at 40 Km/h, should opt for hybrid power, by relying on a humble 300 W (0,4 HP) of assist. This is kept purposely low and sourced from a 4-stroke combustion engine, because:

- present battery systems would overload the concept
- 2-strokers of this size are still hyper-polluting
- physical exercise benefits would be nullified

For gearing and weight reasons I chose three 20-inch (510 mm O.D.) disc-wheels, having a (conservative) rolling-resistance coefficient of 0,007. The discomfort of high-pressure tires are compensated by a longstroked suspension system. As for mechanical efficiencies, it may be assumed that the chain drive yields 95 %, while the friction-transmitted assist drive is no better than 80 %. So, on average a combined coefficient of 0,89 may be realistic.

In order to check concrete design possibilities, it is useful, at this juncture, to apply the already known values to the general vehicle power formula:

$$P = \frac{1}{\eta_m} \times \Sigma \text{ Drag} \times V$$

$$P = \frac{1}{\eta_m} \times (D_r + D_a) \times V$$

$$P = \frac{1}{\eta_m} \times \left( m \times g \times C_r + \rho \times C_w \times A \times \frac{V^2}{2} \right) \times V$$

wherein:

P = input power, in Watt (W)

$\eta_m$  = mechanical efficiency (coeff.)

$D_r$  = rolling drag in Newton (N)

$D_a$  = aerodynamic drag in Newton (N)

V = rel. speed of vehicle in m/sec

m = tot. mass of vehicle in kg

g = earth gravitation ( $\text{m/sec}^2$ )

$C_r$  = rolling resistance (coeff.)

$\rho$  = density of air in  $\text{kg/m}^3$

$C_w$  = aerodynamic drag (coeff.)

A = real frontal area in  $\text{m}^2$

For a flat, hardsurfaced road, in windstill conditions, the vehicle driven at 40 Km/h = 11,111 m/sec, we get:

$$\begin{aligned} 220 + 300 &= \frac{1}{0,89} \left( 9,81m \times 0,007 + 1,29 C_w \times A \times \frac{11,1^2}{2} \right) \times 11,1 \\ 520 &= 12,484 ( 0,06867m + 79,63 C_w \times A ) \\ 41,652 &= 0,06867 m + 79,63 C_w A \\ 0,523 &= 0,0008623 m + C_w A \\ 0,523 - 0,0008623 m &= C_w \times A \end{aligned}$$

an equation with 3 unknowns ( m in kg,  $C_w$  coefficient, A in  $\text{m}^2$  ) !

To unravel the physical size of the projected vehicle, we now pick a few of the most likely achievable mass values ( m fully laden ). Then, based on those figures, we calculate the corresponding expression:

$$\underline{C_w \times A} \quad (\text{in } \text{m}^2)$$

This stands for the aerodynamically 'effective' vehicle profile. For these virtual surfaces, we now select cautiously a set of aerodynamic drag coefficients, say between 0,6 and 0,3 . In dividing the 'effective' vehicle areas by the chosen form-coefficients, we finally obtain the maximum profiles, which in reality the designer may not surpass ( for a given power input ). These figures are handy for consultation in Table (II), whenever design-alternatives are studied on the drawing board:

Table (II) 'Design-Aid' Chart

empty mass	m ( kg ) payload mass	total mass (laden)	$C_w \times A$ ( m <sup>2</sup> ) 'effective' surface	$C_w$ ( - ) aerodynamic drag coeff	A ( m <sup>2</sup> ) real surface (permissible)
17	110	127	0,4135	0,6	0,6892
				0,5	0,8270
				0,4	1,0338
				0,3	1,3783
20	110	130	0,4109	0,6	0,6848
				0,5	0,8218
				0,4	1,0273
				0,3	1,3697
23	110	133	0,4083	0,6	0,6805
				0,5	0,8166
				0,4	1,0208
				0,3	1,3610
26	110	136	0,4057	0,6	0,6762
				0,5	0,8114
				0,4	1,0143
				0,3	1,3523
29	110	139	0,4031	0,6	0,6718
				0,5	0,8062
				0,4	1,0078
				0,3	1,3437
32	110	142	0,4006	0,6	0,6677
				0,5	0,8012
				0,4	1,0015
				0,3	1,3353
35	110	145	0,3980	0,6	0,6633
				0,5	0,7960
				0,4	0,9950
				0,3	1,3267

Should the vehicle eventually better these values, positive side-effects will ensue:

for lower  $C_w$  = better accelerative/speed potential  
 for lower A = better accelerative/speed potential  
 for lower m = better hillclimbing aptitude

Or, conversely, at unchanged performances (40Km/h max, etc), the required power will be reduced: a boon to wobbly knees, mother nature's knocked-about resources and to our ecosphere.

Adhering to this spirit of frugality, the project's design efforts seem to confirm that:

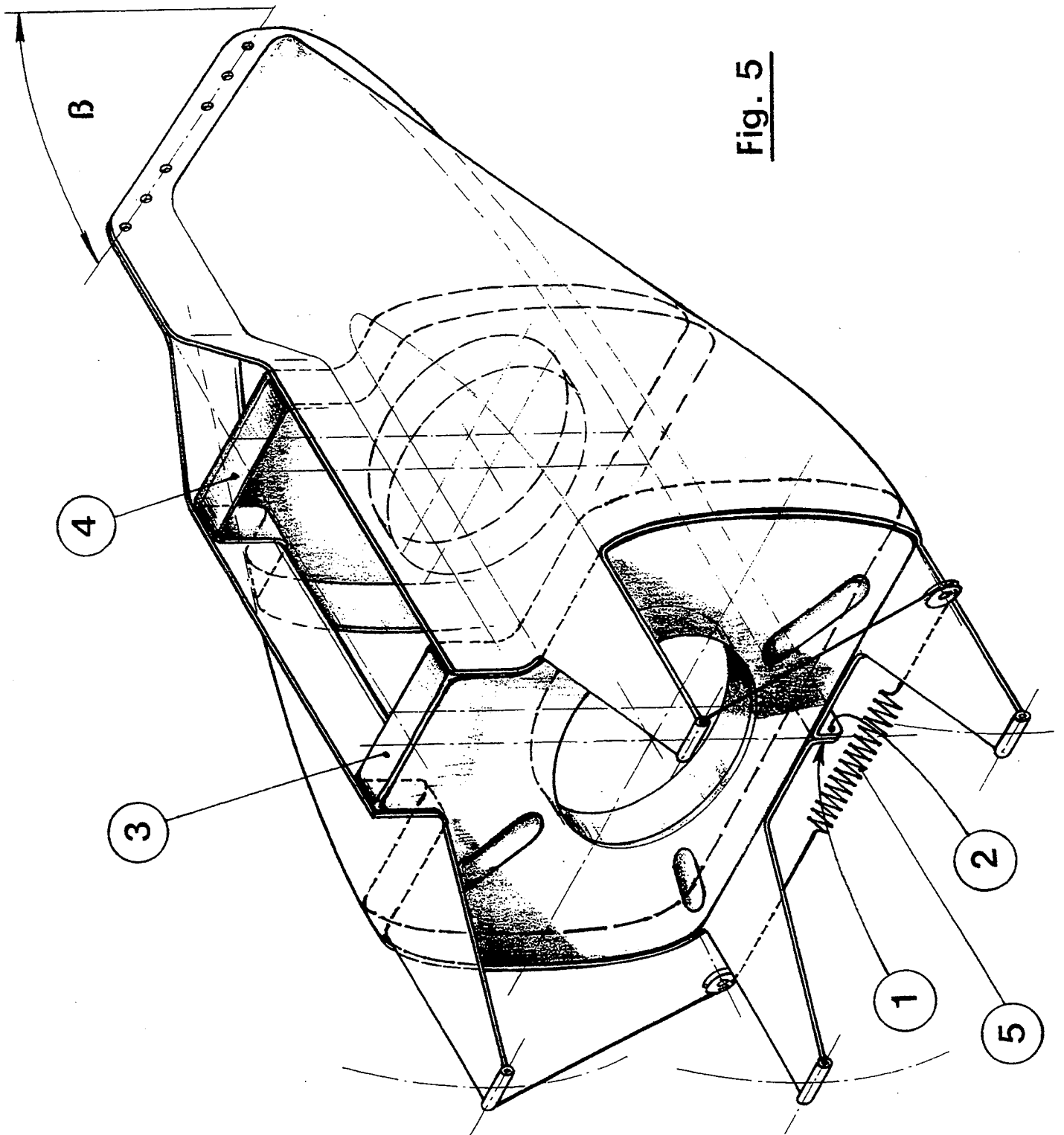
- vehicle width may be kept below 74 cm
- overall length can be no greater than 198 cm
- the mass could be reduced, down to  $18 + 5 = 23$  kg
- today traffic requires an eye-level of 140 cm ( so no flag ! ) with a seat-level of 60 cm, a backrest inclination of approx.  $66^{\circ}$  from horizontal results
- etc,
- as summed up in

Table (III)

**'THE UNWINDER' HPV-PROJECT Specifications:**

vehicle mass (incl. power kit)	18 + 5 = 23 kg
length overall	198 cm
width	74 cm
height	120 cm
eye level	140 cm
cockpit top	open
crash helmet compulsion	yes
tractive wheels	1
differential	-
total number of wheels	3
wheel suspension	yes
fairing type	partial, solid/soft
weather protection	85 %
<hr/>	
payload, occupant(s)	90 kg
payload, number of persons	1 + 1 child
payload, crate carried	15 kg
goods carried	5 kg
<hr/>	
total payload	110 kg
total weight (laden)	133 kg
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max. road speed	40 Km/h
power assist (kit)	( +5 kg )
power assist, energy source	hydrocarbons
power assist, max. boost power	300 W

This tall design height moves the centre of gravity to about 90 cm. Since the track width can only be 68 cm, at the most, the question of roll-stability (under severe cornering) arises. An un-suspended tripod frame experiences maximum strain in this situation. I therefore tend to incorporate two functions in the same frame-elements, namely that of leaning capability and soft springing, as seen in the perspective view of Fig.5.



Legend to Fig. 5

- [1] L.H. Half Shell
- = Monocoque
- [2] R.H. Half Shell
- [3] Stern Bulkhead
- [4] Seat Bulkhead
- [5] Traction Spring (2CV suspension)

$\beta = 90^\circ$  - head tube angle

The monocoque frame is formed by two symmetrical half-shells, held together by flanges skirting the vertical plane. The stern is open-ended and projects horizontally and organically into four thin, flipper-shaped, trailing arms. They assure parallelity and part of the suspension forces for the two rear wheels. The balance is furnished by a 'free-floating' spring-and-cable system, similar to that of the CITROEN 2 CV.

The frame is balalaika-shaped and can be loaded from above and behind. It gets its torsional stiffness from bulkheads, one situated under the seat and the other closing-off the stern. The latter has fasteners to hold a crate crosswise between the 'flippers'. The tip of the frame is bow-shaped and carries two sets of 3 holes with multiple functions:

- first,            they are attachment points for two leaf-springs ( similar to quarter-elliptic car springs ), which suspend the front wheel
- second,        they carry two ball-joints acting as king-pin (or headtube) substitutes.
- third,          they function as a 3-staged bottom-bracket adjustment for a wide range of rider anatomies, as per vehicle elevation drawing Fig. 6:

To avoid the headaches of a long rear transmission, front-wheel drive was adopted, using a standard 1/2-inch (12,7 mm) chain of normal length, disposed almost vertically above the front wheel. This forms a medium wheelbase m.w.b., in HPV terms. Rear-wheel steering was never considered. So, two front steering options had to be studied:

- one with a twisting chain (from a fixed bottom-bracket)
- the other one running a straight chain (from a swaying bracket)

The latter stands for safe derailleur gear-changing and chain longevity. Yet, the legs have to follow the azimuthal steering movements. This is possible with a  $66^\circ$  backrest, provided a shallow head-tube angle of around  $45^\circ$  places the steering axis close to the hip joints and the neck support of the rider.

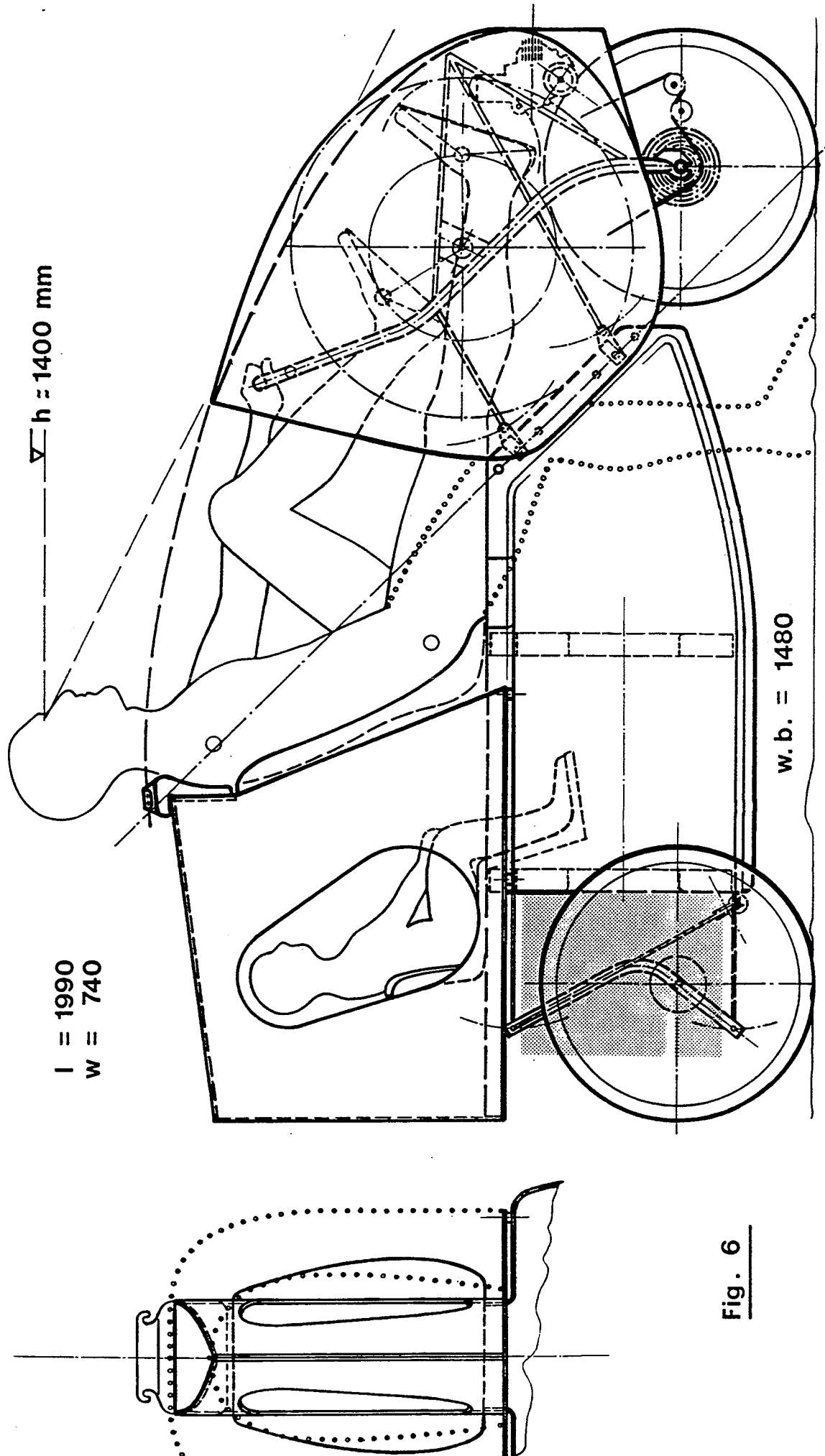


Fig. 6

The backrest is propped-up by two near-parallel webs, converging at the vehicle end. The centre of these webs has an oblong cut-out, so that a child seat can be inserted, with feet safely accommodated in the trunk. Clear of the 'flipper' movements is a trapeze-shaped platform, attached to the underside of the webs.

Up front, chopper-style handlebars rise from fork, via bottom-bracket to the horizontally outstretched arms of the rider. The bars support a light, bulbous nose fairing. While this fairing protects hands and legs, there is a 65 cm gap between it and the neck support. This may be bridged by one of two possible cover solutions:

- a thin fabric unrolls from the fairing and is held clear of 'pumping' knees by two telescopic rods, like extended radio antennas. Slots provide openings for giving hand-signals.
- or
- a similar fabric unfolds, but is held by a number of inflatable air-chambers, replacing the rods.

Should a child, or groceries be carried behind the rider, these may also be weather-protected by an inflatable, tapered tunnel cover, featuring transparent inserts for visibility.

Finally, a word on the optional assist kit. Between the tip of the fairing and the front-wheel top, there is enough space for articulating a small cc engine, complete with a 1/2 litre fuel tank and a friction pulley, similar to the VELOSOLEX. However only about 1/3 of its power are needed. A desirable extra is a twin gear-ratio: A low one for hill-climbing and one for maintaining 40 Km/h.

#### 2.4.1 Conditio 'sine-qua-non'

Within any wholistic problem approach, design specifications must contain provisions that velomobiles can **NOT** be moved with assist power **ALONE** ! Psychologists know the reason why. In terms of good manners at the family table, our password must always remain:

" NO POTATOES ---> NO DESSERT "

I therefore propose a tamperproof link between pedal and assist power, so that the rider gets its benefit only by first flexing his muscles.

There is no need for expensive and scientifically accurate governors. A twist of fuzzy logic will do:

- either - a chain tensioner working on motor controls
- or - a cranked dynamo supplying spark plug current

I believe assist power should not represent more than 100 - 150 % of human input, but this is debatable. Certain is that mopeds contribute 0 % human power and are as such misnomers. Mixed powered vehicles whose laden weight approach 250 kg gradually reduce muscle power to a drop in the ocean.

#### 2.4.2 Building is Better than Bragging

Sceptics may carp at my presentation of dry theories and may ask:

'Why lectured, but not manufactured ?'

The reasons have been analysed and published in SCIENTIFIC AMERICAN, by a group of HPV-visionaries <sup>(11)</sup>:

.... "to produce a practical vehicle of this kind would require an investment and an engineering effort comparable to that made in producing a new automobile....."

### 3. SEMI - FICTION

#### 3.1 Future Now ( an AHPV from USA )

One who outdid science-fiction by abandoning his TV chair is John Tetz, a 61 year old American member of the IHPVA. Let us call him 'Mr.Average Fit'.

John converted his 12 kg recumbent bicycle, a production LIGHTNING P-38, to an assisted human powered vehicle (AHPV). In standard form, the P-38 offers nimble progress in commuting and in touring conditions. For climbing steep hills, he fitted a 21 cc Mc Culloch garden appliance engine, rated at 150 W, or 0,2 HP. The engine plus fuel increased the mass by an extra 3 kg only ! Its location is between seat and rear wheel, so that direct hand-control makes cables superfluous.

On a trip from Florida to New Jersey he averaged 1300 mpg, close to 0,175 l/100 Km, or 571 Km/l ! The engine was in operation during 15 % of the time, which is more than usual, because he took 21 kg of luggage to the Blue Ridge Mountains. I.e. the assist kit turned the vehicle into a 15 kg partially-faired prototype of truly exemplary efficiency:

- on one hand, fuel efficiency works off the biking efficiency ( by not requiring any assist, except on steeper hills )
- on the other hand, biking efficiency is improved through the avoidance of muscle fatigue ( via occasional power assist ).

Tetz drove this lesson home in 1991, without waiting for others to act, without clamouring first for more exotic materials and without expecting initial subsidies. He relied on commercially available hardware. So, one may ask, how is industry reacting ? How does man want to spend his fortunes ? When do politicians wake up to reality ?

#### 3.2 Future for All

Let us not despair, looking into the crystal ball, I can see Moulton wheels on the move, lots of changes and I can only marvel and exhort:

"Dear John !

Why don't you finally accept that seat on the board of GENERAL MOTORS CORPORATION, offered to you in a moment of panic ? Or, are you really forsaking the battleground for a sulky retreat to the Gobi Desert, watching the Paris-Peking Rally<sup>(12)</sup> scream past and wondering which way the kicks of the Devil will swing next ?

No, Dear John, we hope you will face-up and convince the responsible majority of GM's board members:

- first, to reduce board member emoluments and all executive salaries to the levels enjoyed by their Asian counterparts and to pool the difference
- second, to earmark 10 % of all budgeted PR- and corporate-advertising funds for this pool
- third, to perceive 10 US \$ from the recycling-levy per car sold, in order to maintain this pool

Blessed by such windfalls, GM engineers from the greenest corners of this greying empire would solve, one by one, all pending issues exposed scrupulously by the IHPVA over the past 18 years, under the sharp analytical quill of M.I.T. professor Dr. David Gordon Wilson<sup>(13)</sup>.

You, Dear John, will get your hands greasy again. You might review your priorities and you may:

- evaluate slide-in, clip-on, or bayonet-type of quick-fastening methods for the assist engine ( left at home for flat runs )
- try to increase your presently modest weather protection on your two wheeler

- want to sound out the fairing size limits, up to which two wheel configurations may safely be retained
  - investigate different positions of engine/flywheel/shaft drive- elements, in order to use their gyroscopic effects for better low speed/cross-wind stability of two wheeled recumbents
  - experiment, together with Swiss watch technicians, on new micro-electronic and micro-mechanic applications for de-toxing midget 2-stroke engines with novel fuel injectors
  - etc., etc.,
- for which, Dear John, we wish you the best of luck !"

## 4. HUMANITIES

### 4.1 Tomorrow's Gap Fillers

Let us look at the power formula again, but from a more human angle:

$$\text{power demand} = \frac{\text{vehicle mass, vehicle comfort, transport functions}}{\text{overall vehicle efficiency}}$$

Now, if we are to win motorists for a softer mobility, we may never accomplish this with record-breaking vehicles alone, no matter how super-efficient VECTORS, GOLD RUSHES, BEANS, WIND- and other CHEETAHS were in recent years. They don't satisfy the last 2 factors quoted in the numerator.

Velomobiles wisely compromise by offering a modicum of comfort. But they must also improve progress uphill, as well as fluidity at traffic lights. We must also cater for the 'not-so-fit' and for the low budget commuters, if we are to make inroads. Is there really a lack of money to accomplish this ?

### 4.2 The Dearth of Things

Germans e.g. spent in 1992 some 1880 Mio DM on car advertising<sup>(14)</sup> which is roughly 1175 Mio US \$, in order to choose amongst 3,9 Mio new cars. If we multiply this national publicity outlay with world production of around 55 Mio cars, we get the mind-boggling sum of 16'500'000'000 US \$.

Now, this figure is barely equalled by the Gross National Product (GNP) of 24 of the poorest nations of Asia and Africa, put together. There the cost of a bicycle corresponds to about 1/4 to 1/3 of what the world spends every year on car publicity per unit produced. It is also there that the bulk of the world's 90 Mio bicycles per year are produced, sold and used.

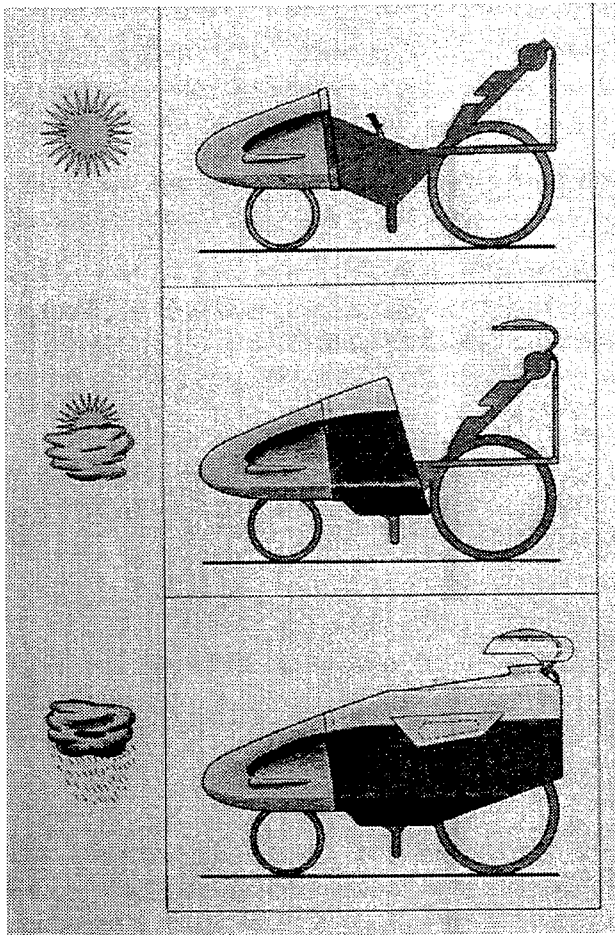
They only need a few Cents per bike for publicity. Bicycles apparently have intrinsic qualities that speak and sell for themselves. Will this reputedly most energy-efficient transport tool in the future tip the balance towards a cleaner mobility, world-wide ?

Unfortunately, the opposite is true, since the Third World is emulating Western automotive sophistication:

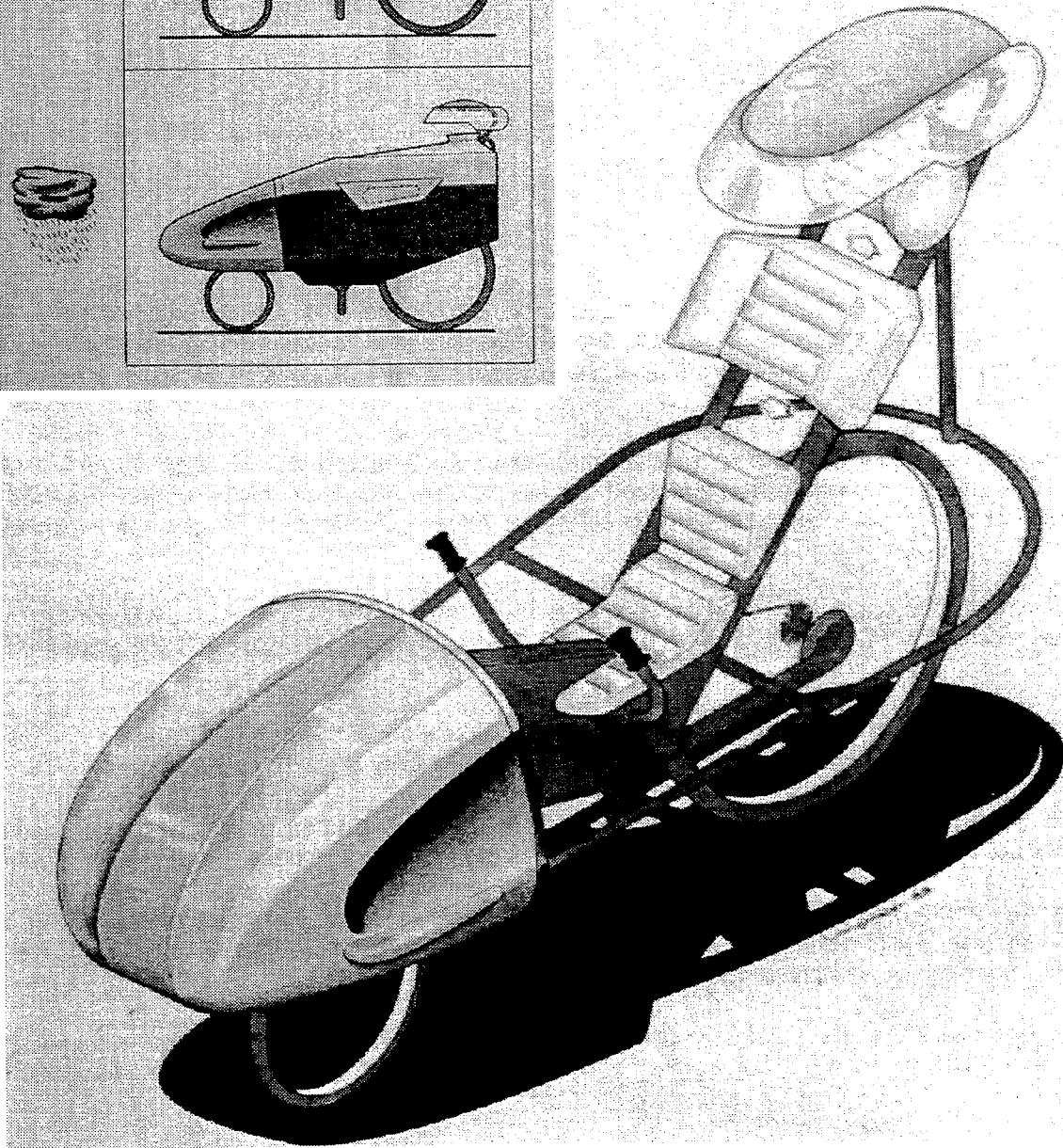
China has begun to produce cars for her nomenclatura. In the southern capital of Canton with 6 Mio inhabitants, there are now a mere 100'000 registred cars, versus 3 Mio bicycles. As of June 1993 bicycles are banned from the large thoroughfares, since they allegedly obstruct the free flow of cars.

In Indonesia, Jakarta's Police has ordered 10'000 pedicabs to be thrown into the sea, to make way for modern diesel taxicabs.

Since we are being emulated, it is **our duty** to make a courageous step in the right direction. Let us perceive in time the unique opportunities laying idle between Michaulines and Limousines, before someone has to pull the emergency chain to stop populous peoples republics from petrol-polluting their proletariat !



*My dream velomobile can be modified for any kind of weather.*



### 4.3 Spiritual Infrastructures

Some of my fellow-speakers will have dealt with physical infrastructures.

Before any hopes for a widespread diffusion of such vehicles can be entertained, users will have to mend their 'gasoline-alley' perception of things. Sadly enough, unless proof to the contrary descends from outer space, man is probably the only higher creature, whose guts are inexplicably disconnected from his brains..... if any.

Otherwise the following car advertisements would never have seen the light of the day and would not tempt incumbent mobility seekers with ecologic misbehaviour against their own species ( as illustrated by a series of English-subtitled slides ).

Humanity needs a few more shocks on the scale of Chernobyl, before grasping how vain it is to talk about human rights, without at the same time implying ecological rights and obligations.

#### 4.3.1 The 'Human Rights Plus' Model

Indeed, why should we have more rights to despoil our space-ship, than the Third World ? Since the Human Rights Declaration sees us as equals, it is time to extend the spirit of that letter to also jointly account for this ecosphere.

- How can such an accountability model work ?
- How can it simultaneously address our long-neglected socio-economic responsibilities towards the Third World ?

#### 4.3.2 Model Mechanism

High-tech surveillance collects climatic data over a closely-knit 3-D network. International scientists extrapolate and correct annually a permissible global pollution level. Corresponding loads are expressed in equivalent resource/oil volumes. This ceiling is then divided by world population, to arrive at an equal ( per-capita) ration of 'spoils'.

These 'spoils' are issued in the form of internationally negotiable POLLUTION DRAWING RIGHTS (PDRs). The original PDR holder, or his national exchange bank as a trustee, may then sell the PDR at any international stock exchange. The price obtainable will be subject to the law of offer and demand, as in any free trade system.

Should a nation, or organisation, have the urge to produce more Formula-1, or Paris-Dakar champions, they will have to purchase PDRs, equivalent to the required extra oil tonnage. Upper Volta may have such extra passports to boundless liberty.

So, without GATT rounds, without ideological indoctrination, without terrorist blackmail by the 'have-nots', hunger in the South ends. Bank credits shoved down the throats of the Third World stop.

While the underdeveloped nations never had a chance to influence world market prices of their commodities, it is only fair that they now will be empowered to assess the price for our hyper-mobility wims. Such spiritual infrastructures will be the forerunner of a cleaner and juster world. Overthere, Ho Chi Minh's spoked mules might mature into hybrid-powered transportation tools. While, overhere, mobility seekers will discover that beyond selfish and multi-valved egos, there is health and unsuspected satisfaction in retiring turbo-charged cylinders, by swingingly ventilating musty socks over green lanes.

I am therefore submitting this 'human rights plus' model for debate, hoping to have intimated democratic ways and means to defuse the currently ticking asphyxiation bomb, in spite of the much vaunted automotive high-tech progress.

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in 1907 per car 1 set of tires, good for 16'000 Km  
in 1992 per car 100 tires + 7000 litres at 3 DM (44 l/100 Km)  
in 1992 per car team 40 groundsupportcrew+mechanics in observ.plane  
in 1992 per car team 6-wheeled all-terrain supply trucks  
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VOLKSWAGEN GROUP       158,6  
MERCEDES-BENZ           158  
BMW                       100  
FORD GERMANY           80 Mio DM  
Source: AUTO BILD, Axel Springer Verlag AG, D-2000 Hamburg 36

## HPV – VERKEHRSMITTEL DER ZUKUNFT?

*von Werner Stiffel,  
Fahrrad-Entwicklungsbureau, Karlsruhe*

Man kann das Objekt unseres gemeinsamen Interesses, das HPV oder muskelkraftbetriebene Fahrzeug, unter sehr unterschiedlichen Gesichtspunkten sehen, z. B. als schnelles Sportgerät, als interessantes High-Tec-Spielzeug, als Freizeitfahrzeug; ich möchte es hier vor allem im Hinblick auf seine Eignung als umweltfreundliches Verkehrsmittel betrachten.

HPVs können vor allem in folgenden Bereichen eingesetzt werden:

1. Im Sport, um Rennen und Rekorde zu fahren
2. Im Freizeitbereich, um kleine und große Touren zu machen
3. Auf dem Weg zu Arbeit, Schule, Einkauf, Kindergarten usw. bei Entfernungen über ca. 10 km
4. Wie 3, aber auf Strecken bis 10 km, vor allem in der Stadt

*Zu 1:* Das ist für viele von uns offenbar das reizvollste Gebiet und als Werbeträger für die HPV-Idee spielen Rennen eine große Rolle. Hier beginnen sich Kurzliegeräder mit tiefliegendem Sitz bis herab zu ca. 150 mm durchzusetzen. Das Vorderrad dreht sich zwischen den Beinen und ist durch die unmittelbar daran vorbeilaufende Kette auf einen Lenkeinschlag auf ca. + 5 Grad beschränkt.

Vielleicht steigen irgendwann die meisten Rennsportler auf HPVs um, das wäre für die HPV-Pioniere eine enorme Genugtung, für die Umwelt allerdings praktisch ohne Bedeutung.

*Zu 2:* Für Touren wird bisher vor allem wegen seines hervorragenden Sitzkomforts das Langliegerad eingesetzt. Für mehr geschwindigkeitsorientierte Fahrer ist sicher auch ein gemäßigtes "Kurzes" geeignet. Das Dreirad bietet hier den Vorteil der größeren Gepäcktransportkapazität. Die für Touren äußerst wünschenswerte Wetterschutzverkleidung bedingt beim Dreirad praktisch keine Seitenwindempfindlichkeit. Mehr zu Dreirädern wird bei dieser Veranstaltung an anderer Stelle gesagt.

*Zu 3:* Auch hier gibt es sicher für HPV Einsatzbereiche, allerdings fährt bisher nur 1% der Radfahrer regelmäßig solche Entfernungen und reine HPV werden zunehmend in Konkurrenz zu elektrisch angetriebenen Klein-PKW stehen. Hier spielt ein möglichst niedriger Fahrwiderstand eine Rolle, der sich nur mit einer strömungsgünstigen Verkleidung erreichen läßt. Diese wiederum ist so seitenwindempfindlich, daß sich für Mister "Every Man" das Dreirad geradezu anbietet.

Zu 4: Hier liegt nach meiner Überzeugung die Domäne für HPVs. Nach Untersuchungen des ADFC liegen 40% der Fahrten unter 3 km. In der Stadt ist die Belastung der Menschen durch den Autoverkehr mit Lärm, Abgasen, Sommersmog, Unfallgefahr und Hektik am größten. Wenn die konventionellen Autos permanent im Stau steckenbleiben, durch den Gesetzgeber auf 30 km/h gedrosselt und mit immer höheren Kosten belastet werden, dann liegt hier ein Markt für Millionen von Fahrzeugen auf der ganzen Welt. Auf diesen Zeitpunkt sollten wir schon jetzt hinarbeiten.

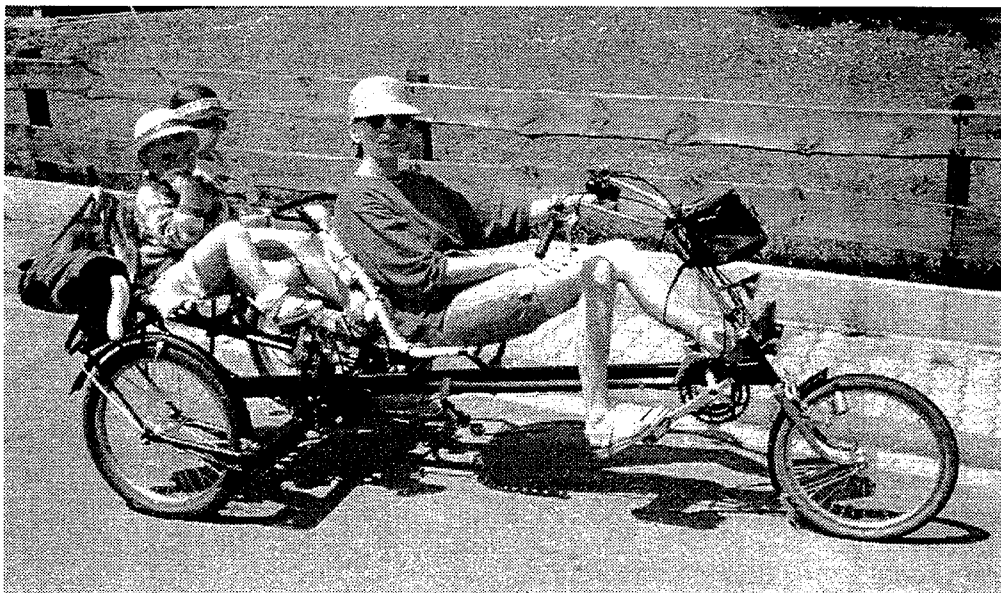
Ein Problem, das immer wieder zu langen Diskussionen führt, liegt darin, daß die Bedingungen, unter denen ein Fahrzeug benützt wird, sehr unterschiedlich sein können. Für einen jungen "Bürokraten", der körperliche Anstrengung mag, 10 km bergige Strecke und eine Duschmöglichkeit am Arbeitsplatz hat, ist vielleicht ein Rennrad das ideale Alltagsgefährt. Für eine ältere Frau, die 3 km zur Arbeit hat und die auf dem Nachhauseweg gern den Einkauf erledigt, sieht das alles anders aus.

Liegeräder werden meist von einem einzigen Menschen gebaut, der leicht seine "Betriebsverhältnisse" als allgemein gegeben ansieht. Er tut deshalb gut daran, aufmerksam auf alles zu hören, was die Leute nach dem Fahren auf seinem Rad sagen.

Welche Anforderungen waren nun an ein für den Stadtverkehr geeignetes HP für jedermann zu stellen?

1. Weitgehender Wetterschutz, wobei die Verkleidung die Seitenwindempfindlichkeit nicht erhöhen darf und beim häufigen Aus- und Einsteigen nicht stört. Außerdem soll sie Schieben und Tragen möglichst nicht beeinträchtigen, möglichst leicht sein, keine Fahrgeräusche verursachen und die Wartung nicht erschweren. Außerdem sollte sie für lange Schönwetterperioden leicht demontierbar oder zumindest im Umfang anpaßbar sein.
2. Gute Sichtbarkeit im Verkehr,
3. Kommunikationsmöglichkeiten des Fahrers mit der Umwelt nicht eingeschränkt,
4. Gute Übersicht für den Fahrer, auch bei Nacht, Regen und Gegenverkehr,
5. Gesamtbreite möglichst schmal fürs "Durchschlängeln,"
6. Guter, dem Auto vergleichbarer Sitzkomfort. Wir wollen Autofahrer und nicht engagierte Radfahrer zum Umsteigen bringen,
7. Gesamtlänge möglichst wenig über dem Normalrad,

8. Bremsvermögen heutigen KFZ angepaßt,
9. Transport über Treppen durch eine Person sollte möglich sein,
10. Verletzungsgefahr bei Stürzen und Unfällen möglichst geringer als beim Normalrad,
11. Weitgehende Wartungsfreiheit,
12. Kette und sonstige "Schmutzquellen" so verkleidet, daß man unbesorgt in guten Kleidern fahren kann,
13. Mindestens eine Aktentasche muß regensicher und ohne zusätzliche Gummi usw. transportiert werden können,
14. Zwei große Handtaschen müssen zusätzlich untergebracht werden können,
15. Ein bis zwei Kleinkinder sollten mitgenommen werden können,
16. Fahreigenschaften möglichst ähnlich dem normalen Fahrrad,
17. Bei sehr bergigem Gelände und für ältere Menschen ist sicher auch eine leichte Motorunterstützung sinnvoll, vielleicht 200 Watt und eine Batteriesatz, der das Fahrrad in seinem Grundcharakter erhält,
18. Niedriges Gewicht, um Beschleunigen und Bergfahren zu erleichtern,



*Ein wirkliches Alltags-HPV, damit werden 2 Kinder täglich über 13% Steigung in den Kindergarten gebracht. Beide Kinder können mitreden.*

Allerdings wird die Bedeutung des Fahrzeuggewichts meist maßlos überschätzt. 1 kg erhöht den Fahrwiderstand um ca. 0,15 (!), an 5% Steigung um 1% (wer spürt beim Fahren diesen Unterschied?). Die Überbewertung des Gewichts kommt wohl daher, da jeder sein Fahrrad immer mal wieder trägt, und da macht 1 kg eben 7 – 10% Unterschied!

Welche Fahrzeugkonzeption käme nun wohl für diese Anforderungen in Frage?

Das Dreirad ist hervorragend zum Transport hoher Lasten, zum Anbau einer strömungsgünstigen Vollverkleidung für lange Strecken und als Seniorenfahrzeug geeignet. Für den innerstädtischen Verkehr bietet es bei niedrigem Sitz wenig Übersicht, bei hohem Sitz ist es etwas kippanfällig. Es ist schwieriger zu transportieren, über Treppen zu tragen, teurer, unbeweglicher und durch das höhere Gewicht nach den zahlreichen Stops in der Stadt schlechter zu beschleunigen als ein Einspurer.

Das "kurze" Liegerad (Tretlager vor dem Vorderrad) wird in Holland viel gefahren und könnte vielleicht zu einem guten Stadtfahrzeug weiter entwickelt werden. In seiner jetzigen Form hat es z.T. gewöhnungsbedürftige Fahreigenschaften, eine ungünstige Sitzposition durch zu hohes Tretlager und erheblich schlechteres Bremsvermögen. Außerdem wird die Hauptbremskraft wie beim Normalrad vom Vorderrad aufgebracht, bei dessen ersehentlichem Überbremsen der ungeübte Fahrer meist zu Boden geht.

Am ehesten können die oben genannten Anforderungen zur Zeit m. E. mit einem "langen" Liegezeirad (Tretlager hinter dem Vorderrad) erfüllt werden, das durch folgende Details gekennzeichnet ist:

1. Sitzhöhe ca. 650 mm, damit kann man mit einem leichtem Heben des Kopfes über die meisten Autos wegschauen und kommt trotzdem mit den Beinen noch gut auf den Boden,
2. Tretlager 200 mm tiefer als der Sitz ergibt eine bequeme Sitzhaltung,
3. Ein Sitz aus Rohrgestell mit Rolladengurt oder stabilem, luftdurchlässigem Stoff bespannt, mit leicht abgeknickter Lehne, (gegen "Katzenbuckel"), Lehneneigung einstellbar (z. B. flach für Touren, steil für die Stadt),
4. Indirekte Lenkung mit Hornlenker unter dem Sitz bringt minimale Verletzungsgefahr bei Unfällen, völlig entspannte Arme und die Möglichkeit, den Gabelwinkel für optimale Fahreigenschaften auszulegen,
5. Eine weiche Federung mit 120 mm Federweg für das Hinterrad läßt einen sanft über Straßenbahnschienen und niedrige Bordsteine gleiten, schont Nieren, Wirbelsäule, Rahmen und Gepäck und ermöglicht kleineres Hinterrad,

6. Räder mit 500 mm vorn und hinten ermöglichen eine Gesamtlänge von ca. 2,0 m und müssen durchaus keinen höheren Rollwiderstand haben,
7. Ein abschließbarer Kofferraum mit 25 l Inhalt nimmt Kleingepäck auf. In 2 Haken seitlich am Sitz können Einkaufstaschen eingehängt werden,
8. Mit wetterunabhängiger Trommelbremse vorn und Hydraulikbremse hinten ist das Bremsvermögen dank niedrigem Schwerpunkt und langem Radstand bis ca. 60% besser als beim Normalrad, und das ohne jede Überschlagsgefahr. Der Zug zur Vorderbremse ist 2mm stark, teflonbeschichtet, Seileinläufe durch Gummibälge gegen Eindringen von Schmutz und Wasser geschützt,
9. Ein Walzendynamo mit Fernschaltung für gefahrloses Einschalten während der Fahrt, oder noch besser ein Nabendynamo, falls erhältlich, und Batterieautomatik sorgt für sichere Beleuchtung, Kabelanschlüsse durch Auto-übliche Flachstecker, Kabel reißfest durch mitgeführte Stahllitze,
10. Dauergeschmierte Lager für Schwinge und Lenkgestänge sind wartungsfrei, alle anderen Lager abgedichtet und ebenfalls praktisch wartungsfrei,
11. Drei- bis Siebengang-Nabenschaltung ist fast wartungsfrei und auch im Stand schaltbar,
12. Für bergiges Gelände ist vorn ein Doppelblatt 53/32 montiert, Kettenlängenausgleich durch Mittelspanner, der Peitschen und Abspringen der Kette verhindert,
13. Die Kette ist gegenüber Hosenbein und Reifen völlig abgedeckt (klapperfreie Kunststoffteile oder beweglich gelagerte Polyamidrohre Dauerschmierung durch Filzblock mit kleinem Vorratsbehälter,
14. Spritzlappen am Vorderrad sehr effektiv, besonders beim Liegeradler, der direkt in der "Schußlinie" des Vorderrads sitzt,
15. Reifenbreite 47 mm, wird nicht so leicht von Straßenbahnschienen eingefangen,
16. Rahmen pulverbeschichtet,
17. Luftpumpe durch ein Blechprofilstück mit Inbusschraube gegen Diebstahl gesichert,
18. Schrauben nichtrostend, alle wichtigen Muttern Stopmuttern,

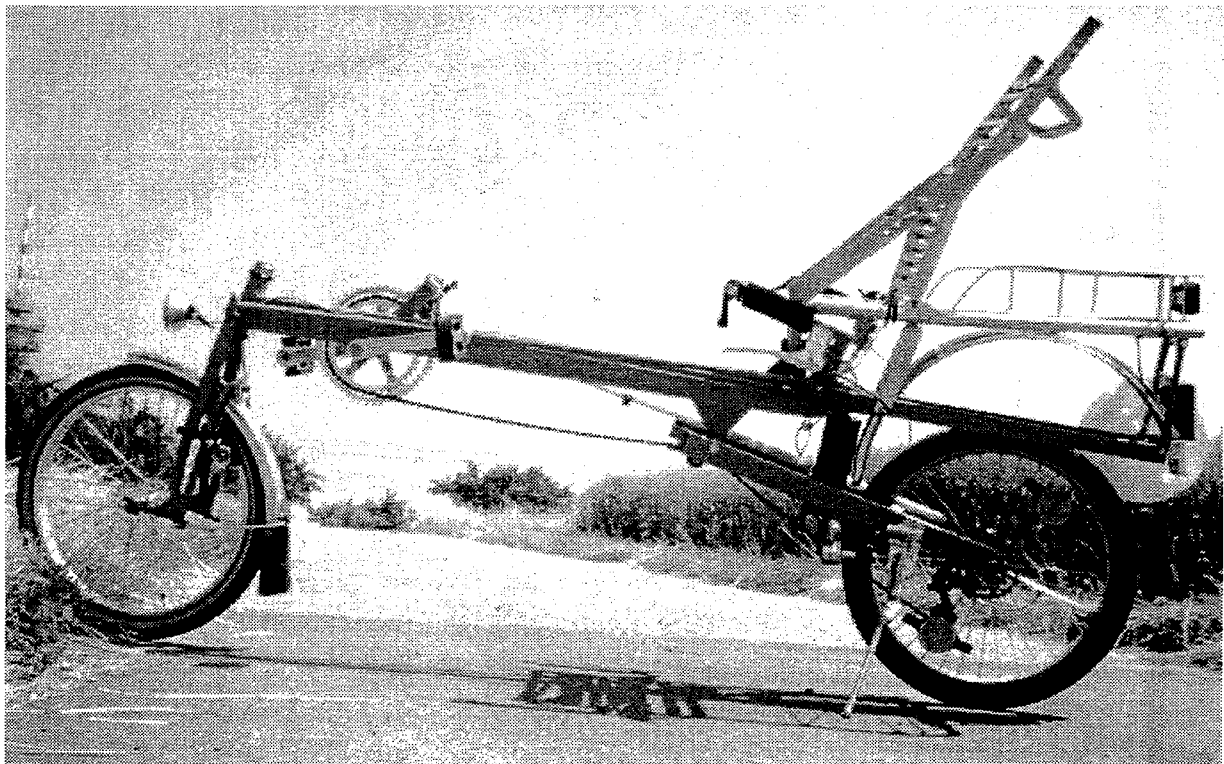
19. Für die Mitnahme von Kindern kann ein Anhänger angebracht werden,
20. Lenkübersetzung 1 : 1,5 und 70 Grad Einschlag für beste Wendigkeit und leichtes Rangieren,
21. Fersenhaltebügel für noch entspannteres Fahren,
22. Gepäck im gefederten Bereich,
23. Wetterschutz, m. E. ein immer noch sträflich von uns vernachlässigter Punkt. Neben der Gefährdung durch den motorisierten Straßenverkehr ist dies der wichtigste Hinderungsgrund für die Benutzung des Fahrrads auf dem Arbeitsweg. Vor einiger Zeit wurde die Meinung vertreten, Verkleidungen seien nicht erforderlich, da es ohnehin in Mitteleuropa nur 4% der Zeit regne. Ich meine, wenn jemand z. B. eine wichtige Besprechung mit seinem Chef hat und auf dem Weg dahin wird er durch und durch naß, dann genügt wahrscheinlich dieses eine Mal, um ihm das Fahrrad für immer zu verleiden.

Ein erster Versuch könnte z. B. so aussehen: Eine leichte Teilverkleidung aus beschichtetem Perlon, über Alurohre gespannt, nur 1,5 kg schwer, deren hinterer Teil zum Einsteigen beweglich ist und bei schönem Wetter nach vorn geklappt werden kann. Die Verkleidung hat eine sehr kleine Seitenfläche und bietet ca. 75% Wetterschutz. Sie ist auffällig gefärbt und zusammen mit Reflexstreifen sicher auffälliger als jeder Normalradfahrer. Der Luftwiderstand gegenüber einem Fahrer mit Poncho auf Normalrad ist um ca 30% verringert. Für ganz schlechtes Wetter könnte noch ein aufsteckbares Dach dazukommen. Dieses ist so weit vorgezogen, daß es einem nicht ins Gesicht regnet, es läßt aber freie Sicht nach vorn und vermeidet damit die noch bei keiner Kabine vollständig befriedigend gelösten Sichtprobleme bei Nacht, Regen und Gegenverkehr. Eine Weiterentwicklung, z. B. zu besserem Schutz nach der Seite ist erforderlich.

Ein Versuch, viele der obigen Anforderungen unter einen Hut zu bringen, ist die Solveig F4. Der Rahmen ist im Hinblick auf einfache Herstellung stark konstruiert. Auf einen großen Gepäckträger ist ein "Kofferraum" aus wasserdichtem Stoff aufgebaut, dessen Oberkante mit Klettband an der Lehne befestigt ist. Soll etwas besonders Sperriges transportiert werden, wird das Klettband gelöst, der Koffer zusammengefaltet und z. B. der Mineralwasserkasten oben drauf gestellt. Für Solveig F4 ist ein Bauplan, ein Bausatz oder der komplette Rahmen erhältlich.

Weitere Forschungs- und Entwicklungsarbeiten wären m.E. z.B. für folgende Probleme erforderlich:

*Solveig F4 mit und ohne Koffer-  
raum. Vollgefedert mit großem  
Gepäckträger und verstellbarer  
Lehnenneigung. Gesamtlänge:  
2 Meter.*



Verkleidungen für Zwei- und Dreiräder, die einen guten Wetterschutz bieten und niedrigen Cw-Wert haben. Cw 0,3 ist wünschenswert und erscheint erreichbar, beim Ein- und Aussteigen sollte nicht mehr Aufwand als das Öffnen einer Autotür sein und die Verkleidung sollte bei schönem Wetter weitgehend verstaut werden können. Viele Leute wollen nicht bei strahlendem Sonnenschein ein Dach über dem Kopf und eine Scheibe vor dem Gesicht haben.

Ein besonderes Problem bei Verkleidungen stellt die Sicht bei Nacht, Regen und Gegenverkehr dar.

Antrieb Bremsen und Beleuchtung brauchen – gemessen am Auto – noch viel zu viel Wartung.

Die Sicherheit bei Unfällen ist noch kaum erforscht. Ist z. B. beim Liegerad ein oben oder unten liegender Lenker "sicherer"?

Wie könnte ein Sitz aussehen, der so bequem ist wie die besten Liegeradsitze, aber zu noch weniger Schwitzen am Rücken führt und das Umdrehen weniger behindert ?

Ist eine Liegeradlenkung möglich, die Freihändigfahren ermöglicht ?

Wie könnte bei unten liegendem Lenker eine Anpassung an verschiedene Körpergrößen aussehen, die so einfach wie bei guten Mountain Bikes zu handhaben ist? (Schnellverschluß für Sattelklemmbolzen) ?

Ein berühmter Mann in einer HPV-Nachbarszene, der Solarauto-Konstrukteur Horlacher, hat gesagt, die S-Klasse (von Mercedes) sei der dicke Punkt am oberen Ende der Fahnenstange! Ich möchte es etwas anders ausdrücken: Das zu Ende gehende Zeitalter war gekennzeichnet durch Leistung, Geschwindigkeit, Komfort, Prestigedenken und unbeschränkte Mobilität, das Symbol hierfür war das Auto. Das kommende Zeitalter wird gekennzeichnet sein durch Leben im Einklang mit der Natur, sanfte Technik, Gefühl für die Bedürfnisse des Körpers und Freude am Naheliegenden und das Symbol hierfür ist das Fahrrad.

Laßt uns an die Arbeit gehen !



*K5, ein für die Stadt geeignetes Kurzliegerad, noch ohne abnehmbaren Kofferraum aus Stoff über Rohrrahmen gespannt.*

## **TOWARDS THE UNDERSTANDING OF (DYNAMIC) STABILITY OF VELOMOBILES: THE FORCES, THEIR DISTRIBUTIONS AND ASSOCIATED TORQUES**

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### **Inhalt**

Die an einem Velomobil angreifenden Kräfte - die Gravitation, Luftwiderstand und Auftrieb, der Rollwiderstand und die seitlich wirkende, zur Steuerung benutzte Reibung - werden besprochen und ihre Verteilungen entlang der Hauptachsen werden berechnet. Aus diesen Verteilungen lassen sich die in ihren Schwerpunkten wirkende Gesamtkraft wie auch die ersten (und zweiten) Momente bezüglich des Massenschwerpunktes ableiten.

Für einige beschreibbare Bewegungszustände eines Velomobiles lassen sich damit die statische (Gier-)Stabilität (positive, neutrale oder negative) sowie die Anfangsbeschleunigungen bestimmen.

Weiter werden Abschätzungen des Verhaltens eines Mobiles bei Seitenwind und der durch die aerodynamischen Kräfte begrenzten Kurvengeschwindigkeit gemacht. Stabilität und Steuerbarkeit sind lebenswichtige Eigenschaften von in dichtem Verkehr brauchbaren Velomobilen. Darum folgen zum Schluss Beiträge zur laufenden Diskussion darüber, ob alltagstaugliche Velomobile besser zwei oder drei Räder aufweisen sollten.

### **ABSTRACT**

The forces acting on a velomobile - gravitational, aerodynamic (drag and lift), rolling resistance and lateral steering - are discussed and their distributions along the main axes are calculated. From these, the sum of all forces acting on the centers of the distributions as well as the first (and secondary) moments relative to the velomobile's center of mass are derived.

In some defined states of movement of a velomobile, the findings enable us to determine its "static" (yaw) stability (positive, neutral or negative) and the initial accelerations.

Further, estimates of the mobile's reaction to crosswind and of the limited cornering speeds of bikes due to aerodynamic forces are made.

Finally, stability or at least controllability is essential if a velomobile is to be used on crowded public streets. Therefore, some contributions are made to the continuing discussion as to whether or not streetworthy velomobiles for regular consumers should have two or more wheels.

### **Introduction**

Since the beginning of cycling history a lot of attempts have been made to understand the stability of bicycles and to describe their ways of moving. Today, automatically computed diagrams are available that define the region of stability of bicycles on which no drag or lift forces act (Ref. 0.1). But, for practical use, these limits have been found long before by trial and error. For safety-reasons, computer models of motorcycles have been built and validated: They allow studies of rider-motorcycle-systems under different conditions (Ref. 0.2, 0.3). For vehicles with more than two wheels, the best possible locations of the center of mass is known from theoretical considerations (Ref. 4.1). Automobiles with four wheels are well understood because the big car-industries have invested a lot in research and development. Conversely, the faired and newer form of cycles, the velomobiles, still seem to be in the experimental status: Today's single-track

vehicles for example may be very fast when going straight but suffer from falling over in crosswinds or in corners. Therefore, not only the parameters mass  $m$ , coefficient of rolling friction  $c_R$ , coefficient of drag  $c_D$  at zero angle of attack ( $\alpha$ ) and frontal area  $A$  have to be considered important for the overall performance of velomobiles: The airflow around fairings at  $\alpha$  different from zero strongly influences stability while cornering and in crosswind. Transverse flow produces lift having lateral components and thus generates torques. Their magnitude governs the stability limits of straightforward motion.

More insight into what happens in the situations mentioned above - at angles of attack, while cornering and in crosswinds - and more engineering tools are needed which would allow designers of velomobiles to start their work with good concepts.

For safety reasons, it is important that the stability limits are not only known to the velomobile designers, but also to the riders.

In order to stay on the practical level and to avoid difficult theories, this work is limited to the determination of static stability of velomobiles. For certain defined and, for practical purposes, important situations it is possible to calculate with relative ease the centers of the distributions of the forces acting on velomobiles and the total forces and then to decide in which direction the velomobile moves and turns. Considering dynamic stability would include the computation of the accelerations and the velocities of these movements. It is up to further works to describe this more complicated task.

### 1. Degrees of freedom and Forces

To keep it simple, not all degrees of freedom of velomobiles are considered here. The ones important in this work are the three dimensions of space and the three rotational degrees of freedom roll, yaw (gieren) and pitch (nicken): Fig. 1.

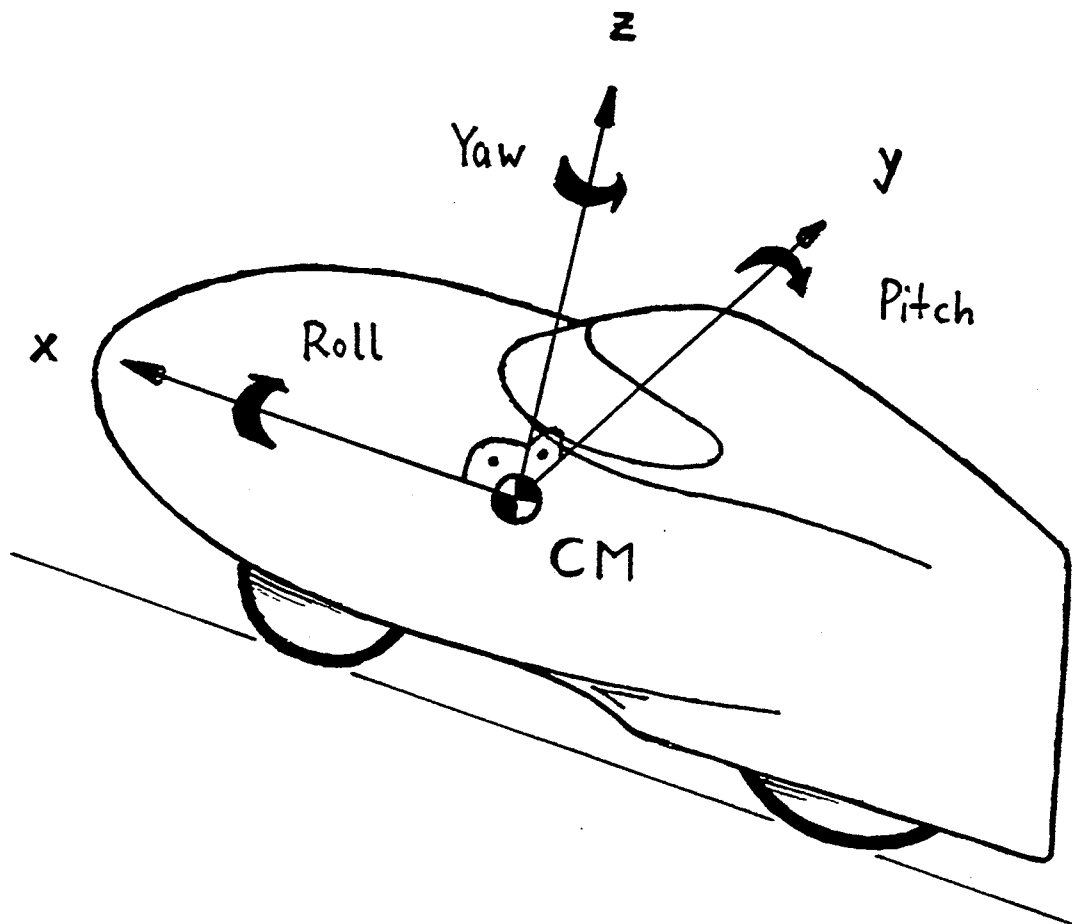


Figure 1. Axis of a velomobile

An important feature of bikes is the strong coupling of roll and yaw movements. This interrelation is essential for stabilization, and makes it impossible to explain the behaviour of bikes with simple models. Therefore, later in this article, only qualitative discussions of effects encountered with bikes will be possible. Trikes (tricycles) and quikes (quadracycles) do not experience such strong couplings. Quantitative descriptions can and will therefore be made.

The forces to be considered are the gravitational force, rolling resistance and lateral steering forces of the wheels and drag and lift forces on the fairings. The rider of the velomobile influences the magnitudes of all forces except gravity by braking, steering and leaning to the side in corners to shift the center of mass of the vehicle-rider-combination.

## 2. Mass, Center of Mass (CM) and Moment of Inertia (MOI)

Gravity exerts on each piece of a velomobile the force

$$(II.I) \quad \vec{f}_G = m_i \vec{g}$$

$\vec{f}_G$  : Force of gravity, [N]  
 $m_i$  : Mass of part i, [kg]  
 $\vec{g}$  : Acceleration of gravity,  
 $\sim 9.8 \text{ m/s}^2$

The total force of gravity on the velomobile is determined by the sum of all the vehicle's masses and the mass of rider and payload:

$$(II.II) \quad \vec{F}_G = \vec{g} \underbrace{(m_r + m_p + \sum_i m_i)}_{M_{RPV}}$$

$\vec{F}_G$  : Total force of gravity, [N]  
 $m_r$  : Mass of rider, [kg]  
 $m_p$  : Mass of payload, [kg]  
 $\sum_i m_i$  : Mass of vehicle, [kg]

The center of mass (CM) is where the sum of all the gravitational forces acts on the velomobile (with the rider and payload in it). To know the location of the CM is essential: Maximum cornering-acceleration and deceleration (braking!) and slippage of wheels depend on it. (See below, in the chapters "Bicycle Model" and "Frictional, Rolling Resistance and Steering Forces".)

By summing moments and comparing the sum with the moment of the total gravitational force, the location of the CM can be computed:

(II.III)

$$a) x_{CM} |\vec{F}_G| = |\vec{g}| (x_r m_r + x_p m_p + \sum_i x_i m_i) \quad x_{CM}: \text{X-coordinate of CM, [m]}$$

$$b) x_{CM} = \frac{x_r m_r + x_p m_p + \sum_i x_i m_i}{m_r + m_p + \sum_i m_i} \quad x_j : \text{Distance Mass j - axis of reference, [m]}$$

$$c) y_{CM} \quad \text{analogous}$$

Other designations analogous

$$d) z_{CM} \quad \text{analogous}$$

As axis of reference, the nose of the vehicle can be chosen for x and for example the base of the fairing for z. Usually, the CM lies in the plane of symmetry of the vehicle and  $y_{CM} = 0$ .

In a similar way, total forces and the centers of distributions of other kinds of forces - aerodynamic forces for example - can be determined. See below, chapters "Center of Pressure" and "Static Stability".

The moment of inertia (MOI) measures how the masses the velomobile is made of are spread in the space around the CM. For all parts that are extended several centimeters, their own mass distribution has to be taken into account by applying Steiner's law. All other parts (screws for example) can be treated as if their mass was concentrated in a single point by using only their mass and neglecting their small moment of inertia:

$$(II.IV a) \quad I_{V_x} = \sum_i I_{i_x} = \sum_n I_{n_x} + \sum_m I_{m_x} \quad I_{V_x}: \text{MOI of vehicle related to x-axis, [kgm}^2\text{]}$$

$$I_{V_x} = \left[ \sum_n m_n (x_n - x_{cm})^2 \right] + \left[ \sum_m \{ m_m (x_m - x_{cm})^2 + I_{m_x} \} \right]$$

$I_{n_x}$ : MOI of point mass  
 $I_{m_x}$ : MOI of extended mass  
 $I_{RPV_x}$ : MOI of rider/payload/vehicle

b)  $I_{V_y}$                       analogous

Other designations analogous

c)  $I_{V_z}$                       analogous

$$d) \quad I_{RPV_x} = I_{V_x} + [m_r (x_r - x_{cm})^2 + I_r] + [m_p (x_p - x_{cm})^2 + I_p]$$

$I_r$ : MOI of rider  
 $I_p$ : MOI of payload

The longer the velomobile is, the bigger thus the MOI due to the squared lever arms.

Usually, the rider is the heaviest object in or on the velomobile and his or her extensions are nearly the same as those of the vehicle. Therefore, his or her mass and the moments of inertia can not be neglected and should be known precisely. To measure the rider's mass by weighing is easy. The determinations of the CM and of the moments of inertia are more complicated.

The location of the CM of an object can be determined by measuring the loads on two or more points of support and by backcalculating the location of the CM. To bicyclists, it is well known how the wheel loads and the location of the CM are interrelated: The bicycle is an example of an object with two points of support (See chapters "Normal Forces" and "Bicycle Model"). If the object is composed of several parts with known masses and locations of CM and from one with known mass but unknown CM, by applying formula (II.III) the unknown CM can be backcalculated from the total mass and the location of the CM of the composed object. For example, the CM of a rider who leans back at a certain angle (seat angle) and who holds the arms in a position for either front or underseat steering can be measured by putting a plank symmetrically on two balances and by letting him or her sit in the desired position on the plank. From the readings of the two balances and from the masses of the plank and the rider, his or her CM is then calculated as mentioned above.

The main moments of inertia of composed objects are usually measured by oscillating them to and from with calibrated torsion wires or sprung turn-tables or seats. The first method is well suited for smaller velomobile parts, whereas the latter is better for bigger parts and to measure the moments of inertia of riders. See physics texts and Ref. 0.2 if you would actually like to make such measurements.

From (rare) anthropometric data, the CM and the main moments of inertia of a "typical" man can be calculated (Ref. 2.1). Results are given in Table 1a, 1b and Fig. 2.

Segment	Mass (Kg)	Description (cm)
Head	5.575	sphere: $r = 11$
Trunk	32.400	rectangular solid: $60 \times 30 \times 18$
Upper arms (2)	2.356	cylinder: $r = 5, h = 30$
Forearms (2)	1.781	cylinder: $r = 4.5, h = 28$
Hands (2)	0.523	sphere: $r = 5$
Thighs (2)	8.650	cylinder: $r = 8, h = 43$
Lower legs (2)	4.086	cylinder: $r = 5.5, h = 43$
Feet (2)	1.436	sphere: $r = 7$

Table 1a. Body segment masses and shapes of "typical" man (Total mass 75.64 kg, height 1.82 m). From Ref. 2.1.

Figure 1	Description	$I_1$	$I_2$	$I_3$
<i>A</i>	Layout throw	1.10	19.85	20.66
<i>B</i>	Layout sault	1.10	14.75	15.56
<i>C</i>	Pretwist layout	3.42	16.38	19.17
<i>D</i>	Twist position	1.06	16.65	17.24
<i>E</i>	Twist throw	1.08	17.41	18.20
<i>F</i>	Loose pike	4.83	10.45	7.53
<i>G</i>	Pretwist pike	5.54	10.09	10.42
<i>H</i>	Tight pike	1.75	5.89	6.05
<i>I</i>	Tuck	20.3	3.79	3.62

Table 1b. Principal moments of inertia (MOI) of "typical" man in positions shown in Fig. 2.

$I_1$ : Principal MOI for the axis closest to that of the man's spine

$I_2$ : Principal MOI along a left-to-right axis

$I_3$ : Principal MOI for the axis closest to the front-to-back axis

Units are  $\text{kgm}^2$ .

From Ref. 2.1.

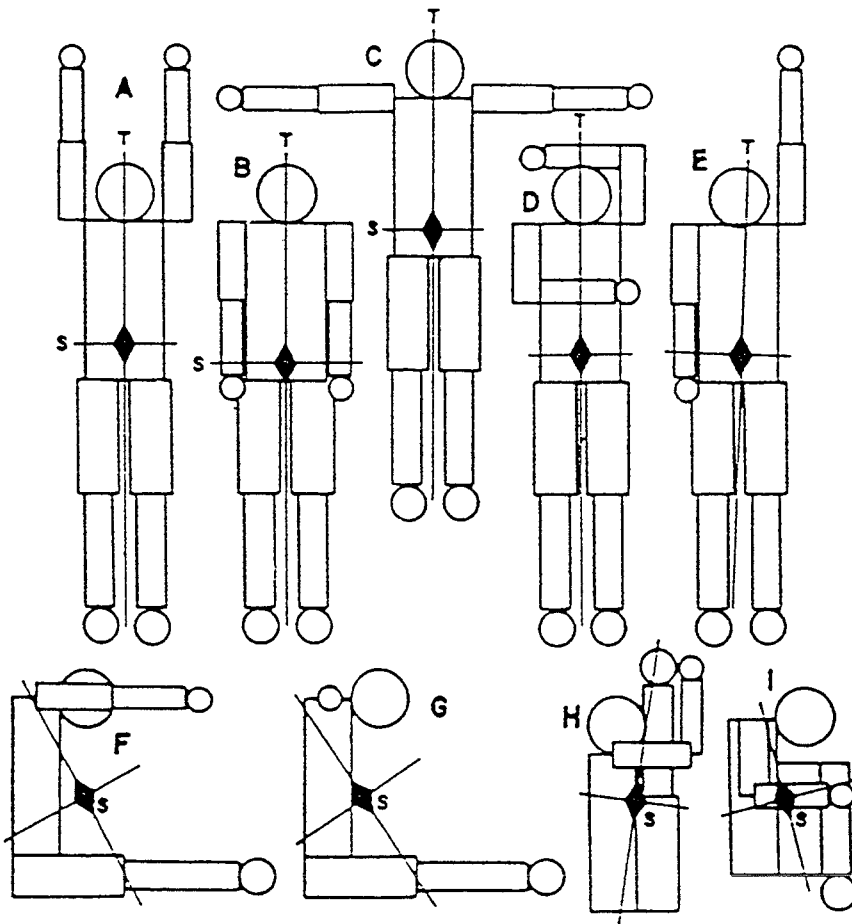


Figure 2. Center of mass (CM) locations and principal axis of some configurations of "typical" man (Taken from Ref. 2.1).

The diamond marks the CM. The long axis of the diamond is oriented along the principal axis associated with the principal moment of inertia  $I_1$  (Table 1b).

If the mass and the MOI of the rider-vehicle combination are known, initial accelerations due to external forces and torques are computable. The bigger the mass, the slower the velomobile accelerates due to any force:

$$(II.V a) \quad a_x = F_x / m_{RPV}$$

$a_x$  : Acceleration in x-direction,  
[m/s<sup>2</sup>]

$F_x$  : X-component of force, [N]

$m_{RPV}$  : Mass of rider/payload/vehicle

b)  $a_y$                       analogous

c)  $a_z$                       analogous

Other designations analogous

The bigger the MOI, the slower the velomobile starts to turn under any torque:

$$(II.VI a) \dot{\omega}_x = T_x / I_{RPV_x}$$

$$b) \dot{\omega}_y \quad \text{analogous}$$

$$c) \dot{\omega}_z \quad \text{analogous}$$

$\dot{\omega}$  : X-component of angular acceleration, [Rad/s<sup>2</sup>]  
(1 Rad ~ 57.3 Degrees)

$T_x$  : X-component of torque, [Nm]  
 $I_{RPV_x}$  : MOI of rider/payload/vehicle related to x-axis, [kgm<sup>2</sup>]

Other designations analogous

### 3. Normal Forces

The total normal force acting on a velomobile is opposite in sign, but of the same magnitude as the force of gravity acting in the CM:

$$(III.I a) |\vec{F}_N| = |\vec{F}_G|$$

$$b) \frac{\vec{F}_N}{|\vec{F}_N|} = - \frac{\vec{F}_G}{|\vec{F}_G|}$$

$\vec{F}_N$  : Normal force, [N]

$\vec{F}_G$  : Force of gravity, [N]

The normal forces acting on each wheel of a velomobile are distributed in the same way as the weight is divided into different wheel-loads. To undertake the calculations, the bicycle model below is used.

### 4. Bicycle Model

The two-dimensional structure of the bicycle makes it easy to calculate the load and the normal force on each wheel as well as the change of the wheel-loads under acceleration if the location of the CM is known. The model is shown in Fig. 3.

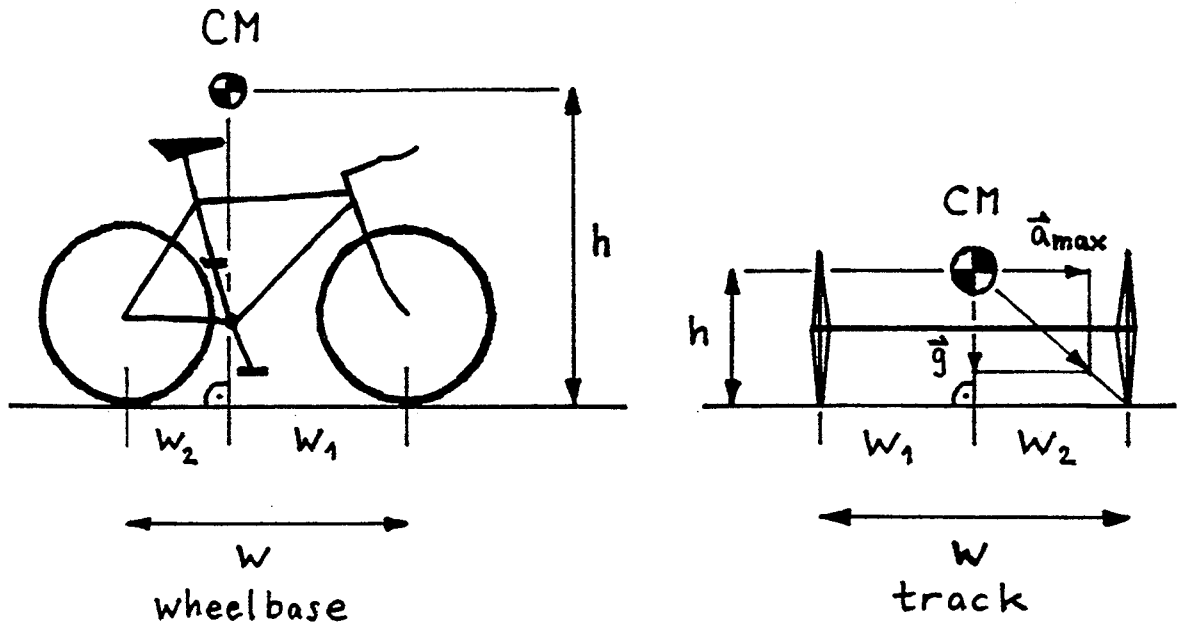


Figure 3. Bicycle model designations.

Normal forces:

$$(IV.I a) \quad W = w_1 + w_2$$

$$b) \quad F_{N_1} = |\vec{F}_{N_1}| = F_G \frac{w_2}{W}$$

$$c) \quad F_{N_2} = |\vec{F}_{N_2}| = F_G \frac{w_1}{W}$$

$$d) \quad F_G = |\vec{F}_G| = F_{N_1} + F_{N_2}$$

$W$  : Wheelbase (or track), [m]

$w_1$  : Horizontal distance CM - axle 1 (left wheel), [m]

$w_2$  : same for axle 2 (right wheel)

$F_{N_1}$  : Normal force on axle 1, [N]

$F_{N_2}$  : Normal force on axle 2, [N]

Additional axle-loads (wheel-loads) due to longitudinal acceleration (eg. braking):

$$(IV.II a) \quad F_a = m_{RPV} \cdot a$$

$$b) \quad \Delta F_{N_1} = F_a \cdot \frac{h}{(w_1 + w_2)}$$

$$c) \quad \Delta F_{N_2} = -\Delta F_{N_1}$$

$a$  : Ac- or Deceleration, [m/s<sup>2</sup>]  
 $m_{RPV}$  : Mass of rider/payload/vehicle

$h$  : height of CM, [m]

$w_1$  : Horizontal distance CM - axle 1 (left wheel), [m]

$w_2$  : Horizontal distance CM - axle 2 (right wheel), [m]

While accelerating, the load on the front axle is reduced and the load on the rear axle is increased. The opposite is true for braking (decelerating).

Maximum longitudinal acceleration of the CM (eg. Maximum braking acceleration):

$$(IV.III) \quad a_{max} = g \frac{w_1}{h}$$

$g$  : Acceleration of gravity, [m/s<sup>2</sup>]  
 $w_1$  and  $h$  as above

The bicycle model can also be applied to trikes and quikes (quadricycles) either in longitudinal (front and rear axles) or lateral direction (left and right wheels):

To determine the distribution of the normal forces on both axles of trikes and quikes, the bicycle model is applied exactly in the same manner as in the case of bikes: Formula IV.I.

Usually, the CM lies on the centerline of a trike or a quike. The normal force on the axle(s) with the two wheels is therefore equally distributed to the left and right wheel. Longitudinal acceleration is taken into account exactly as with bicycles: In the case of trikes or quikes there are axles with one or two wheels instead of single wheels.

The bicycle model allows us, as in the case of the bike for longitudinal acceleration, to calculate the change in wheel-loads due to lateral acceleration: See formula IV.II.

Maximum lateral acceleration is determined as easily as the longitudinal one for bikes: See formula IV.III.

In a curve, the load on the inner wheel(s) is reduced and the load on the outer wheel(s) is increased.

Maximum cornering speed is given by

$$(IV.IV) \quad v_{max} = \sqrt{a_{max} \cdot r}$$

$v_{max}$  : Maximum speed, [m/s]  
 (1 m/s = 3.6 km/h)  
 $r$  : Curve radius, [m]

Since, according to Ref. 4.1, for yaw stability the CM of a trike should be near the axle with the two wheels, the error of the calculations of lateral acceleration or maximum cornering speed does not exceed 1/3 of the result. With a simple rule of three this error can be reduced to only a few percents (Fig. 4):

$$(IV.V) \quad a_{maxI} \sim a_{maxI} \frac{l_{II}}{l_I}$$

$a_{maxII}$  : Max. acc. with little error  
 $a_{maxI}$  : From formula IV.III  
 $l_I$  : Wheelbase, [m]  
 $l_{II}$  : Distance rear axle - actual CM, [m]

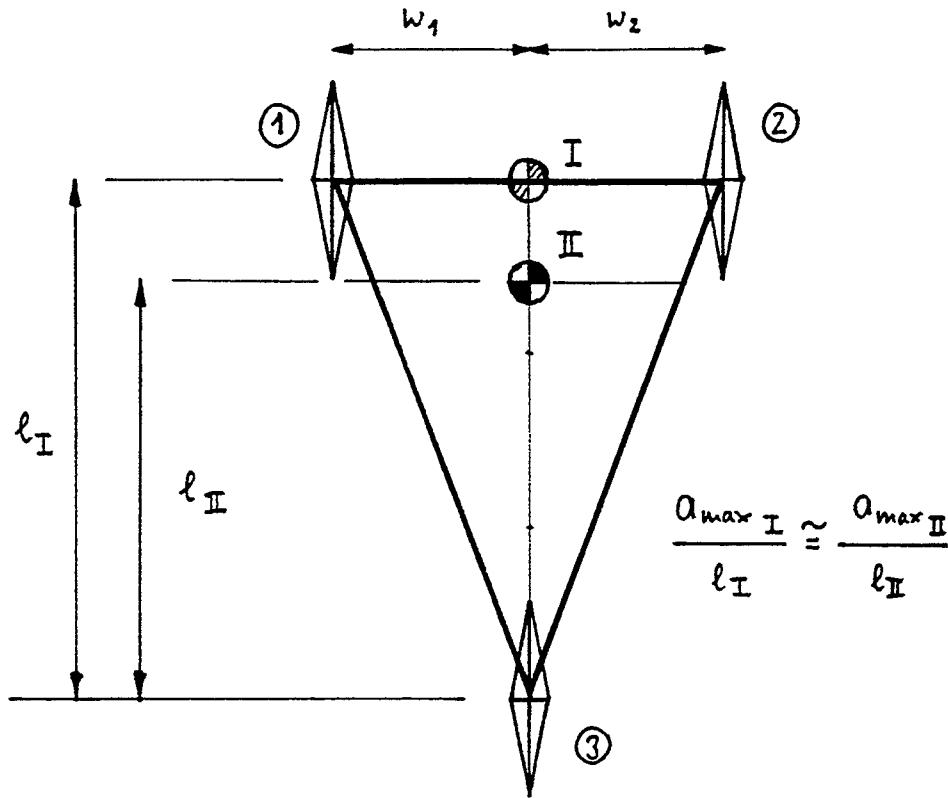


Figure 4. The geometry of a tricycle and the rule of three. The solid symbol for the center of mass marks the actual CM.

### 5.1 Frictional, Rolling Resistance and Steering Forces

Two types of friction exist: Static or adhesive friction and kinetic or slipping friction. The direction of the frictional forces is opposite to a possible or actual movement and the magnitude of the frictional forces is proportional to the normal force:

$$(V.1) \quad |\vec{F}_F| = \mu |\vec{F}_N|$$

$\vec{F}_F$  : Frictional force, [N]

$\mu$  : Coefficient of friction, [-]

$\vec{F}_N$  : Normal force, [N]

The factor of proportion, the coefficient of friction, depends on the two materials that are in contact. Generally, the coefficients of static friction and thus the forces are higher than the coefficients and forces of slipping friction. This is why slipping should be avoided while braking.

The coefficients of friction and their importance for the acceleration, movement and deceleration of vehicles can be studied in more detail in physics textbooks, tables or Ref. 4.1, 5.1 and 5.2.

Rolling resistance is also opposite to movements but is (fortunately!) much smaller than the two other frictional forces and, in first order, is inversely proportional to the diameter of the wheel. If the coefficient of rolling resistance is used, this force is described with formula (V.1). See Ref. 5.1, 5.2, 5.3 and Table 2 (taken from Ref. 5.3) for further detail.

Tire	Size	Weight	Tread	Pressure	Coeff. of R.R.
	[Inches]	[Grams]		[bars]	[%]
Honda Express	14x2-1/4	1120	Rib	4.1	0.813
				5.5	0.703
				6.9	0.643
Moulton	17x1-1/4	254	Rib	5.5	0.338
				6.9	0.298
				8.3	0.268
Moulton	17x1-1/4	254	Rib	6.9	0.390 (*)
Wolber C3 Spec	17x1-1/4	234	Smooth	6.9	0.265
Avocet Fastgrip	20x1-3/4	370	Smooth	5.5	0.403
				6.9	0.368
				8.3	0.318
Avocet Worn	20x1-3/4	370	Smooth	6.9	0.300
Avocet Fastgrip	26x1-3/4	?	Smooth	6.9	0.300 (1)
				"	0.350 (2)
				"	0.540 (3)
Silk Road	27x1	190	File	4.1	0.300
				5.5	0.280
				6.9	0.260
				8.3	0.240

Tests: Coast down tests on Linoleum using a special tricycle with a weighted front wheel.

The tests on the 26" Avocet were done by Alex Hood (Australia) using the oscillating pendulum method.

- (\*) Surface: Smooth Asphalt
- (1) Surface: Glass
- (2) Surface: Rolled Asphalt
- (3) Surface: Rough Macadam

Table 2. Coefficients of rolling resistance from Ref. 5.3.

Without friction, it would be impossible to induce lateral forces to control the directions of travel of velomobiles and to steer them around corners. In addition to the friction between road and tire, the lateral steering forces also depend on the stiffness of the wheel itself. This phenomenon is well known to riders of trikes: Their wheels - often built from rims and spokes like bicycle wheels that are intended to carry loads only in the direction of the main plane - deform visibly in corners. If both friction (dependent on normal force) and stiffness of a wheel are described by a parameter called "cornering stiffness" (Ref. 4.1), the lateral force produced by a wheel is given by

$$(V.II) \quad F_L = \sigma \cdot c_\sigma$$

$F_L$  : Lateral force, [N]  
 $\sigma$  : Slip Angle, [Rad]  
 $c_\sigma$  : Cornering stiffness,  
dependent on Slip, [N/Rad]  
(1 Rad ~ 57.3 Degrees)

The slip angle is the angle between the direction of travel of a velomobile and the intersection of the main plane of a wheel with the plane of the roadsurface.

Unfortunately, hardly any data exists on cornering stiffness of velomobile wheels. The only one known to the author is on Moulton 17" x 1.25" tires, measured by Kyle during the design process of the "Sunraycer"-solarmobile (Ref. 5.3) : Fig. 5. At least Moulton tires are very common in velomobiles. For wheels bigger than 17" lateral force at a certain slip angle is probably less than for the Moulton. This is due to the fact that the spokes of bigger wheels are at a steeper angle and therefore can not take that much lateral force.

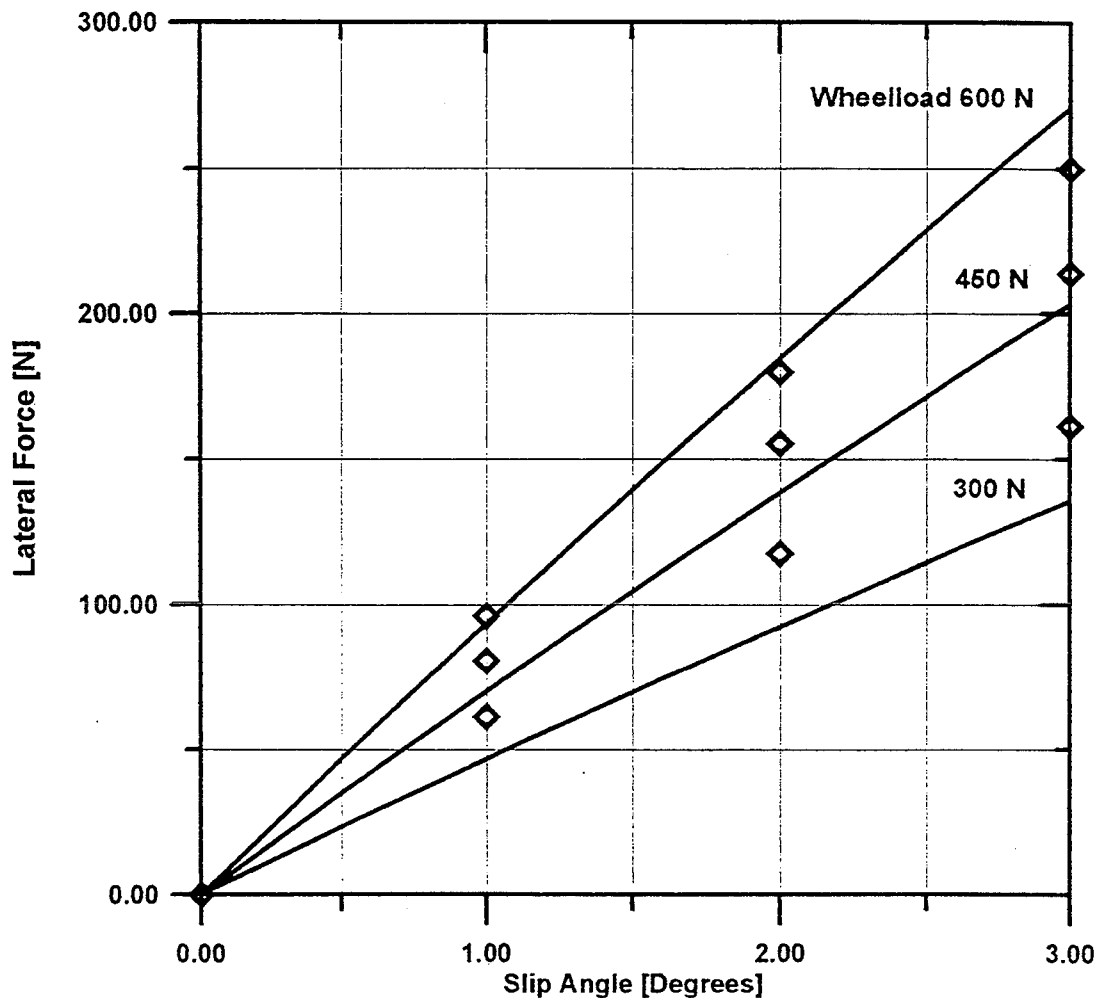


Figure 5. Lateral forces produced by a Moulton 17" x 1.25" as measured by Kyle (Taken from Ref. 5.3). Tire pressure was 113 PSI (7.8 bars). The data was collected in a drum test. The symbols mark datapoints read from original graph and the solid lines show the sine-"fits".

The lateral force not only depends on friction and wheel load, wheel stiffness and slip angle, but also on tire pressure and camber angle. Camber angle is the angle between the main plane of the wheel and the vertical (For definitions of various important angles on velomobiles, see Ref. 4.2): Fig. 6. The 17" x 1.25" Moulton tire produces maximum lateral force at a tire pressure of 90 to 100 PSI (6.2 to 6.9 bars). Lateral force changes with 6.75 N per degree camber at 1 degree slip and at a wheel-load of 450 N. The slope is bigger for higher wheel-loads and smaller for lower ones.

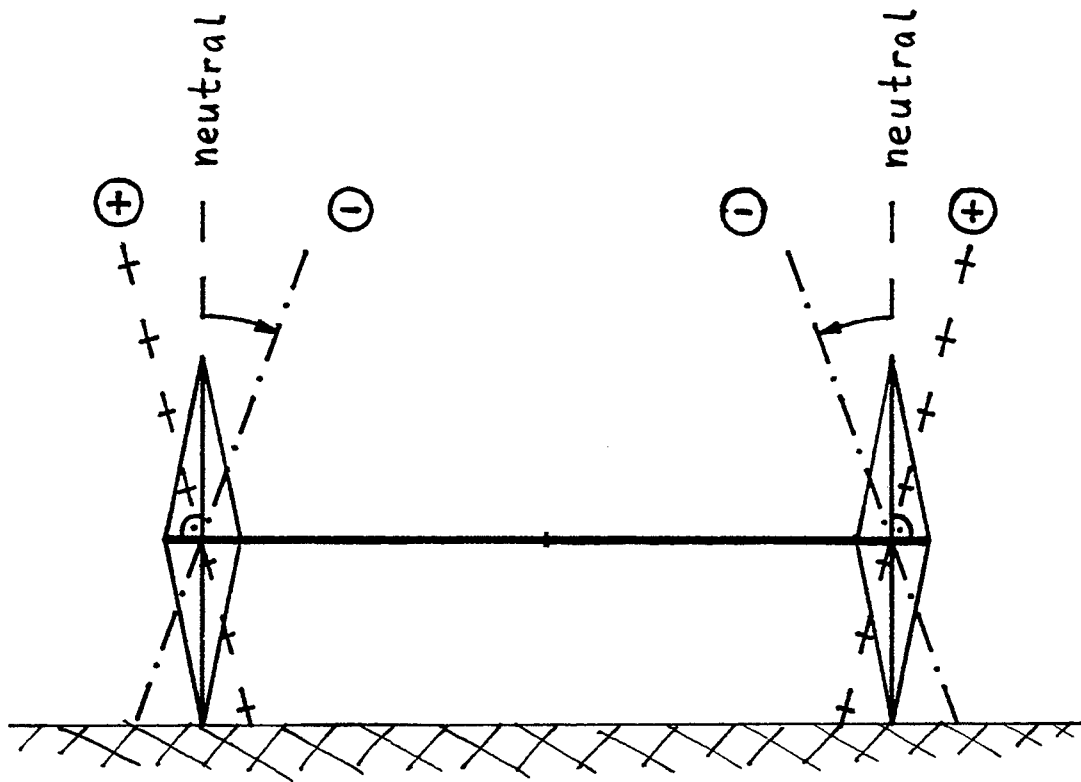


Figure 6. Camber angle, definition. From Ref. 4.2.

For calculations and extrapolations to somewhat higher slip angles, the data in Fig. 5 was parameterized as follows:

$$(V.III) \quad F_L = L \sin(9\sigma)$$

$L$  : Wheel-load ( $L = F_N$ ), [N]

$\sigma$  : Slip Angle, [Degrees]

$-10 \leq \sigma \leq +10$  Degrees

Much better fits are possible, but there is some physical meaning behind the sine-fit. The lateral force at a slip angle of 10 degrees is the same as adhesive friction. A much better parameterization of tires was used in motorcycle simulations. For details, see Ref. 0.2 and 0.3.

Since the lateral force is perpendicular to the wheel's main plane, a component parallel to the longitudinal axis of the velomobile starts to build up with steering angles different from zero. Therefore, if a velomobile can only be kept in straight travel with a lot of steering commands given by the rider, rolling resistance is not minimal. This fact is just another reason why studies of stability (also dynamic stability) of velomobiles should not be neglected.

### 5.2 Center of Friction (CF)

Once the longitudinal and lateral forces on wheels are known, a center where the total frictional- and steering-force acts on the velomobile, the "center of friction" (CF), can be determined (In analogy to the center of pressure. See chapter "Center of Pressure"). All the wheel-loads, which depend on the CM-location as well as on longitudinal and lateral accelerations of the CM, have to be known to compute the forces acting in the contact points of wheels and street (See chapter "Bicycle Model"). First, rolling resistance and lateral force are added vectorially. Then the components parallel and normal to the longitudinal axis of the velomobile are calculated:

(V.IV a)

$$F_o = F_L \sin \gamma + F_F \cos \gamma$$

$$F_{go} = F_L \cos \gamma - F_F \sin \gamma$$

b)

$$F_F = F_o \cos \gamma - F_{go} \sin \gamma$$

$$F_L = F_o \sin \gamma + F_{go} \cos \gamma$$

$F_o$  : Comp. parallel to long. axis, [N]

$F_{go}$  : Comp. normal to long. axis, [N]

$\gamma$  : Angle between long. axis and wheel main-plane

$F_L$  : Lateral force, [N] (depends on sigma)

$F_F$  : Rolling resistance, [N]

These components are then used in moment-balances similar to II.III to calculate either the longitudinal or the lateral position of the CF. To get the longitudinal position of the CF the components normal to the longitudinal axis of the velomobile are put into II.III together with the distances from a reference line (eg. Front or rear axis). To get the lateral position of the CF the components parallel to the longitudinal axis of the velomobile are put into II.III together with the distances from a reference line (eg. Left or right wheel).

Terms for the wheels that do not contact the ground are - of course - omitted from the moment balance.

### 6.1 Aerodynamic Forces

Fairings of velomobiles are usually symmetrical and therefore produce drag but no lift when the mobile is travelling straight. But as soon as there is an angle between the longitudinal axis and the direction of travel, called "angle of attack" ( $\alpha$ ), a sideways and or upwards pulling force starts to build up. This force, the lift, adds with the drag to the total aerodynamic force. Fairings that are not rotationally symmetrical and thus cambered, produce lift even at zero  $\alpha$  if far from ground. Near the ground, fairings should be cambered to minimize the "ground effect" (See Ref. 6.4). In this case lift against gravity may be zero and drag may be minimal if cambered correctly.

Drag and lift, antiparallel and perpendicular to the direction of travel, are used in calculations of vehicle performance (Ref. 6.3). If the movements around the vehicle's main axes are studied, it is more convenient to look at the components of the total aerodynamic force that are parallel and perpendicular to these main axes: They are called chord force and normal force (Do not mix up the latter with the normal force generated by the street surface that supports the velomobile). If drag and lift are known, chord- and normal-force are determined and vice versa. Formula V.IV can be used to change from one to the other set of forces: Just identify the forces correctly!

Roughly, there are two types of velomobiles: Some resemble more a fin, others more an airship or a rocket. Drag and lift of a lot of these shapes and bodies were determined in wind tunnel experiments (Ref. 6.1 and 6.2). For airfoils, there is also a lot of data about the torques produced by the total aerodynamic force. Therefore, the center of lift of a wing or fin, usually called center of pressure (CP), is computable. Less published data exists on the CP of rotationally symmetrical bodies.

Yet for several reasons the determination of the aerodynamic forces and torques on velomobiles is more complicated than just finding proper data in a table: First, the aerodynamic forces depend very much on the velocity of the velomobile. Second, while cornering and in crosswind the airflow around fairings is at a high  $\alpha$ . Airfoils are used near zero  $\alpha$  ( $\alpha < 15$  Deg), therefore only little data exists for the range of higher angles of attack. Precise calculations will be made only for small angles of attack. Third, velomobile fairings are usually much thicker than airfoils used on wings and fins and do not have a nose as sharp. Most of the wind-tunnel data was collected for airfoils of a thickness of up to 15% of the chord. Extrapolations will have to be made. Fourth, velomobiles are often much stubbier than a typical fin or wing and are not as slender as airships and rockets. Crossflow is considerably higher on blunt shapes and it is difficult to account for. If based on the available data, very precise predictions are impossible. All these four points will briefly be discussed below:

Each of the components of the aerodynamic force (drag, lift, chord force, normal force) can be written as follows:

$$(VI.I a) \quad F_i = \frac{\rho}{2} v^2 c_i A$$

$\rho$  : Density of air, [kg/m<sup>3</sup>]  
 (~ 1.2 kg/m<sup>3</sup> at 20 Deg C)  
 $v$  : Velocity of airflow relative  
 to the fairing, [m/s]  
 $c_i$  : Coefficient of ...  
 $A$  : Area of reference, [m<sup>2</sup>]

$$b) \quad \rho = 1.293 \frac{273}{273 + \tau}$$

$\tau$  : Temperature, [Deg C]  
 (From Ref. 6.9)

In the case of fins and wings, the coefficients of both drag ( $c_D$ ) and lift ( $c_L$ ) are usually related to the wing area. Drag- and lift-coefficients of slender bodies are referenced to the cross-section or to the width squared.

These four forces are all proportional to the speed of the airstream squared.

Unfortunately, a remainder of dependency on velocity is hidden in the fact that the coefficients  $c_i$  vary with the Reynolds-number (Re-number):

$$(VI.II a) \quad Re = \frac{vL}{\nu}$$

$v$  : Velocity of airflow, [m/s]  
 $L$  : Length of object in flow, [m]  
 $\nu$  : Kinematic viscosity, [m<sup>2</sup>/s]

$$b) \quad Re \sim 70'000 \nu L$$

For Re-numbers bigger than one, pressure effects (pressure drag) are more important for the magnitude of the coefficients than friction between the air and the surface of the fairing (friction drag). Velomobiles typically move at Re-numbers between  $5E+5$  and  $3E+6$ . Therefore, it is more important how the air flows around a smooth and slender body than how it is slowed down by a non-mirrorlike, rough surface. In the range of  $5E+4$  to  $1E+6$ , the coefficients of drag can become smaller very abruptly at the so-called "Critical Reynolds Number" ( $Re_{crit}$ ): Ref 5.1, 5.2 and 6.2. At the corresponding speed of the airstream, the flowing air starts to change from a quiet and orderly status - laminar - into a turbulent one. Turbulent flow follows a curved surface of a fairing better than laminar flow. In this way, less energy-consuming vortices are formed which finally makes it easier for the velomobile to move: The coefficient of drag is reduced (Ref. 5.1, 5.2, 6.2)! At  $Re_{crit}$ , the coefficient of lift becomes bigger as abruptly as the  $c_D$  becomes smaller (Ref. 6.2, 6.8):

But the friction is lower between attached flow and the surface of fairings if it is laminar. Therefore, if the curvature is smooth, "laminar" airfoils (with the maximum thickness far back) will have the lowest  $c_D$  at small  $\alpha$ .

The critical Re-number depends also on location of maximum thickness: The more back it is, the higher  $Re_{crit}$  (Ref. 6.2).

For small  $\alpha$ , the lift-coefficient  $c_L$  is proportional to it:

$$(VI.III) \quad c_L \approx \frac{dc_L}{d\alpha} \alpha$$

$c_L$  : Coefficient of lift, [-]  
 $dc_L/d\alpha$  : lift-curve slope, [1/Deg]  
 $\alpha$  : Angle of attack, [Degrees]

The thickness of an airfoil influences the lift-curve slope. Generally, lift of thinner airfoils increases faster with  $\alpha$  (Ref. 6.1, 6.6). Rough values for the lift-curve slope in the range  $Re > Re_{crit}$  are given in Table 3. If flow separation occurs on thick airfoils, the lift-curve slope may even be negative at small  $\alpha$  (Ref. 6.1).

Thickness [-]	Lift-curve slope [1/Deg]	Remarks
0.0	0.100	} Typical airfoil
0.1	0.090	
0.2	0.075	
0.4	0.045	
0.7	0.015	
1.0	0.000	Cylinder (fairing)

Table 3. Lift-curve slope dependence on thickness. From Ref. 6.1.

If the nose radius of an airfoil is too small, this simply means that the high curvature of the front part can not be followed by the air. The flow separates early, which leads to unnecessarily high drag and a loss of lift: Maximum lift will be lower than in situations with attached flow. Blunt noses on velomobiles are therefore better than sharp ones.

The coefficients of drag and chord force do not vary as much with  $\alpha$  as those of lift and normal force: At zero  $\alpha$  the drag-coefficients are not zero and at 10 degrees they are roughly doubled, whereas lift increases from 0 to 100% in this range. As a first order approximation:

$$(VI.IV) \quad C_D = C_{D0} + \frac{dC_D}{d\alpha} \alpha$$

$C_D$  : Coefficient of drag, [-]  
 $C_{D0}$  : Coeff. of drag at  $\alpha=0$ , [-]  
 $\frac{dC_D}{d\alpha}$  : Drag-curve slope, [1/Degree]  
 $\alpha$  : Angle of Attack, [Degrees]

At a Re-number of  $3E+6$   $C_{D0}$  varies from 0.003 for thin laminar airfoils to 0.005 for thin airfoils with maximum thickness at 30% chord (Ref. 6.7). Thicker airfoils have a much higher  $C_{D0}$ : The one of NACA 0033 (33% thickness) is roughly 0.03 at Re  $1.5E+4$  (Ref. 6.6). Data in Ref. 6.1 for NACA 0070 (70% thickness) indicates a  $C_{D0}$  of 0.07 at Re  $6E+5$  (above Re<sub>crit</sub>).

The drag-curve slope varies around  $1E-3/\text{Deg}$  for thin airfoils (Re  $3E+6$ ). Whether it is steeper or flatter for thicker airfoils depends much on the boundary-layer-quality which in turn is strongly influenced by the surface roughness.

At higher  $\alpha$ 's ( $> 15 \text{ Deg}$ ), the flow is no longer able to stay attached to the surface: The drag increases and the lift diminishes. Therefore it is important that the airflow around velomobiles is smooth even if coming from the side and that, as a consequence, only a little wave is formed on the downstream-side. Fairings with blunt noses and cylindrical cross-sections have the lowest  $C_D$  in lateral flow:

For angles between 25 and 155 degrees lift and drag can be estimated (For details, see Ref. 6.1):

$$(VI.V \text{ a}) \quad C_L = (1.8 \text{ to } 2.0) \sin \alpha \cos \alpha \quad C_L : \text{Coefficient of lift, [-]}$$

$$\text{b)} \quad C_D = (1.8 \text{ to } 2.0) \sin^2 \alpha \quad C_D : \text{Coefficient of drag, [-]}$$

What has been said about lift is also true for the normal force. For small  $\alpha$  lift (proportional to  $C_L$ ) and normal force (proportional to  $C_N$ ) are nearly equal and data about either force can be used with little error for calculations of the other (See also formula V.IV).

The drag coefficients given above are much smaller than the well-known ones in Ref. 6.3. The reason for this is that they are related to the wing area which is proportional to the chord length, whereas the coefficients in Ref. 6.3 are multiplied with the much smaller cross-sections (Cross-sections are proportional to the thickness of the airfoil). Therefore, the following transformation yields the same magnitudes of the drag-coefficients:

$$(VI.VI) \quad C_{i \text{ Cross.}} = C_{i \text{ Wing}} \frac{A_{\text{Wing}}}{A_{\text{Cross.}}} \quad \begin{array}{l} A_{\text{Wing}} : \text{Wing area, [m}^2\text{]} \\ A_{\text{Cross.}} : \text{Area of cross-section, [m}^2\text{]} \end{array}$$

But even then, the coefficients of fins and fairings with finite span are not the same as those of the airfoil that resembles their cross-section. In situations with non-symmetrical flow, that is at an angle of attack, the pressure on both sides of a fin is different. On one hand this causes lift, but near the tips of a fin, the air on the high-pressure side gradually starts to move in lateral direction toward the other, lower-pressure side. The lift near the tips is thus reduced and drag is increased due to energy unnecessarily transferred from the kinetic energy of the moving object to the energy of the airstream. This additional drag occurs only in the presence of lift and is therefore called "induced". The shorter the fin, the bigger the portion of the area with distorted

flow and the bigger the induced drag. A measure for the shortness of a wing or fin is the Aspect Ratio:

$$(VI.VII) \quad AR = \frac{b^2}{A}$$

AR : Aspect ratio, [-]  
b : Wingspan, [m]  
A : Wingarea, [m<sup>2</sup>]

(Note: Wingspan and wing area equal two times the height of the fairing and two times the area of the sideview, respectively.)

Since velomobiles are comparable to fins (or short rotationally symmetrical bodies) with small aspect ratio, the lift-curve slope is reduced and the drag is increased if compared to slender wings and fins as those of typical aircraft.

From Ref. 6.1 lift in dependence of  $\alpha$  is taken for different, also small aspect ratios: Fig. 7.

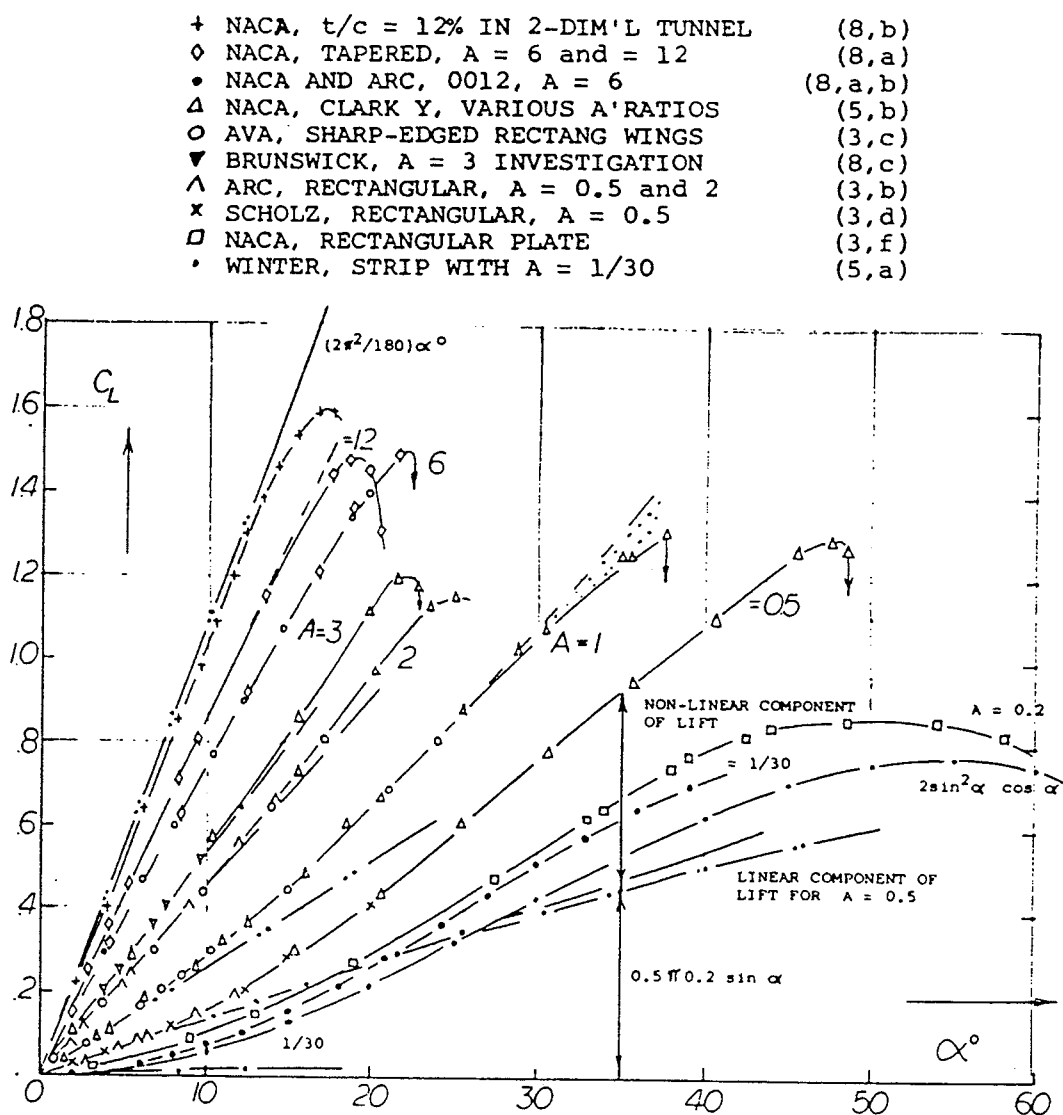


Figure 7. Coefficient of lift in dependence of angle of attack and aspect ratio (Taken from Ref. 6.1).

Equations in Ref. 6.2 allow us to account for drag in presence of lift on small aspect ratio fins:

(VI.VIII a)

$$C_{D_L} = C_{L_0} \tan \frac{\alpha}{2} + k \sin^2 \alpha \tan \alpha$$

b)  $C_{L_0} = \frac{\pi}{2} AR \sin \alpha$

$C_{D_L}$  : Coeff. of drag in presence of lift, [-]

$\alpha$  : Angle of Attack, [Degrees]

$AR$  : Aspect ratio, [-]

$k$  : Factor, given in Fig. 8

$\pi$  : Pi = 3.14...

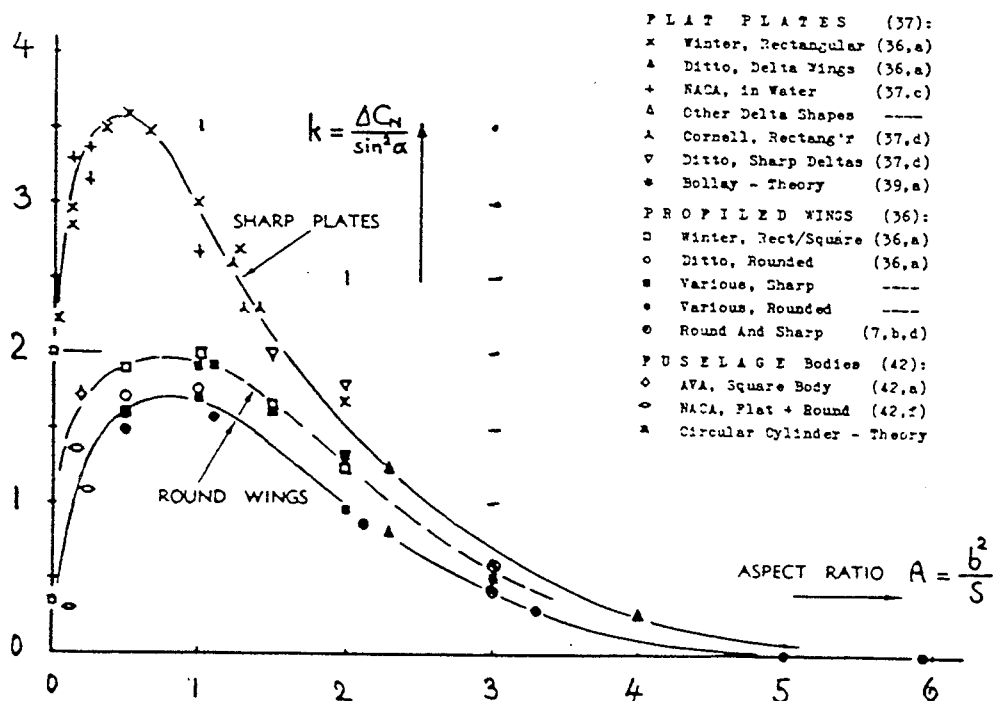


Figure 8. Factor  $k$  in dependence of aspect ratio (Taken from Ref. 6.2).

The coefficients of fins and airfoils are only identical in the case of infinite wingspan because then by definition no flow around wingtips can occur.

In Ref. 6.2 there is also a lot of data on the influence shapes of windshields and forms of wingtips have on drag. Discussing these things as well as parasite and interference drag is beyond the scope of this paper.

With the exception of the effects of Reynolds-number  $Re$  on drag and lift most of what is said above is true for airfoils and fins but not for (rotationally symmetrical) streamline bodies. If we compare them to wings, we would say that they have an extremely small aspect ratio. Crossflow is important and the lift-curve-slope is much smaller than on wings. In Ref. 6.1 and 6.2 streamline bodies are discussed in complete chapters with a lot of useful graphs for the velomobile designer.

The equivalent for slender bodies to the aspect ratio of wings is the fineness ratio:

(VI.IX)  $FR = l/d$

$FR$  : Fineness ratio, [-]

$l$  : Length of body, [m]

$d$  : Diameter of body, [m]

Drag-coefficients based on frontal area are given for different fineness ratios in Fig. 9, taken from Ref. 6.2. Optimum length to diameter ratio is about 3.

$\Delta$  T U R B U L E N T   C O N D I T I O N S   A T  $R_1 = 10^6$   
 $\equiv$  W I T H   R O U G H   S U R F A C E ,   E V A L U A T E D   F R O M   F I G ' S   8   A N D   2 4  
 $\circ$  T U R B U L E N T   B ' L A Y E R   F L O W   A T  $R_1 = 10^7$   
 $-$  O P T I M U M   L A M I N A R   C O N D I T I O N   A T  $R_1 = 4 \cdot 10^5$   
 $\times$  W I T H   N A T U R A L   T R A N S I T I O N   A T  $R_1 = 10^6$

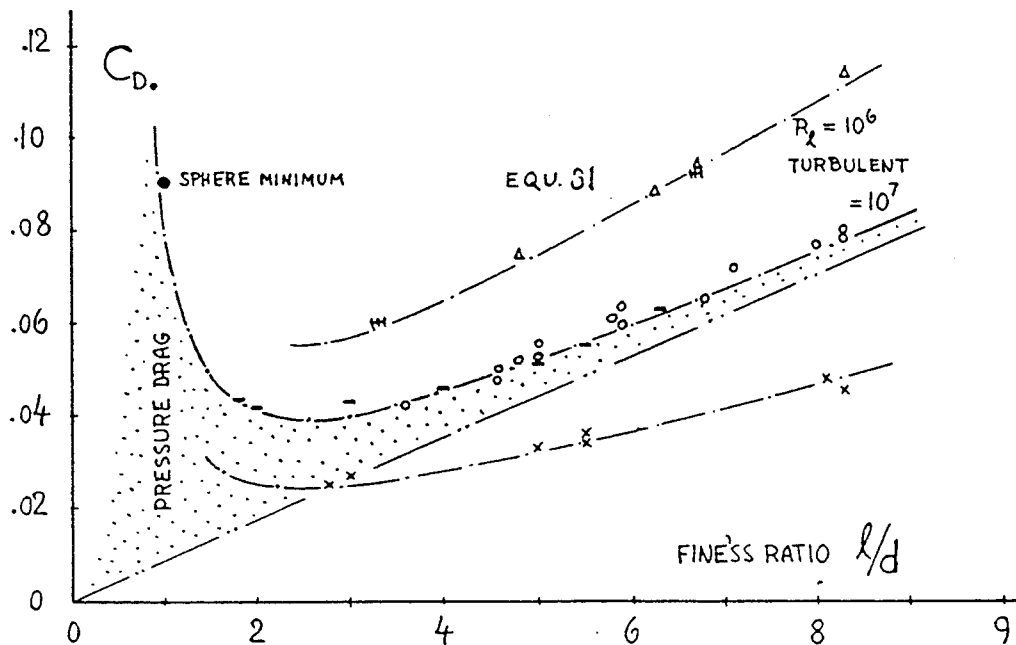


Figure 9. Drag coefficients (on frontal area) of streamline bodies as a function of their fineness ratio (Taken from Ref. 6.2).

This drag-coefficient is related to the width of the body by the following transformation:

$$(VI.X) \quad C_{D_b} = C_D \cdot \frac{\pi}{4}$$

$C_{D_b}$  :  $C_D$  based on width, [-]

$C_D$  :  $C_D$  based on frontal area, [-]

$\pi$  :  $\pi = 3.14...$

In Fig. 10 the lift-curve slope can be read as a function of the latter coefficient.

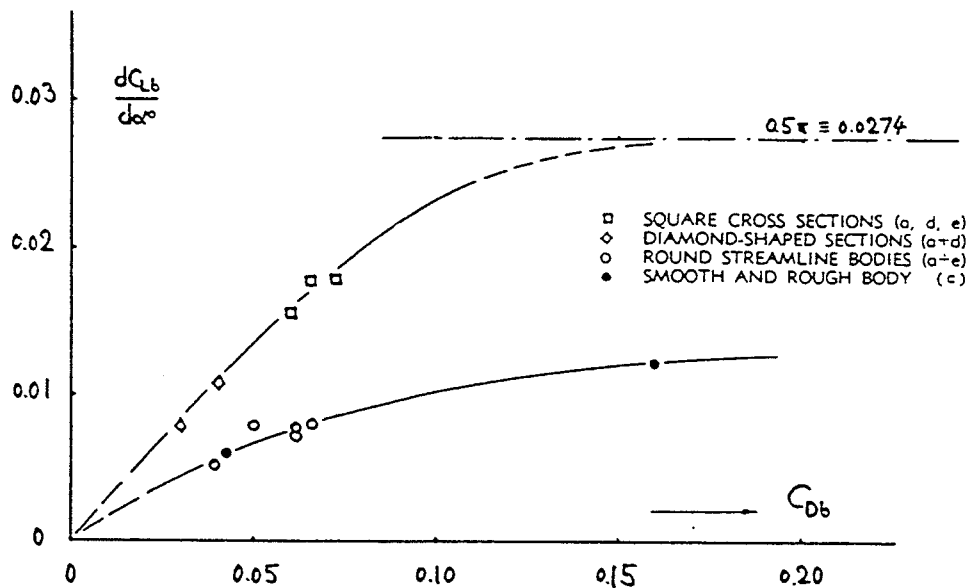


Figure 10. Lift-curve slope of streamline bodies as a function of their drag coefficients (Taken from Ref. 6.2).

From the slope the lift coefficient based on width is then calculated and transformed back to the lift coefficient based on frontal area by using formula VI.X. To this lift coefficient, a non-linear term has to be added:

$$(VI.XI a) \quad C_L = \underbrace{\frac{dC_L}{d\alpha}}_{\text{linear}} \alpha + \underbrace{k \sin^2 \alpha}_{\text{non lin.}} \quad k \cong 0.26$$

$\alpha$  : Angle of attack, [Degrees]

The lift coefficient from VI.XI a) and the factor  $k=0.26$  (Ref. 6.2, Lift of Streamline Bodies, Drag Due to Lift) can be used in formula VI.VIII a) to calculate the additional drag due to lift. The total drag-coefficient finally is

$$(VI.XI b) \quad C_D = C_{D0} + C_{DL}$$

$C_{D0}$  : Coeff. of drag at  $\alpha=0$ , [-]  
 $C_{DL}$  : Coeff. of drag in presence of lift, [-]

Besides: In Ref. 6.1 lift-curve-slopes for bodies with circular cross-section are given in dependence of the fineness ratios typically found on velomobiles. Additionally, sideforce-coefficients can be found in a chapter on blunt bodies for near square and other forms of cross-sections.

### 6.2 Center of Pressure (CP)

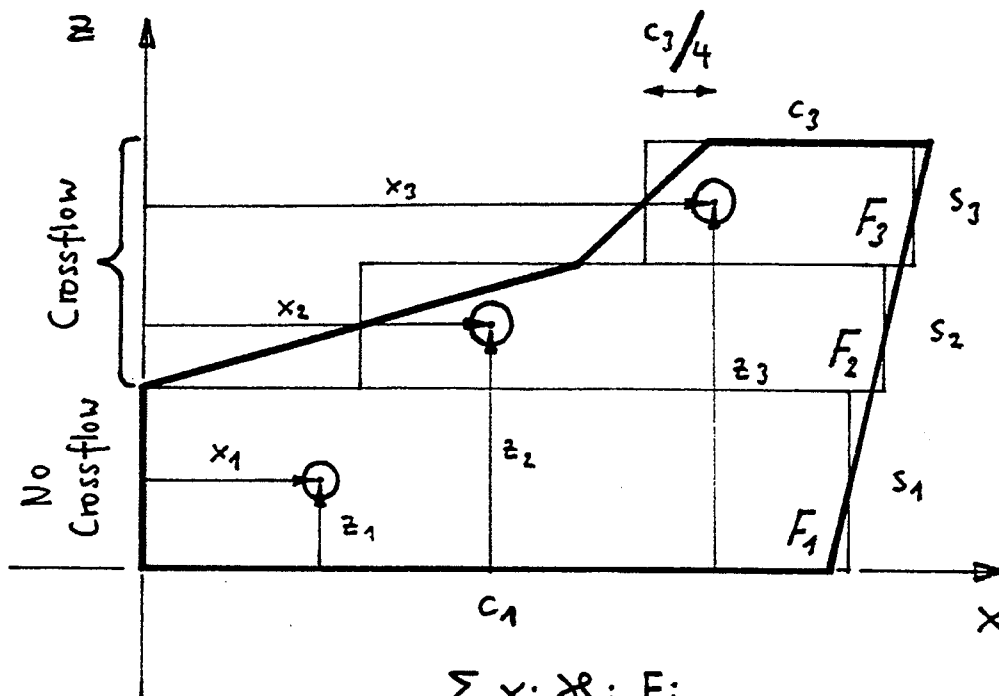
In order to predict torques due to lift on fairings, the locations of the centers of lift or centers of pressure (CP) need to be known. If the pressure distribution along a streamline body at an angle of attack  $\alpha$  was given, the CP could be computed. In windtunnel experiments it is usually not the pressure along flowlines that is measured but the torque relative to a fixed axis. Total aerodynamic force is given by lift and drag, and thus the lever arm and the location of the CP can be derived from the torque and the two forces. Not the torque itself but the moment coefficient is reported. It is defined by

$$(VI.XII) \quad C_M = \frac{M}{\frac{\rho}{2} v^2 A \ell}$$

- $C_M$  : Moment coefficient, [-]
- $M$  : Torque, [Nm]
- $\rho$  : Density of air (See VI.1 b)
- $v$  : Airspeed, [m/s]
- $A$  : Area of reference, [m<sup>2</sup>]
- $\ell$  : Length of reference, [m]

At zero  $\alpha$ , the CP is located on the longitudinal axis of symmetry, but its longitudinal position is not defined. Then drag only acts in the CP and produces a nose-up torque. If the fairing is not rotationally symmetrical, the CP lies in the plane of symmetry. The vertical position of the CP is near the geometrical center of the front view.

For symmetrical airfoils it was found that for small angles of attack the location of the CP is fixed: It is near 25% chord length. Wing-like fairings can be considered as being built up from several rectangular fins all having their CP at 0.25 chord length. By summing moments, the CP of whatever wingshape is computable (Fig. 11):



$$x_{cp} = \frac{\sum x_i \alpha_i F_i}{\sum \alpha_i F_i} \quad \left. \begin{array}{l} \\ z_{cp} = \text{similar} \end{array} \right\} F_i = c_i \cdot s_i$$

$$\begin{array}{ll} \text{No crossflow :} & \alpha_i = 1 \\ \text{Crossflow :} & \alpha_i < 1 \end{array}$$

Figure 11. Center of pressure computation of fins (or velomobile fairings).

(VI.XIII a)

$$x_{cp} = \frac{\sum x_i \alpha_i F_i}{\sum \alpha_i F_i}$$

$x_{cp}$  : Long. pos. of CP, [m]

$x_i$  : Long. pos. of CP of part i, [m]

$F_i$  : Area of part i, [m<sup>2</sup>]

$\alpha_i$  : Weighting factor, [-]

No crossflow: 1, else < 1.

b)  $z_{cp}$  analogous

$z_{cp}$  : Height of CP, [m]

Crossflow-effects are taken into account by weighing down the parts of the wing near its tip. Since only a few parts have to be weighed down, the difference between all weighing factors being one and some being smaller than one is usually small. Since the shapes of fairings are defined by the position of the rider and since there is an optimum position, the existing fairings are quite similar and therefore "Bürk's Rule" (Ref. 6.4) applies (to designs with supine rider position): The CP is at approximately 1/3 vehicle length. The lift-distribution on faired prone position designs is different and has to be calculated using formula VI.XIII (Their CP is further front compared to supine

position designs).

At angles of attack of 90 degrees the CP is near the geometrical center of the sideview, called center of lateral area (CLA). It is found by balancing a cardboard cutout of the sideview: The CM of the cutout is the CLA (The CLA can be calculated with formula VI.XIII if the levers to the geometrical centers of the individual rectangles are taken instead of the levers to the centers at 1/4 chord).

For angles of attack between 10 and 90 degrees, CP location has to be found by interpolating since no simple theories exist and today only measurements give reliable results.

To summarize we note that the CP shifts towards the rear if  $\alpha > 15$  degrees.

For fairings resembling airships or rockets without fins the neutral point (same as CP) or "trim point" can be read from Fig. 12 for angles of attack of up to 30 degrees.

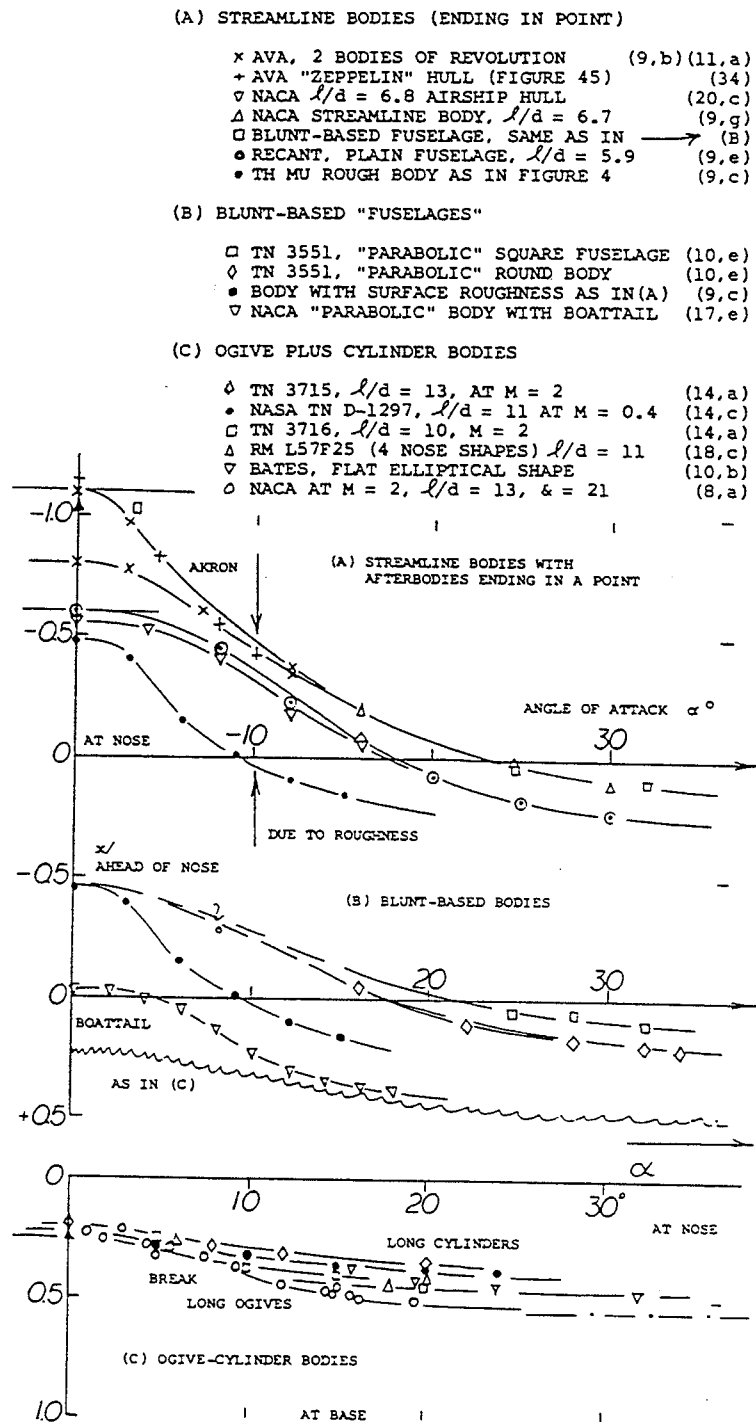


Figure 12. Trim points of various streamline bodies as a function of angle of attack (Taken from Ref. 6.1).

For rocket-like shapes with fins - fairings of wheels in the case of velomobiles - built from simple geometrical shapes (noses, cylindrical bodies, conical transitions, elliptical or trapezoidal fins) the CP and the normal force are computable: See Ref. 6.5. Again, when  $\alpha$  approaches 90 degrees, the CP of all these shapes will be near the CLA.

A summarizing overview is given in Table 4.

Shape	CP-Location [bodylengths]
"Perfect" streamline body	- 1
Streamline body in turbulent air or with rough surface	- 0.5
Blunt-based parabolic-arc bodies	- 0.3
Boattailed cylindrical shapes	- 0.1
Cylindrical afterbody shapes	+ 0.2

Table 4. Center of pressure locations of streamline bodies in bodylengths. Reference point is the nose of the shape. Negative sign means front of the nose. Example: The CP of bodies with cylindrical afterbody shape is 20% of the bodylength behind the nose. From Ref. 6.1.

The influences of shape variations on the CP-location are listed below together with other remarkable points:

- Cylindrical bodies produce nearly no lift up to an  $\alpha$  of 15 degrees.
- Streamline bodies with elliptical cross-sections have a maximum moment-curve-slope (maximum shift of CP with  $\alpha$ ) if the axis ratio is near 2.
- The shift of the CP with  $\alpha$  is bigger for lower fineness ratios and the CP is located more to the front.
- If the forebody becomes a fuller shape the CP moves forward.
- If the afterbody is reduced to a point the CP moves forward.
- If the afterbody is cylindrical with blunt end the CP is more to the rear and the shift of CP is less compared to the same body with a pointed tail.
- The CP of cylindrical bodies with blunt end is always within the nose whatever shape the nose may be (ellipsoidal, paraboloidal, conical or ogival).
- Boat tails shift the CP forward because their lift is pointing to the upwind side.
- If a streamline body does not have a pointed but a wedge-like tail, the shift of the CP with  $\alpha$  is lower and its location is not as far front.
- Fins (wheel fairings) near the rear move the CP back more and more the higher their aspect ratio is. Adding fins is the most effective design measure to shift the CP towards the rear.

## 7. Static Stability

### a) General Remarks

As we have seen for frictional and aerodynamic forces, the center of the distribution of any force can be calculated exactly in the same way as for the gravitational forces: By summing torques generated by the distributed forces (also called first moments) and dividing by the sum of all the forces (the total force):

$$(VII.Ia) \quad x_{center} = \frac{\sum x_i f_i}{\sum f_i}$$

b)  $y_{center} = \dots$

c)  $z_{center} = \dots$

$x_{center}$  : Long. pos. of center of ..., [m]  
 $f_i$  : Any force, [N]  
 $x_i$  : Point of attack of  $f_i$ , [m]

The torques that try to rotate the velomobile are then easily computed (and compared to the torques induced by the rider to steer the vehicle):

$$(VII.II) \quad T_f = (x_{center} - x_{cm}) \sum f_i$$

$T_f$  : Torque, [Nm]  
 $x_{cm}$  : Long. pos of CM, [m]  
 Other design. as with VII.I

Generally, the torques that have to be taken into account are those from frictional and aerodynamic forces. If all wheels lost ground-contact, the only forces that produce an external torque are the aerodynamic ones.

Under external torques (by aerodynamic forces for example) a velomobile rotates around axes through its CM (center of mass) whether or not all wheels are in contact with the ground.

Three types of static stability exist: Negative, neutral and positive.

A vehicle is positively stable if it automatically returns to the original state of movement after having been disturbed. The orientation of the torques that build up at an angle between the intended and the actual direction of travel and at an angle of attack is such that these angles are reduced.

Stability is negative if the reaction to a disturbance is parallel to what was induced by the disturbance itself: The deviation from the intended path becomes bigger even faster and the mobile never returns to the original state of movement.

A velomobile is neutrally stable, if, according to formula VII.II, no torque exists (lever zero) that either turns the mobile back (positively stable) or increases the deviation from the original direction of travel (negatively stable). But the total force (acting in the center of friction or center of pressure) pushes the velomobile sideways.

Since wheels sometimes lose ground contact, it is important that a velomobile is not highly aerodynamically unstable (negatively stable).

Negative static stability is not generally bad. A normal bicycle for example is statically unstable in roll. We know that bicycles can be ridden very well, if their speed is not too low. Therefore dynamic stability is as important for functionality as is static stability.

Conversely, static stability does not assure dynamic stability: Torques may have the proper direction of turn to potentially re-establish equilibrium, but for example they may be too weak to overcome inertia. Of importance is primarily the magnitude of positive or negative stability. But negative stability has to be controllable (in most situations) by steering commands in order to be acceptable.

Entities similar to the moment of inertia (also called secondary moments) could be calculated for other forces: If for example they are aerodynamic, this parameter is called aerodynamic damping moment coefficient (Ref. 6.5). The decay rates of wobbles around the roll, yaw and pitch axes depend on the damping moment coefficients.

Therefore these coefficients are important in studies of dynamic stability and we do not consider them here in more detail.

By summing moments, the frictional and the aerodynamic forces could be combined to a single force acting in a single center. But this way of analysis may be interesting only when looking at special situations.

With the linear and angular accelerations that are computable from the forces and the torques, simple kinematic calculations can be done. If for example during a jump  $\alpha$  is increased to a magnitude that can not be corrected by countersteering after having landed or if the angles between intended and actual direction of travel could increase

very much during the reaction time of a human being, then the velomobile considered is uncontrollable and therefore dangerous.

#### b) Stability of multi-track velomobiles

A multi-track velomobile is aerodynamically unstable (negatively stable) if the CP (center of pressure) lies front of the CM (center of mass). CP and CM at the same position would mean neutrally stable, whereas CP behind CM means (positively) stable. In a jump, positive aerodynamic stability is welcome. But if the lever between CP and CM is too long, the vehicle would be very sensitive to crosswind and front waves of trucks.

The rider is able to influence the torque produced by the frictional forces by means of the controls. Therefore, an aerodynamically unstable (negative stable) vehicle can finally become (positively) stable if the torque of the steering force is bigger than that produced by lift (==> Trikes in applications a and b below).

#### c) Stability of single-track velomobiles

As already mentioned in chapter 1, roll-yaw-coupling is the very characteristic of single-track vehicles (bikes). They can only fully be described if dynamics are considered. But some qualitative statements are possible.

In Ref. 7.1 Doug Milliken reports the results of some experiments undertaken to find the best location for the CP (center of pressure) of a single-track velomobile. Contrary to intuition it was found that if the CP was in front of the CM (center of mass), the bike was easier to control and that it was easier to keep it on a straight path. He summarized this in saying that for bikes controllability is more important than inherent stability.

Matt Weaver simulated the performance of the single-track racing-velomobile he planned to build and tried to adjust the CP-CM-relation in order to get as little sensitivity to crosswind as possible. The CP of his finally built bike, "Cutting Edge", actually lies well in front of the CM. In Ref. 7.2 he writes that he has to steer gently out of wind. Since Matt placed far ahead in a number of IHPVA-races this is probably a weak proof of Milliken's findings.

We therefore conclude and summarize that for controllability (which is not the same as stability!) the CP of bikes should be in front of the CM.

If bikes with the CP in front of the CM - controllable ones - loose ground contact, they don't stop turning if once they have started to do so. Suspensions could help to minimize the probability of such situations.

### 8. Applications

#### a) *Center of pressure (CP) and center of mass (CM) of some recent velomobiles.*

From photographs showing the sideviews of the vehicles, the location of the CP was calculated and the CM was estimated by assuming that it is identical to the rider's CM. The locations are given in percent of the total vehicle length with a precision of several percent. This is good enough to illustrate the state of the art in balancing the relative position of the two most important centers (Table 5).

For comparison formula VI.XIII (applicable to fins) was used to calculate the CP of all designs although this is not correct. Mavic, Cutting Edge and Windcheetah are aerodynamically more similar to airships and their CP actually lies further front of the tabulated ones.

Velomobile	x <sub>CM</sub>	x <sub>CP</sub>	x <sub>CLA</sub>	x <sub>F</sub>	x <sub>R</sub>	d	(x <sub>CP</sub> -x <sub>F</sub> )
	All in % of bodylength						
BIKES:							
Desira	62	40	58	28	78	-22	+12
Lightnings:							
- Mark Wyss	52	32	53	29	80	-20	+3
- X-2	52	37	56	31	78	-15	+6
92-Mavic (Delcroix)	56	35	56	35	80	-21	0
Cutting Edge	61	31	55	44	88	-30	-13
TRIKES:							
Standard Leitra	53	32	55	41	78	-20	-8
Windcheetah (*)	49	31	55	39	85	-18	-8

(\*) Older version of fairing

x <sub>CM</sub>	Longitudinal location of CM
x <sub>CP</sub>	Longitudinal location of CP
x <sub>CLA</sub>	Longitudinal location of CLA
x <sub>F</sub>	Longitudinal location of front wheel
x <sub>R</sub>	Longitudinal location of rear wheel
d	= (x <sub>CP</sub> - x <sub>CM</sub> )

Table 5. Center of pressure (CP) and center of mass (CM) locations of recent velomobiles. The location of the CP was calculated on the basis of photographs showing sideviews and the location of the CM was estimated based on the guessed position of the rider. Both should be precise to several percent of vehicle length, still good enough to see the characteristics of the different concepts.

References to pictures (Not the ones used to get the dimensions for the calculations): Desira Ref. 8.5, Lightning Mark Wyss Ref. 8.1 and Standard Leitra 8.5. All others Ref. 8.2: Lightning X-2 p. 80, 92-Mavic p. 120, Cutting Edge p. 43 and Windcheetah p. 81.

Tables like No. 5 allow to reproduce good handling characteristics since the CP-CM-relation is the key parameter governing stability in crosswind. If the behaviour of the tabulated vehicles is known from observations or interviews with their riders, then a convenient set of values for d and (x<sub>CP</sub>-x<sub>F</sub>) can be chosen for own designs. Interestingly enough, the CP's of all vehicles lie in front of their CM (d < 0). In cases of negligible roll-yaw-coupling, that is if there are more than two wheels, the vehicles will turn out of wind in crosswind-situations (Ref. 6.4). If the lever arm between CP and CM is too long, the rider will have to steer very much against the wind. The wheels will roll all the time at a slip angle, which yields higher rolling resistance. If the crosswind is gusty or if the gust is the front wave of a truck, such a vehicle will react very quickly, sometimes too quickly to be safe for rider and vehicle. Therefore the leverarm should not be very long. But at least they will turn away from the trucks! C.G. Rasmussen once rode his Leitra in a storm (Approx. 25 m/s windspeed) with the wind coming from a direction rectangular to the street: He found that the Leitra was pushed sideways but did not start to turn (personal communication). This is in good agreement with the calculations: According to the results the center of lateral area CLA (which is the center of pressure at  $\alpha = 90^\circ$ ) is near the CM! Thus the length of the lever CP-CM is nearly zero as are the torques.

Bikes experience extensive roll-yaw-coupling. According to what is discussed in chapter 7 part c) the tabulated single-track velomobiles (having the CP in front of the CM) will turn into the wind as long as their wheels contact the ground.

Delcroix found that his "Mavic"-streamliner was easy to keep going straight in crosswind (personal communication). The CP-CM-relation of this design as well as the location of the front wheel are therefore close to optimum.

Probably the location of the CP is not very critical in multi-track vehicles as long as the distance between CP and CM is not very big (Smaller than or equal to 20% of the vehicle length, as shown by overall positive experiences with the Leitra). The optimum distance (For everyday or for racing use / In low, strong or usually heavy wind) has yet to be found for bikes as well as for trikes and quikes. This could be done by developing and running dynamic velomobile computer-models and studying the reactions to disturbances (steady crosswind and wind-gusts, front waves and suction in rear waves of trucks and movements induced by a wavy surface of the ground).

*b) Static yaw stability of a multitrack velomobile on the example Leitra (Same as in application a)*

The sum of the torques by lift on the fairing and lateral forces on the wheels was calculated (with a commercial spreadsheet computer-code) for different combinations of angle of attack and steering angle of the front wheels. No-wind was assumed. The results are given in Table 6.

Angle of attack [Deg]	Steering angle [Deg]	Slip- angle [Deg]	Resulting Torque [Nm]		
			Velocity [m/s]		
			5	10	20
0	0	0	0.0	0.0	0.0
0	1	1	30.6	30.6	30.6
0	2	2	60.4	60.4	60.4
0	3	3	88.7	88.7	88.7
0	4	4	114.8	114.8	114.8
0	10	10	195.3	195.3	195.3
0	0	0	0.0	0.0	0.0
1	0	1	0.4	1.4	5.8
2	0	2	0.7	2.9	11.5
3	0	3	1.1	4.3	17.3
4	0	4	1.4	5.8	23.0
10	0	10	3.6	14.4	57.5
0	0	0	0.0	0.0	0.0
1	-1	0	-30.2	-29.1	-24.8
2	-2	0	-59.6	-57.5	-48.9
3	-3	0	-87.6	-84.4	-71.4
4	-4	0	-113.4	-109.1	-91.8
10	-10	0	-191.7	-180.9	-137.8

Table 6. Torques on Leitra at several velocities for different combinations of angle of attack and (opposite) steering angle. (Conditions assumed: 380 N load per wheel, all wheels produce lateral forces, lateral forces from fit to the measurements by Kyle on the 17" x 1.25" Moulton tire, CP 15 cm in front of the front axle, no crosswind,  $\rho = 1.2 \text{ kg/m}^3$ , lift-curve slope at 0.036 per degree, area of fairing 1.6 squaremeters.)

If Leitra jumps over a rise in the street surface such that no wheels touch the ground and the start of the jump is at an  $\alpha$  greater than zero, then the torque by lift will increase  $\alpha$ . If the rider steers with the same but opposite steering angle after having landed after a very short time, an  $\alpha$ -reducing torque exists. Since aerodynamic forces are proportional to the velocity of the airstream squared, the corrective moment is reduced with increasing speed. If the duration of the flight has been long enough, angular velocity has been built up and  $\alpha$  may have a magnitude too big to be reduced again by counter-steering. For  $\alpha = 4$  degrees, zero steer angle and a velocity of 10 m/s, initial acceleration of the rider-vehicle-combination having an overall MOI (moment of inertia) of 10 kgm<sup>2</sup> will be 0.6 Rad/s<sup>2</sup>. After a time of 2 seconds only  $\alpha$  will have increased to approximately 60 degrees! Situations as these are very dangerous, because at high angles of attack the drag increases considerably and slows down the Leitra very fast. Following cars would not be able to stop before crashing into the rotating velomobile! Or the lift could push the vehicle in front of a car on the other lane or into the sides of the street.

Therefore, on down slopes the speed should be kept at a limit of say 10 meters per second to minimize the probability of a turn around the vertical axis of the vehicle.

The Leitra has a very short wheelbase which makes it agile in traffic and in avoiding potholes and obstacles. The price paid for this is a high pitch-excitability. Angles of attack in pitch-direction further increase drag and on bumpy downhill slopes maximum speed should be even better controlled.

A long wheelbase and the CP near the CM are characteristics of fast and longitudinally stable velomobiles.

Only velomobiles with the CP rear of the CM would keep their direction of travel upon jumping. In crosswinds and in front waves of trucks such mobiles would turn into the relative wind. How fast depends mainly on the length of the lever CM - CP.

*c) Propulsion of multitrack velomobiles by crosswind on the example of the Leitra (Same as in application a)*

The propulsive force due to lift was calculated for several angles between the velocity-vector of the velomobile and the crosswind blowing at a constant rate: Table 7 and Fig. 13. These two velocities add vectorially (change sign of the mobile's velocity) to the relative wind: The example was calculated at 5 m/s groundspeed and 10 m/s crosswind. It was found that if the relative wind comes from an  $\alpha$  of between 8 and 9 degrees, the drag changes sign from resistive to propulsive. With an ever-increasing  $\alpha$  the propulsion would become stronger and stronger if not separation of the flow on the downwind side of the fairing occurred. At zero  $\alpha$  the power needed to overcome drag is more than 30 Watts. At 12 degrees between crosswind and velomobile-velocity these 30 Watts are delivered by the wind. Compared to the 75 W delivered by a touring bicyclist 30 W are a lot (Ref 5.1.).

Dir. of Wind	Alpha	Fres	Power
[Grad]	[Grad]	[N]	[W]
0	0.00	-6.56	-32.81
1	0.67	-6.65	-33.24
2	1.33	-6.62	-33.09
3	2.00	-6.48	-32.39
4	2.67	-6.22	-31.12
5	3.33	-5.86	-29.31
6	4.00	-5.39	-26.96
7	4.67	-4.82	-24.08
8	5.34	-4.13	-20.67
9	6.00	-3.35	-16.74
10	6.67	-2.46	-12.29
11	7.34	-1.47	-7.33
12	8.01	-0.37	-1.87
13	8.67	0.82	4.08
14	9.34	2.11	10.53
15	10.01	3.49	17.47
20	13.36	11.85	59.23

Table 7. Propulsion of a Leitra at 5 m/s groundspeed by a crosswind of 10 m/s. (Conditions assumed: Mostly the same as for Table 6. Only the front wheels produce countertorque to lift, lift-curve- and drag-curve-slopes 0.036 and 0.001, coefficient of drag at zero angle of attack 0.03)

## Propulsion by Crosswind

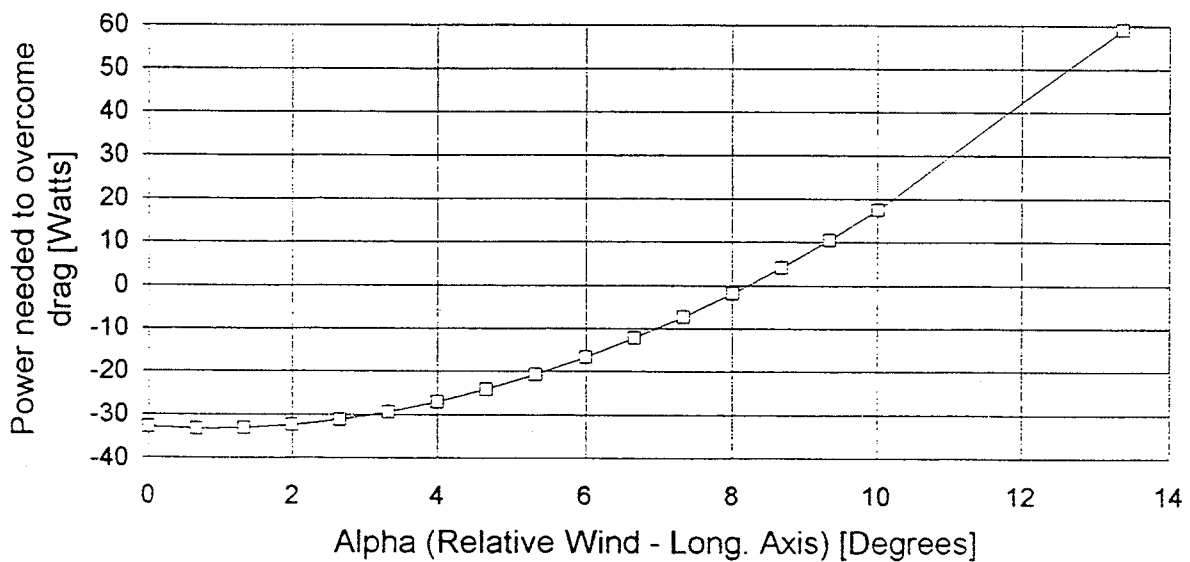


Figure 13. Propulsion of a Leitra at 5 m/s groundspeed by a crosswind of 10 m/s. Plot of data from Table 7.

This finding is compatible with what is experienced when actually riding a Leitra in crosswinds and with what is also shown in Reference 8.3.

A debate on "negative" drag took place in several issues of BIKE TECH. See Ref. 8.4 for a compilation of the issues.

*d) Riding in crosswinds and cornering with single-track vehicles*

To check the hypothesis that lift on the front part of fairings makes single-track velomobiles fall over, steady state turn was analyzed. Compared to the situation with no lift, the lean angle of a velomobile with a lifting fairing has to be bigger so that the torque due to gravity compensates the torques of the centrifugal- and the lift-force. Therefore, since the maximum lean angle is limited (proportional to the inverse tangent of the adhesive friction coefficient), the maximum velocity in corners in the presence of lift is reduced. But this reduction is only several percent of the maximum velocity which can be attained with no lift and the vertical component of the lift force working against gravity is much smaller than the wheel-load of, for example, the front wheel. (Long wheelbase recumbents have the least amount of load on their front wheel compared to medium or short wheelbase designs. Therefore load reduction on the front wheel by lift is most severe on long wheelbase single track velomobiles.) From all this we conclude that lift is not the sole reason for the tip-over of faired single-track vehicles, also since this may happen not only in corners but also on straights. Another possible explanation is that bikes with fairings suffer from stalling as airplanes do when they are flying at high  $\alpha$  and at low speed. Stalling happens when suddenly at a certain  $\alpha$  (with thin airfoils usually between 10 and 20 degrees) the drag increases very much and the lift vanishes. As a consequence a fast and high loss of kinetic energy occurs.

Airplanes then have to dive to gain the lift-producing velocity again. Stalling near the ground is therefore fatal.

Faired single-track velomobiles are unstable at very low speeds because the rider can not shift the CM a lot by moving his body. Low speed is the same as low kinetic energy. Therefore, after a loss of kinetic energy due to suddenly increased drag, the vertical position with its maximum of potential energy may never be reached again (Remember: Kinetic energy can be transformed to potential energy and back again): The faired bike falls!

The drag increases at high angles of attack due to separation of the airflow from the surface of the fairing. High angles of attack are encountered either in corners or in crosswinds on straights. There are means of minimizing the risk of flow-separation which normally are in use with STOL-airplanes (short takeoff and landing) and with model airplanes specially built to sail in thermals such as leading-edge slots or slats, camber or the deflection of nose flaps, boundary-layer control by blowing or by suction and turbulators. Some of them could also be used for velomobiles. See Ref. 6.1 for further details.

Do not only minimize the coefficient of drag  $c_D$  at  $\alpha = 0$  degrees. As mentioned earlier, blunt nose shapes prevent premature separation and bodies with cylindrical cross-sections have lower lateral drag than fin-like fairings. Blunt noses and cylindrical cross-sections are the simplest design measures to assure low drag at higher angles of attack.

*e) On the stability of practical vehicles*

The velomobile pioneers dream of a widespread use of their vehicles by the public. But among them, there exists no consensus on what the practical velomobile of the future should look like: Conventional bike or recumbent, partially or fully faired, two or more wheels? In the racing scene, there is a tendency towards single-track vehicles that are sometimes partially faired. On the other hand, fully faired vehicles considered to be practical are with the exception of Desira (Ref. 8.5) all three wheeled: The classical ones Leitra and Windcheetah and the newer ones Alleweder, Jouta and Kingcycle K3.

Considering stability, we find that few or no single-track (fully) faired vehicles exist that are easy to ride also in strong, gusty crosswind. The roll-moments of inertia of most such designs are too big to ride them safely in such wind, because the actual path will oscillate with a big amplitude around the mean straight path. Desira for example is probably easy to steer in no-wind-conditions, whereas riding it on windy days might be difficult. Threewheelers are safer in gusts because they do not suffer from extensive roll-yaw-coupling and are therefore easier to keep going straight.

Today, velomobiles can not rely on a complete network of routes specially made for them. So they have to mix with the other traffic. An important measure for the practicality of a velomobile is therefore the "apparent width". This is the space needed by a velomobile to go straight under even the worst weather conditions. Often, the space needed by single-track vehicles is much too wide compared to the width of the lane, and automobiles can not overtake if there is oncoming traffic.

Apparent width of a single track velomobile:

(VIII.I)

$$AW \leq 2(\emptyset + H \sin \varphi + \frac{1}{2} EW \frac{1}{\cos \varphi})$$

AW : Apparent width, [m]

$\emptyset$  : Amplitude of tirepath, [m]

EW : Effective width, [m]

H : Height above ground of effective width, [m]

$\varphi$  : Maximum lean angle, [Degrees]

Maximum lean angle = inverse tangent(coefficient of friction).

Apparent width of a multitrack velomobile is given by VIII.I for zero lean angle:

(VIII.II)  $AW = 2\emptyset + EW$

Designations as for VIII.I

It follows that bikes are only "narrow" under ideal conditions. Then their effective width is smaller than the one of multitrack vehicles which is very convenient in dense rush-hour traffic, whereas with a Leitra for example, it is impossible to overtake cars in a bank-up since its track is nearly 1 m.

Lowering the CM and the CP of single-track velomobiles as much as possible probably would allow vehicles that combine small effective width (important in dense traffic) with small apparent width (roll-stability in gusty crosswind).

Single-track velomobiles with stability parameters ( $x_{CP}-x_{CM}$ ) and ( $x_{CP}-x_F$ ) near or similar to those of L. Delcroix '92-Mavic-Racer (==> Application a) would be near to optimum.

Of course, other problems would arise with such low vehicles: The field of view would be lower than that of car-riders and people would consider them to be dangerous although this might not actually be true (Most people feel safer on a normal bike than on a recumbent even though they would fall much deeper!).

#### Final remarks

The author hopes that the overview given will help designers of velomobiles to avoid basic design flaws, to improve existing concepts and to tune their vehicles to the optimum. Static stability calculations might be useful in some more situations than the ones treated in the applications a) to e).

It is important for the understanding of velomobile behaviour that computer-models will be made that are not based on as simplifying assumptions as the bike-models that exist today and that will include also the rider-movements, the influences by suspensions and the forces on fairings.

#### Acknowledgement

The author thanks David Picken, Carl Georg Rasmussen and Andreas Weigel for reviewing the paper.

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## THE TEST-VEHICLE MULTILAB AND ITS NEW FRONT-WHEEL-GEOMETRY

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### Introduction

The test-vehicle Multilab was designed to test the effect of different design parameters of a single-track-HPV on security, controlability and strain of the driver-HPV-system in road traffic. It is an unfaired, short-wheel-based (SWB) recumbent bicycle with several adjustable parameters : wheelbase, track and head-angle. In addition to this different handlebars, seats and suspension systems are interchangeable (Fig. 1).

Several physical and physiological measurements as well as subjective rating scales are used to evaluate the different designs (Table 1). As can be seen in Figure 1 the Multilab has an unconventional front-wheel-geometry. The following explanations will show the reasons why we did so and describe further advantages and disadvantages.

Stress	Driver	Action	Strain
Test route	Sex	Electromyogram of	Heart rate and variability
Design-parameters	Age	m. vastus medialis and	Skin conductance
Driving task	Body size	triceps brachii	Electromyogram of forehead and abdomen
Video	Driving experience	Steering angle	Blink activity
			Rating-scale

*Table 1: Measurement concept*

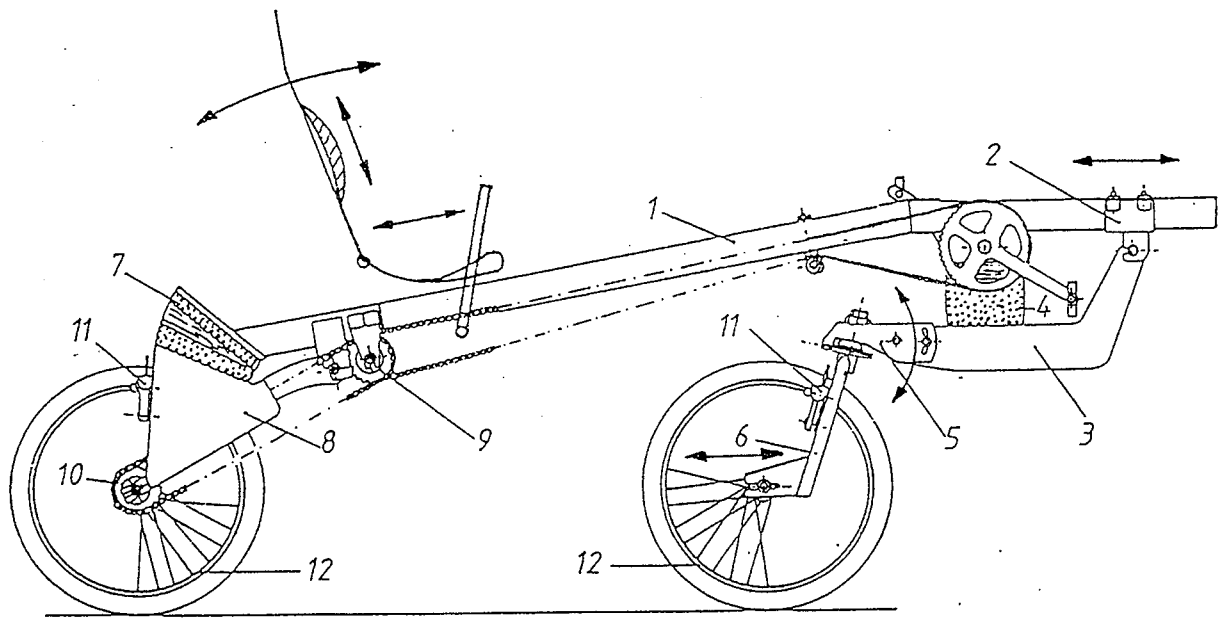


Figure 1: The test-vehicle Multilab.

### Space Saving

Everyone who has ever tried to build a short-wheel-based (SWB) recumbent bicycle knows the problem of collision between the drivers feet and the front-wheel during crank rotation in tight curves (Figure 2).

It can be solved by placing the front-wheel closer to the rear wheel. A consequence of this is a poor braking performance (brake loop) and a high front wheel load. The problem will be increased by small drivers (center of gravity more in front).

The other solution is to use an asymmetrical mounting of the front wheel and steering axle. The new geometry has a mirror-symmetrical headangle to the normal geometry and the same track (Figure 3). For the given configuration ( $\alpha = 10^\circ$ ,  $n = 50\text{mm}$ ,  $R = 200\text{mm}$ ) the collision free steering angle increases from  $17^\circ$  for the normal geometry to  $32^\circ$  for the new geometry (Figure 4). This is sufficient for all practical relevant manoeuvres including narrow turns. If a 20 inch wheel is used, the steering angle increases from  $12^\circ$  to  $21^\circ$ . This is not enough for all manoeuvres, but sufficient for racing and sport.

For the test-vehicle Multilab this offers the opportunity to increase the wheelbase from 900mm to 1100mm, which is 22%.

The result is a medium wheel based HPV. The improvement in maximum breaking deceleration (rear wheel loses ground contact) for a small rider (body size 1500 mm) is from 0.36g to 0.64g (78% increase), and for a tall rider (body size 2000 mm) from 0.86g to 1.14g (33% increase). In comparison the maximum breaking deceleration of a standard racing bicycle is about 0.55g, depending on the leg length of the rider.

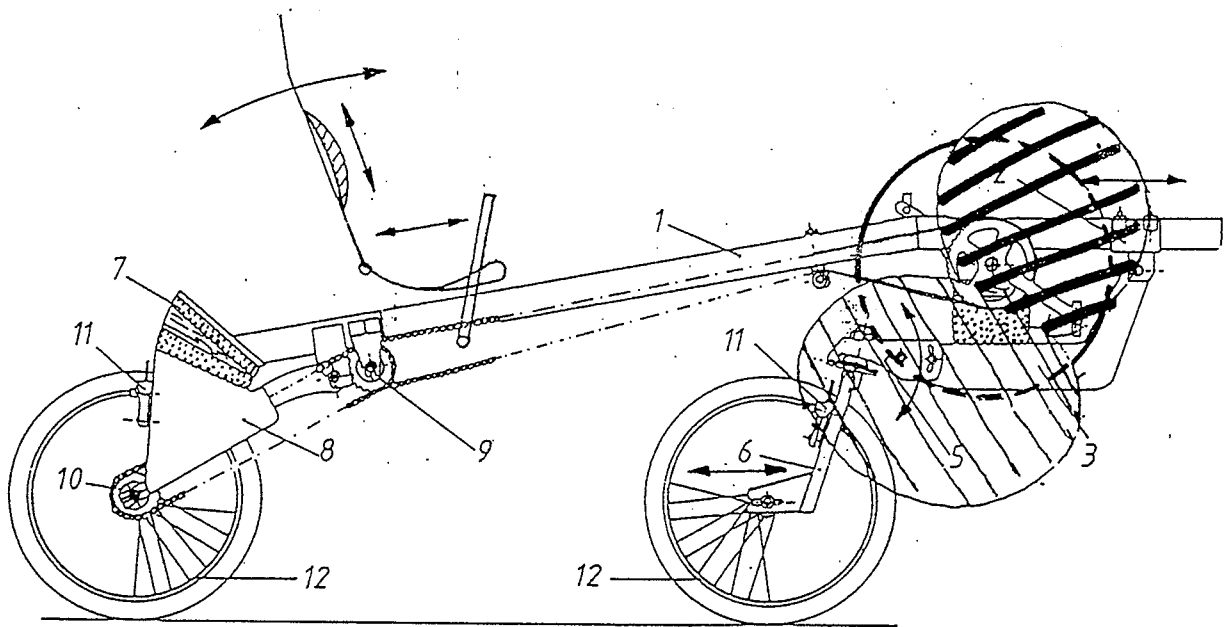


Figure 2: Collision of front wheel and feet.

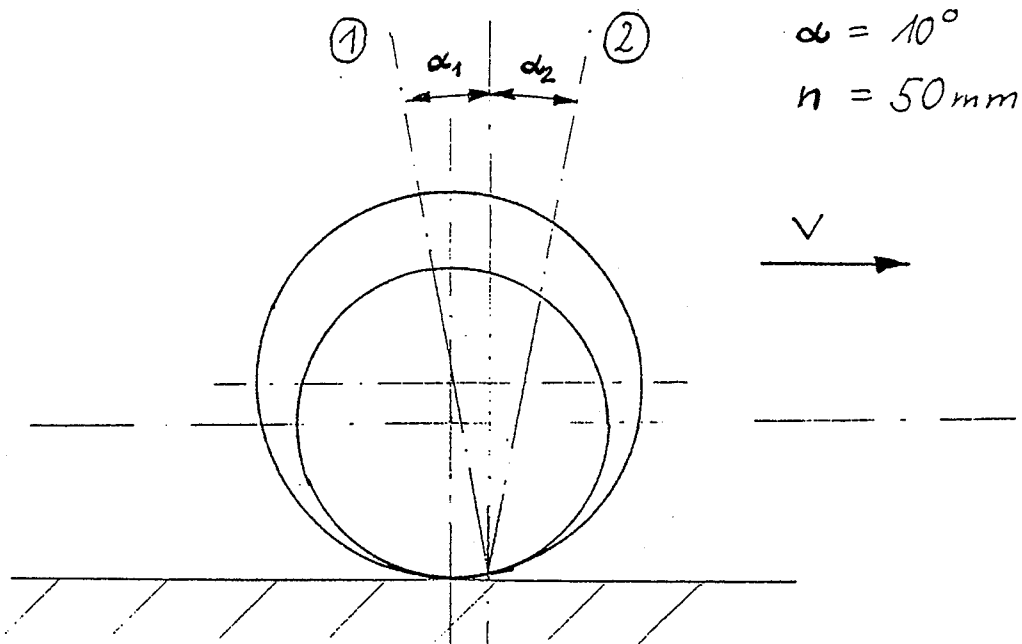


Figure 3: Conventional (1) and new (2) mirror-symmetrical geometry ( $\alpha = 10^\circ$ ,  $n = 50 \text{ mm}$ ,  $R = 200/250 \text{ mm}$ )

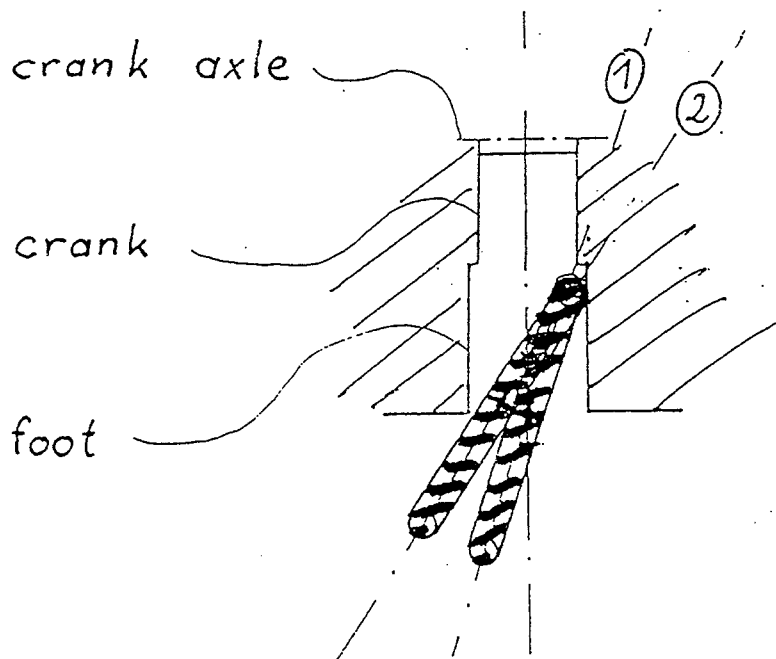


Figure 4: Collision free steering angle for conventional (1) and modified (2) geometry ( $\alpha = 10^\circ$ ,  $n = 50 \text{ mm}$ ,  $R = 200 \text{ mm}$ ).

### Steering torques

In the following we will look qualitatively at the changes in steering forces and torques, neglecting gyroscopic effects. They are not relevant under city traffic conditions (low speeds;  $< 20 \text{ km/h}$ ) and for vehicles with small wheels ( $R = 200 \text{ mm}$ ).

The steering torque caused by the track increases according to a sinus-function with the steering angle, as shown in Figure 5. The curve gets steeper with increasing track and velocity and more acute head angle. This is valid for the conventional as well as the modified geometry.

The steering torque caused by the head angle is decreasing with  $-1 + \cos \varphi$  for the conventional geometry and changes sign for the modified geometry (Figure 6). The reason is, that the center of gravity normally sinks but is lifted by using the mirror-symmetrical geometry. This effect increases in the specific direction by a long track, a small wheel and a flat head angle. The resulting steering torques are shown in Figure 7.

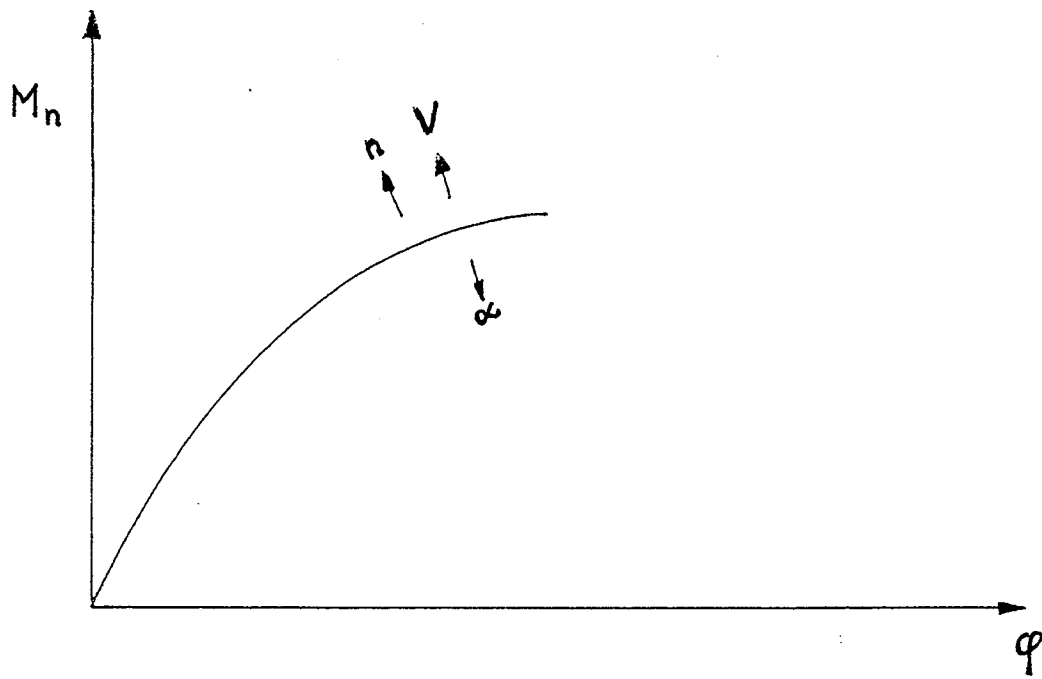


Figure 5: Steering torque caused by the track.

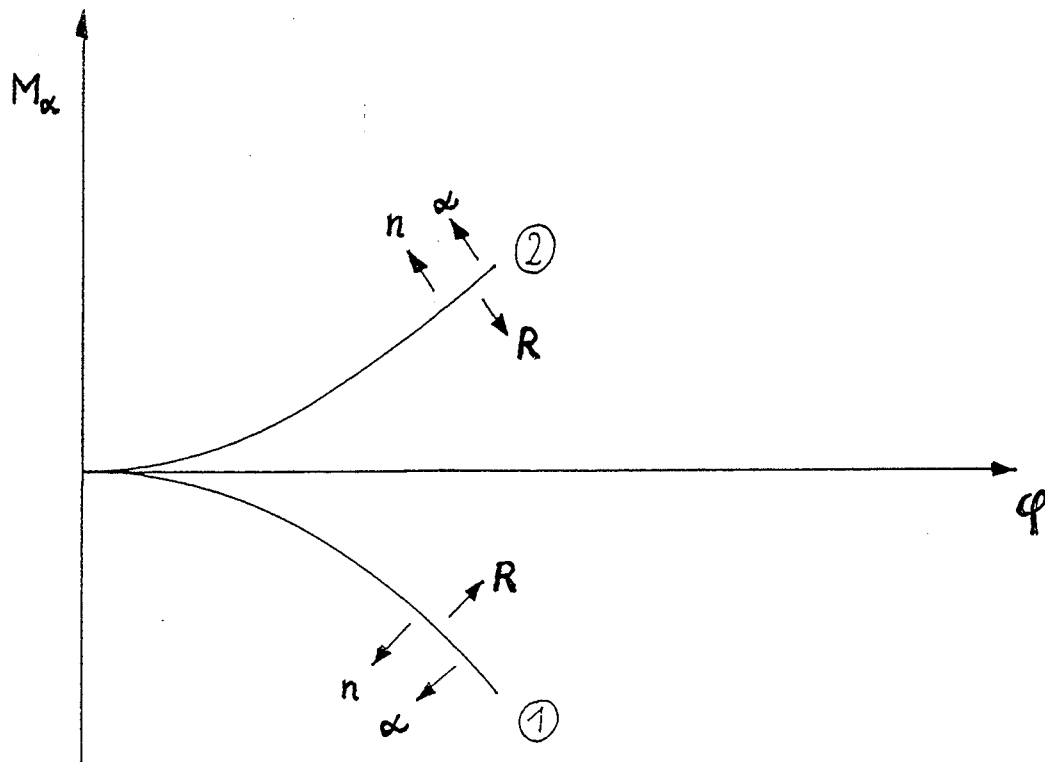


Figure 6: Steering torque  $M$  caused by the head angle for conventional (1) and modified (2) geometry.

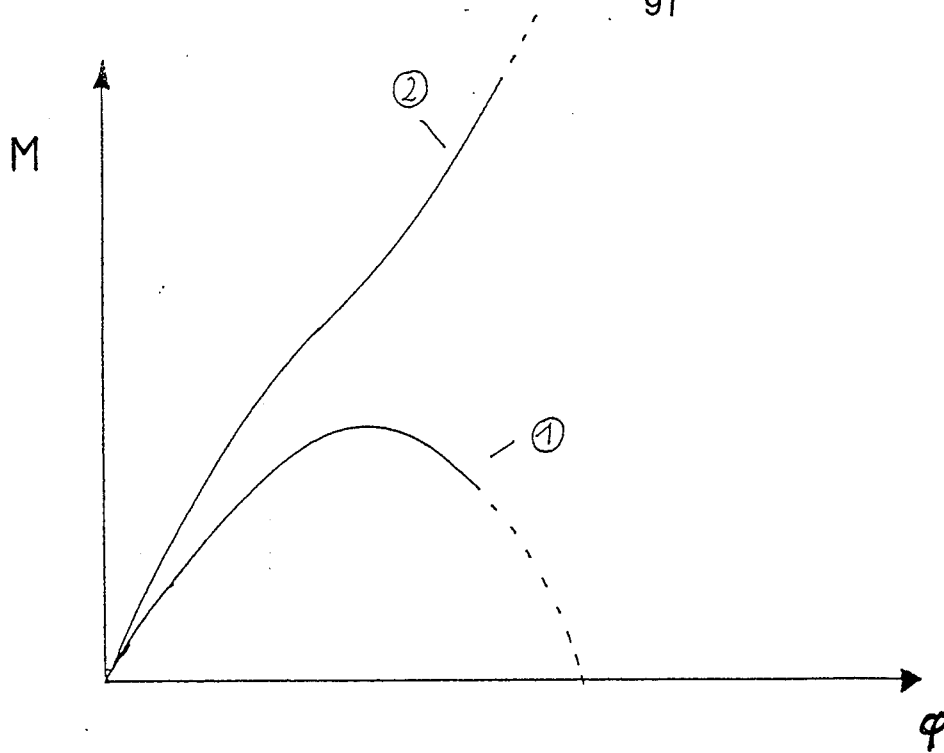


Figure 7: Resulting steering torques for conventional (1) and modified (2) geometry.

### Obstacle Crossing

When the vehicle meets an obstacle of the height  $h$  with a steering angle  $\varphi$ , this causes a destabilization torque. The perpendicular to the steering axle of the force  $F(h)$  is shorter for the modified geometry than for the conventional geometry (Figure 8). So the effective lever length  $d_1$  of  $F(h)$  is shorter than  $d_2$ . For the given geometry data the destabilization torque is exactly 25% smaller for any obstacle height.

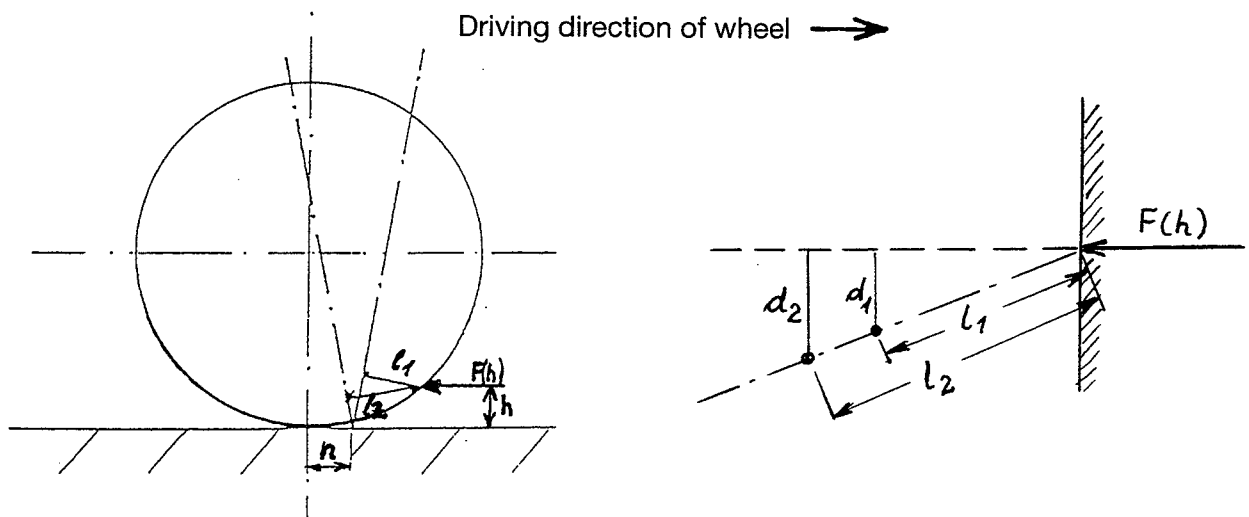


Figure 8: Side view and top view of front wheel during obstacle crossing.

### Aerodynamical effects

From conventional bicycles it is well known, that disc wheels in front cause difficulties in steering and stabilization. The reason is, that the area in front of the steering axle has nearly the same size (or is bigger) than the area behind.

The aerodynamical forces increase proportional with wheel size and square of speed. This can be used for positive effects with the modified geometry and relatively small wheels. As seen in Figure 9 the area in front of the steering axle is now much smaller than the area behind. This causes a stabilizing effect.

In addition the driver gets a kinesthetic signal about side winds through the steering. It is the same signal mode that he knows well from rough roads and obstacles. So the same mechanisms of irritation and reaction can be used successfully. That is important for fully faired vehicles.

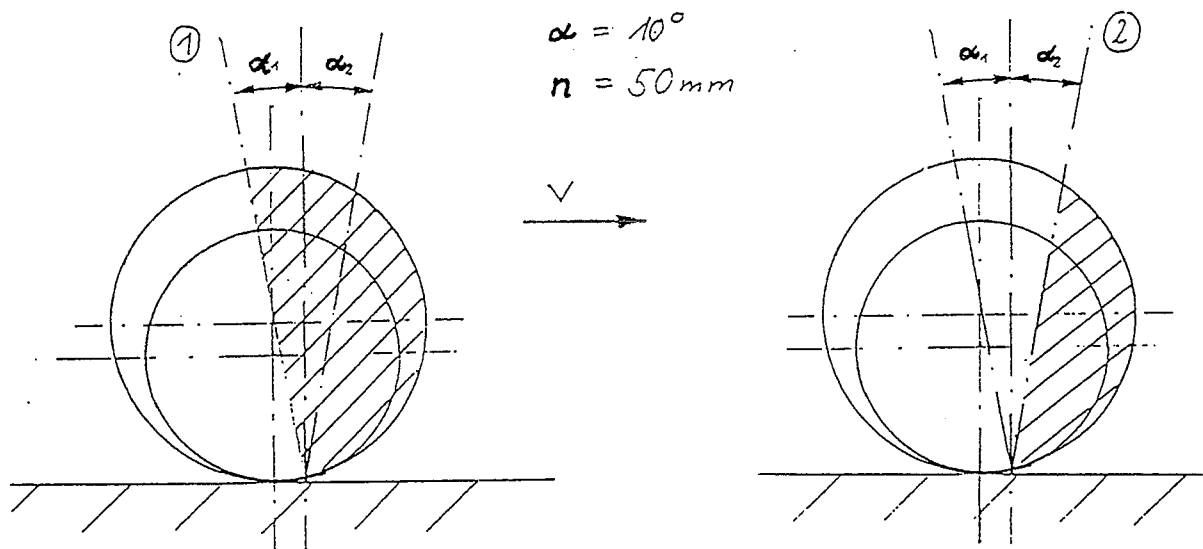


Figure 9: Aerodynamical effect of disc wheel on conventional (1) and modified (2) geometry.

### Wheel stress

In addition to all the advantages there is a disadvantage in the mirror-symmetrical geometry. The resulting force on the front wheel is caused by the wheel load ( $F_g$ ) and the rolling resistance ( $F_P$ ). Both are dependent on road surface and speed.

The relation between the two components is nearly constant on normal surfaces and qualitatively shown in Figure 10. The resulting force ( $F_{res}$ ) is nearly parallel to the steering axle in case of the conventional geometry but gets a component ( $F_b$ ) at right angle to the steering axle in case of the modified geometry.

This causes a bending torque on the fork (normally no problem) and a bending torque on the front wheel, if the steering angle is different from zero. Fortunately a small wheel is stiffer than a big wheel (if the same number of spokes is used) because the spoke angle increases.

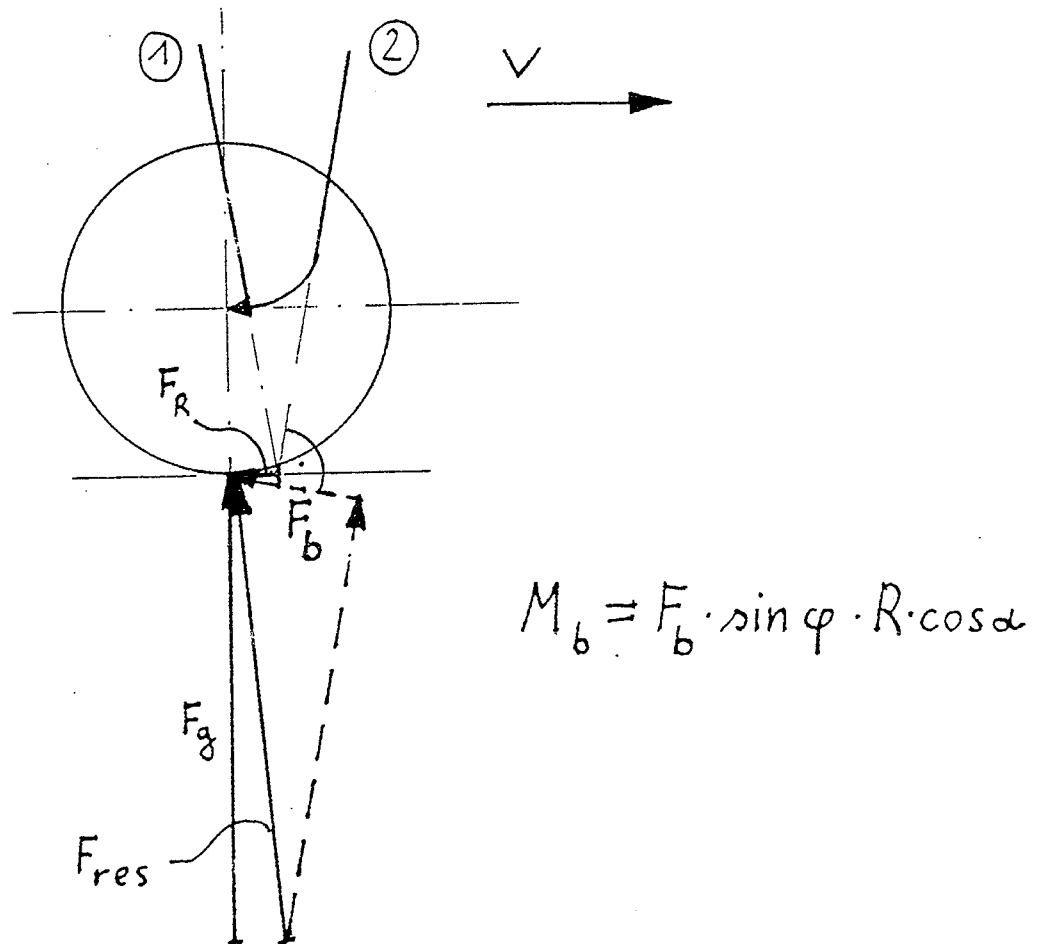


Figure 10: Forces on the front wheel in case of conventional (1) and modified (2) geometry.

## Conclusion

The new front wheel geometry of the test vehicle Multilab offers an opportunity to design a middle-wheel-based recumbent bicycle with improved characteristics, especially in braking performance and collision free steering in relation to the pedals for all practical conditions. It gives a better static and dynamic (obstacles, crosswinds) stability to the vehicle compared to a conventional geometry.

The practical experience has shown, that the designer, therefore, has to operate with steeper head angles and shorter tracks compared with a conventional geometry. The new geometry is easier to ride for recumbent beginners than any other HPV we have seen. It is expected that, by using disc wheels, the high speed stability will increase and the driver will have better conditions to cope with cross winds especially in fully faired vehicles. Together with a comprehensive measurement concept the test vehicle Multilab will show us the relations between vehicle parameters, traffic conditions and environment on one hand, and the action, performance and strain of the driver-vehicle-system on the other hand.

### Abbreviation List

$\alpha$	head angle
$\phi$	steering angle
M	torque
n	track
R	wheel radius
v	velocity

## PASSIVE SECURITY OF HPV'S

*by W. Rohmert and S. Gloger*  
*The Technical University of Darmstadt*

### Functions of Security Design

An important aim of every vehicle designer is to prevent the vehicle driver from accidents. This aim cannot be achieved in every case because of mistakes by the driver or other road users or in case of situations that are not to be foreseen. If such accidents happen, the passive security of the vehicle should prevent the driver and the crash partner from injuries and death.

As we know from inquiries, the security of the driver is the most important quality of a HPV for everyone (ROHMERT/GLOGER, 1992). If the designer wants to know, what is to be done to protect human beings in those cases, he/she has to analyse what is going on during the accident. The problem is, that up to now nobody knows how typical HPV-accidents take place, because there are only a few HPV's in traffic. If we would know this, we need people with enough time and money to make crash tests with dummies as the automobil industry is doing.

To overcome these problems we first made the assumption, that accidents of HPV's are similar to those of bicycles. Then we validated this by an inquiry among HPV drivers and by our own experiences. We formulated the results as design proposals and called them The May-Bug-Principle.

### Analysis of Bicycle Accidents

The research that has been done on bicycle accidents gives some important information for vehicle design. The following data and pictures are taken from OTTE and ALLRUTZ (1986). As it is seen in Table 1 the most typical collision types are the number 1 (the car bumps against the rider in a nearly right angle), number 2 (the rider bumps the car into the front) and number 6 (the car bumps the rider from behind).

The next important question is how the accident proceeds in those cases. Table 2 shows, that bicycle accidents are fundamentally different from car accidents. In most cases (III and IV) the kinetic energy of the bicycle rider isn't lost in deformation, but the rider changes moving direction and loses kinetic energy in several secondary bumps, and at last in friction on the road surface. This can be seen in Table 3, where the reasons and the locations of injuries are shown. Less than 27% of the injuries are caused by the primary bump (vehicle

front), all others are caused by secondary bumps while the motion of the rider continues. In accidents with trucks the secondary rollover (collision type 4) has dramatic consequences.



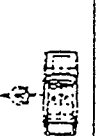

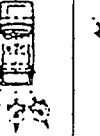

							
KOLLISIONSTYP	1	2	3	4	5	6	Gesamt
mögliche KOLLISIONSWINKEL (Grad)	90 ± 20 270	180 ± 70	90 ± 20 270	180 ± 70	0 ± 70	0 ± 70	
Straßenführung	%	%	%	%	%	%	n
Strecke	34,8	13,6	7,4	8,6	4,9	30,9	81
Knoten	61,4	15,7	1,4	12,1	—	9,4	140
Gesamt	51,6	14,9	3,6	10,9	1,8	17,2	221

Table 1: Collision types in bicycle-car-accidents (Otte and Allrutz, 1986).



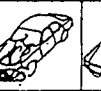

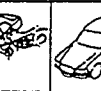
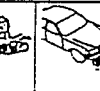
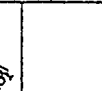

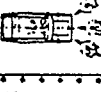

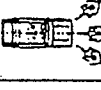
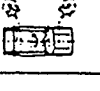
Kollisions- typ								
	I	II	III	IV	V	VI	VII	Gesamt
Strecke	100 %							n
1 	3,6	3,6	64,3	28,6	—	—	—	28
6 	4,0	—	64,0	20,0	—	4,0	8,0	25
Knoten	100 %							
1 	—	1,2	66,3	31,4	1,2	—	—	86
2 	—	—	50,0	31,8	4,5	9,1	4,5	22
4 	—	—	29,4	64,7	—	—	5,9	17

Table 2: Kinematics of bicycle-car-accidents for typical collision types (Otte and Allrutz, 1986).

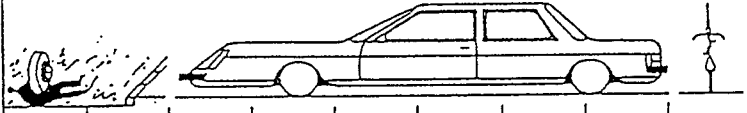




Kollisions- typ											Gesamt
	Überrollen	Straße	Fahrzeug-front	Front- haube	Frontsch-A-Pfosten	Fahrzeug-dach	Fahrzeug-seite	Fahrzeug-heck	eigenes Fahrrad	Sonstige	
1 	-	21,9	26,6	11,4	21,4	8,0	4,2	0,2	4,2	2,1	827
2 	2,2	26,5	21,9	6,5	23,7	8,2	7,2	-	3,6	0,4	279
4 	33,3	37,6	6,7	1,8	5,5	2,4	6,1	0,6	4,8	1,2	165
6 	1,9	26,3	23,7	11,8	24,4	5,7	1,1	-	3,4	1,5	262

Table 3: Reasons and locations of injuries in bicycle-car-accidents (Otte and Allrutz, 1986).

### Accident Experience of HPV-Drivers

Our own experience with accidents, gained from riding the DESIRA-I Prototype (fully faired, short-wheel-based two-wheeler) in normal traffic, is based on two collisions of the type 4 with the kinematics of type IV. In both cases nobody was hurt.

To get more information, we started an inquiry among HPV drivers using fully faired vehicles. It was done at the European HPV-Championships in Munich in September 1992 (Rohmert and Gloger, 1993). We got back 10 questionnaires in spite of more than 100 participants. The reason is, that few drivers are using fairing every day and only a few had been involved in accidents.

The relevant results are shown in table 4.

The protection from body contact with other objects is the most important effect of the fairing. The other effects indicate the similarity of kinematics compared with bicycle accidents but with better protection.

We know, that the number of questionnaires in this investigation is not big enough for representative statistics, but there is no indication that HPV-accidents are different from bicycle accidents, specifically those of two-wheelers. So it is reasonable to draw conclusions about the mechanisms of HPV-accidents and to give design recommendations.

Crash Partner	Nobody		Solid Object		Car	Bicycle
	3		3		3	1
Injuries	Driver			Crash Partner		
	1			0		
Protection Effect	1	2	3	4	5	6
	0	2	3	10	4	0

Effect 1: no protection effect

Effect 2: crushable bin

Effect 3: deflection from original direction of motion

Effect 4: protection from body contact with other objects

Effect 5: sliding of fairing on the road surface

Effect 6: other effects

Total: 10 drivers, 10 accidents, 110.000 km

*Table 4: Results of an inquiry about accident experience of HPV-drivers*

### **The May-Bug-Principle**

The mechanism of passive security by HPV accidents is based on three effects:

- 1) Deflection from the original direction of motion (low losses of kinetic energy in the bump, low body acceleration),
- 2) Protection from body contact with other objects (primary and secondary bump),
- 3) Sliding of fairing on the road surface (loosing the kinetic energy by low acceleration, moving away from crash partner).

We called this the May-Bug-Principle because it is similar to the protection mechanism of insects by their chitin-shell. For a given strength of the fairing material this works better with less mass.

This is just the opposite to what is happening in the development of automobil security (vgl. Hamm et al., 1993). This principle seems to be a chance even for other ultra light vehicles and for disarmament in traffic, because the security of one driver would no longer imply more risk for the other.

## Design Recommendations

To make the May-Bug-Principle work, some design parameters have to be realized and some other will support the described effects. The necessary conditions are:

- 1) Two-wheeler (with a 3 or 4-wheeler the deflection will not work that easy),
- 2) Protection of driver by hard shell fairing (fabrics will not resist the friction against the road surface).

In addition the protection effect can be supported by the following design parameters:

- 1) hard, smooth surface (deflection),
- 2) rounded shape of vehicle (deflection and sliding),
- 3) low friction on metals, plastics, rubber and road surfaces (deflection and sliding),
- 4) high centre of gravity (fly over the crash partner),
- 5) safety belt or something with a similar function,
- 6) elastic deformation of the fairing without structural failure (low body accelerations),
- 7) "brick" shape, not "airfoil" shape (prevention of secondary running over by trucks).



## Conclusion

We hope that in the future there will be as few accidents with HPV as in the past (Fuchs, 1990). The fact that we have seen only few accidents till now is, of course, that there are still very few of these vehicles in the traffic. When the number is growing, we'll probably see more and more serious accidents.

Designers should do their best to prevent human beings from injuries and death in those cases. After all, security is the best argument to change from automobilization to selfmobilization.

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## FIT FOR SURVIVAL – IN A VELOMOBILE

*by C. G. Rasmussen, LEITRA ApS*

The introduction of velomobiles in the general traffic would almost certainly be met with some scepticism and conservatism by other road users, and with critical attention by the police.

Perhaps these reactions are not very different from what happens, when other new types of vehicles appear in the traffic, e.g. new types of electric cars.

The mode of driving should not be very different from that of other road users. If the vehicle is too slow in acceleration, or it can not follow the main stream, or it reacts too slowly due to a limited manoeuvrability, then you are in troubles. Road users, in particular car drivers, do not tolerate anything, which may be even the slightest hindrance to them in the traffic.

For many years to come the velomobiles must be able to use the existing infrastructure and operate in mixed traffic without any greater risk than that of other road users – or even better: The velomobile driver should be more safe in traffic than those using other means of transportation.

Safety is a necessary condition for acceptance. A high security against accidents and injuries will probably motivate more people to use a velomobile. To-day many people are afraid of using a bike in the town. All the good reasons for using the bike are generally accepted: The exercise is good for people's health and well-being, they save energy and protect the environment in an efficient way – but they just do not want to take the risk.

The velomobile has the potential to become the safest and most flexible means of individual transportation. It can use not only the streets and roads but also the bicycle roads. This offers much more freedom to choose the safest route from point A to point B, a freedom which is not available to the small electric cars.

The velomobile itself provides by it's fairing a protection of the driver, which an ordinary bicycle doesn't. So, the conditions for a substantial improvement of security are there, it is just up to the designers to give top priority to safety in their product development.

### **Rules and regulations**

When designing an aircraft it is necessary to follow strict normes and rules in order to get the aircraft approved by the authorities and obtain an air worthiness certificate.

This is not the case for bicycles or velomobiles. They do not need to be checked and approved by the authorities, and in most countries the rules and regulations in respect to their design are limited to a few specifications of the minimum outfit.

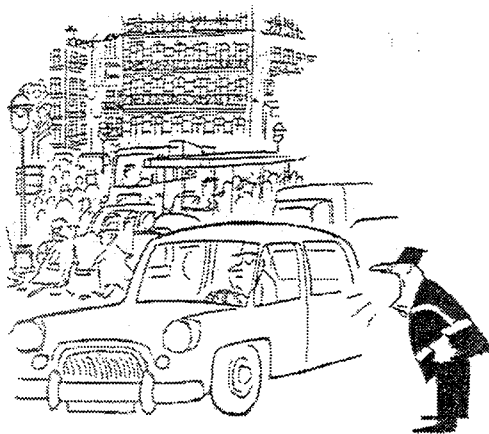
It leaves much freedom, but also a great responsibility to the designer. In most coun-

tries the authorities specify the maximum width and length of a HPV, the height of the seat, the number of independent braking systems, the position of head and tail light, cat eyes, types of lock etc., but specific requirements such as minimum braking action, power of the light etc. are not given.

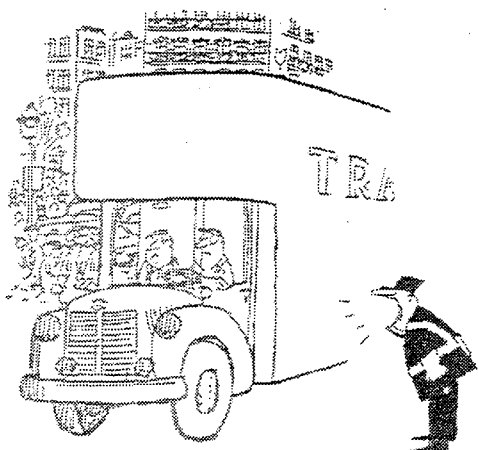
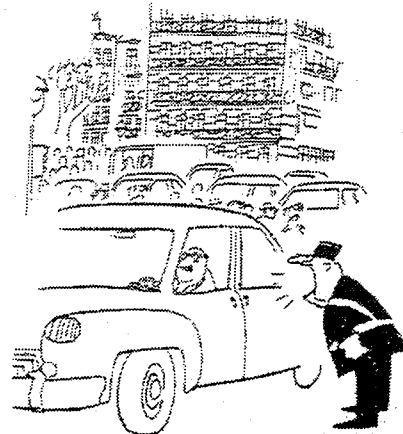
In some cases the official regulations impose limitations, which are not logical. For example in Denmark it is not permitted to use electric turn- and stop-indicators on a velomobile. Why can it be used on a motor-car and not on a velomobile ?

Even though there is nothing like type-certification for velomobiles, the LEITRA became the first velomobile in Europe to be approved by the authorities (The Danish Ministry of Transport). The story goes as follows:

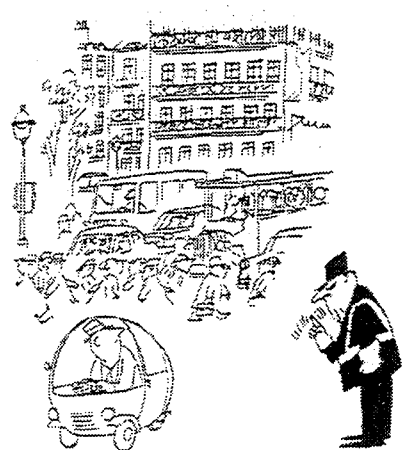
During the first years of my practical tests of the LEITRA in normal traffic (1978/80) I experienced several episodes, where a police patrol stopped me and questioned the legal status of my vehicle. They didn't do it because I had done something wrong in the traffic, but simply because the vehicle looked too peculiar to them. Perhaps they were also a little curious, and they usually let me continue after having checked the brakes and the light.



2



3



4

One day in the cold winter of 1981 I was stopped in Copenhagen by a police patrol. The two policemen looked very mystified at my small, red vehicle and called their home base over the radio. By listening to the description they gave over the radio: "It looks like a space ship from Mars", I was not surprised by the order they got back from the station: "Don't let him go any further ! Bring the vehicle to the police station !"

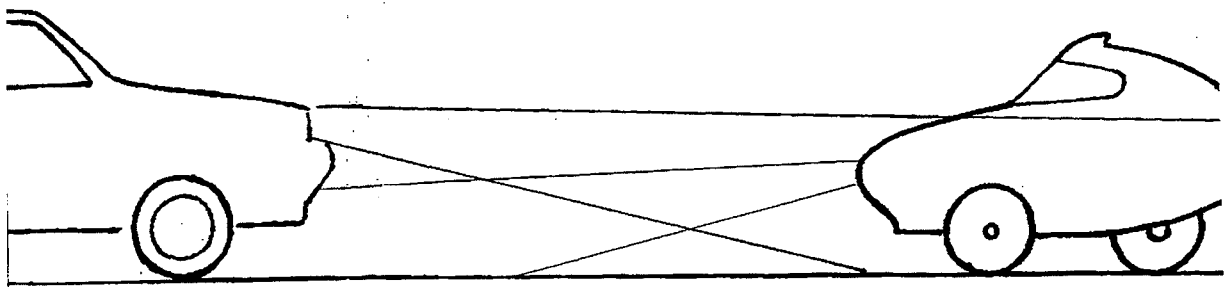
I protested, but without result, and I had to walk to the nearest train station to get home, in bitter frost without a coat (you don't need a coat when riding a velomobile). The next day I contacted the Ministry of Transport and complained, and I asked for the legal basis for the police to confiscate my vehicle. Two days later the small LEITRA was brought to my office on a big truck, and two very polite policemen handed it back with a smile and - thank you for the loan !

Since then there have been no problems with the police. On the contrary: a few policemen (in Denmark and England) have bought LEITRA-velomobiles for their private use. However, the episode led me to the conclusion, that it would be wise to get some kind of an official approval of the vehicle before the start-up of the first prototype series.

The ministry accepted to test the vehicle, although it took some time to find an inspector, who would accept to perform the test of a non-motorized pedal-car. The tests were successful, but the ministry argued that the LEITRA was too low, and on that basis they refused to issue a permission.

We didn't give up that easy, but demonstrated to the officials, that the level of the drivers eyes is higher in a LEITRA than in a MG-sportscar, and - after all - they permit the sportscars to drive in the city traffic. We finally got our approval in 1982, on certain conditions, e.g. that it should be possible to use the arms for indication of turn and stop.

In 1992, ten years later, the LEITRAs had done more than one Million kilometers in traffic all over Europe, also in big cities like Paris, London and Berlin, without any accidents with injuries of the driver - except for small scratches. So I may conclude, that the velomobile can, indeed, be a very safe means of individual transportation. This is not only theory, but also demonstrated in actual practice !



### **Design features for safety**

Since there are no official guide lines for the design of safe velomobiles for general use, we must develop our own. In the following I shall present the criteria used for the design of the LEITRA, and I will also make some comments on, what I consider as good and bad design – from a safety point of view.

In any design work you must make compromises in order to optimize the product in the direction you want. People making racing machines will use another priority-list than those designing practical velomobiles. Therefore, you will see extremely low racing machines with little manoeuvrability and very limited view, but they are perfect for their particular purpose.

The points I will deal with in this presentation are:

- (1) The ability to see/hear and to be seen/heard and, thereby, to communicate with other road users,
- (2) The manoeuvrability and stability,
- (3) Protection in case of collisions and crashes

Ad (1): The velomobile must operate in mixed traffic together with private cars, busses, trucks etc. The view should be as good as, or better than from the drivers seat in a private car.

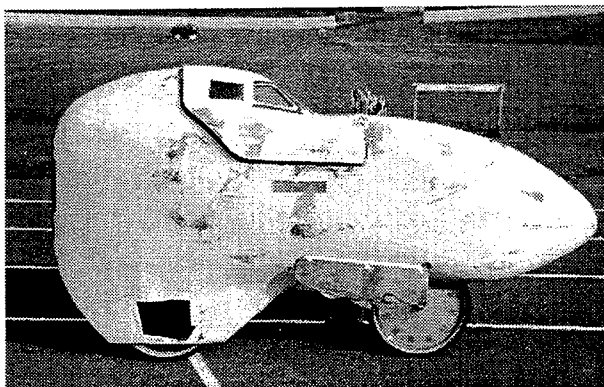
The level of the drivers eyes should be about the same as the car drivers. With good eye-contact it is easier to communicate in the traffic and to judge the intentions of other road users. This point has also been emphasized by the authorities. Moreover, when riding in the dark against the head light of cars, the blinding effect is the stronger the lower you sit. In the LEITRA the drivers eye level is about 5 cm lower than in most private cars, but about the same as in a sportscar.

The field of view covers all directions: Forward and to the sides through the wind screen, and backwards in the back mirror. On the LEITRA the back mirror is placed on top of the fairing in order to keep it well protected, clean and ventilated and close to the eyes. Also the wind screen is ventilated on the inside to keep it clear and free of condensation e.g. from the drivers respiration and transpiration.

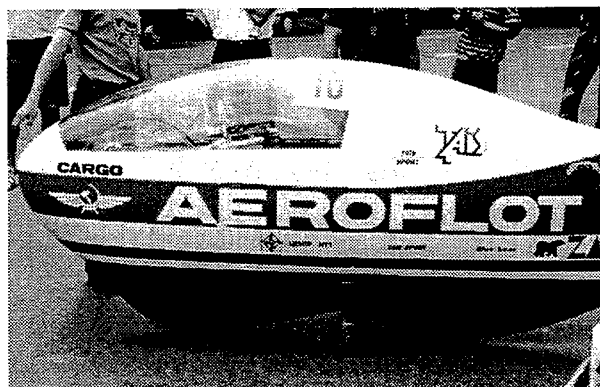
The wind screen should be placed as close as possible to the eyes, because it will minimize the disturbances from light scattered from droplets, dust particles or scratches on the wind screen.

It is a common misunderstanding that a large wind screen gives a better vision than a small. The truth is that it is almost impossible to look through a large and very slanting wind screen when driving in rain, fog, in the dark with traffic against you, or against a low sun.

If you choose a small and not too slant wind screen, preferably made of glass, and place it close to the eyes, then the problem can be minimized. You may even add a wiper (of the type used for front light on cars).



*Small wind screens close to the eyes, like here on Martin Sørensens road rocket, are very suitable from a safety point of view.*



*Large wind screens may look elegant, and they are, therefore, popular as styling feature, but give a poor vision in rain and against the sun.*

Sounds are also important as early warning in traffic. The velomobile fairing should, therefore, be open enough to permit the driver to hear approaching cars – in particular from behind.

The other way around: to be seen and heard by other road users, is just as important. A fairing with light colours and good contrast is a real eye-catcher (and, therefore, also an efficient carrier of advertisements). Here again the very low velomobiles have problems, because they can easily be hidden behind cars, signs or vegetation etc. They must use other means to improve their visibility, eg. a pole with a flag. A bell or horn belongs to the standard outfit, as well as good front – and tail light, cat-eye(s) and reflexes: white on the front, yellow on the sides and red behind. Flash light for direction indication is recommended, but it is, unfortunately, not permitted in some countries.

Ad (2): Manoeuvrability and stability are basic safety factors for a practical velomobile. The driver will occasionally meet situations, where he/she must try to avoid a dangerous situation by quick and adequate manoeuvres. This may be due to the (unexpected) behaviour of other road users or road and weather conditions.

The most important characteristics in this respect are:

- easy stop and start
- braking action
- acceleration
- ability to back
- small turning radius
- stability against overturn
- direction stability during braking
- steering stability on bumpy roads
- direction stability in strong winds.

Ad (3): In case of collisions and crashes the velomobile driver should be well protected against injuries. It can be achieved by designing the seating position, the frame and the fairing so that they offer maximum protection.

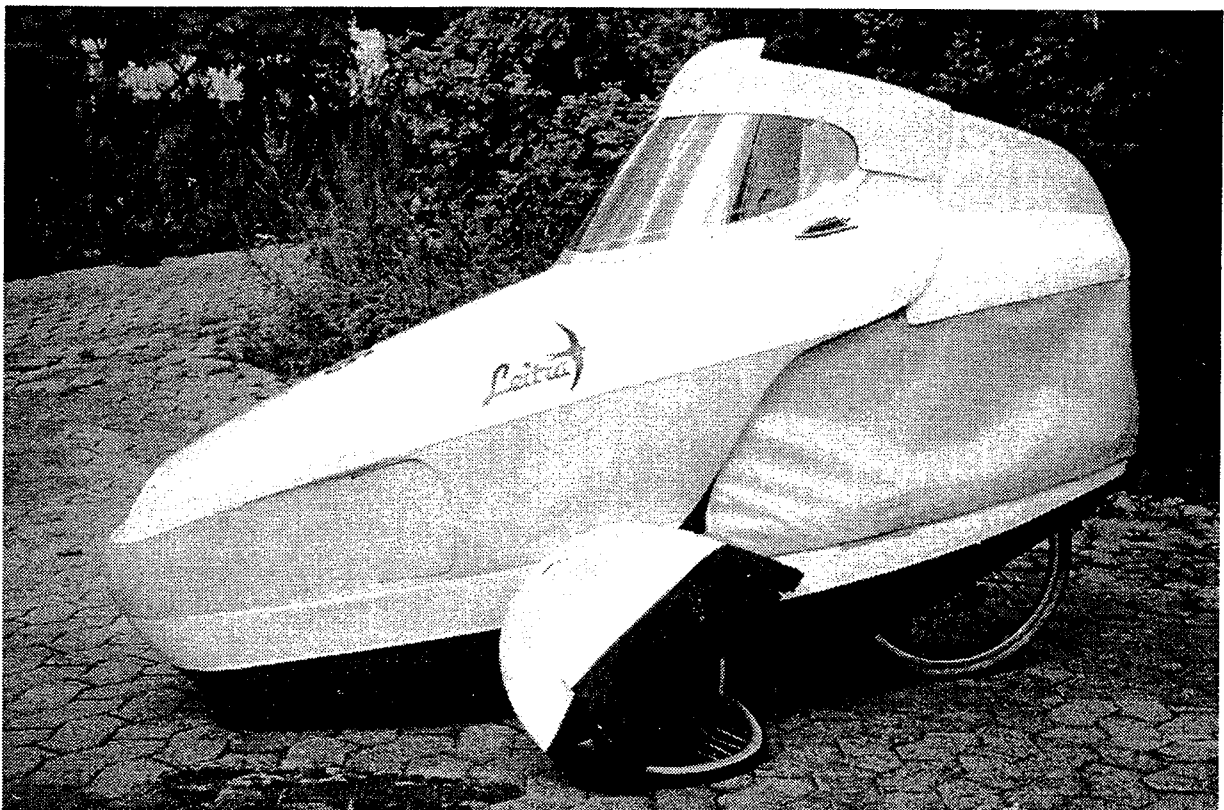
The recumbent position in a velomobile, with feet first in case of a frontal collision, is in itself a basic safety concept. The shape of the seat should fit the body of the driver, not only for reasons of comfort, but also in order to provide a distribution of the forces of inertia during an impact. A headrest is particularly important in case of a collision from behind.

The frame and the fairing should be able to absorb the kinetic energy and stay integrated during a collision or crash. In the LEITRA this is achieved by a central frame, formed as a cage of steel tubes around the driver, with arm rests and roll bar to protect the body from the sides (ref. 2). The central frame and crank beam carry other structures, which form a deformation zone around the frame. These structures, which include coupling for the fairing, front wheels with suspension, rear wheel with suspension and luggage carrier, can be bent and crushed, and in this way they absorb kinetic energy in case of collision.

The fairing is smooth, flexible and tough with excellent wearing qualities, and it covers the whole body, including the head. In an overturn and crash the fairing can slide on the side and prevent direct contact between the drivers body and the road. It saved my life in the Paris-Brest-Paris Rally (ref. 3).

Let us consider an actual case: a collision between a velomobile and a car.

A LEITRA is riding on the bicycle lane in Copenhagen with a speed of 40 km/h. Suddenly a van turns right and starts to cross the bicycle lane only 5 meters in front of the LEITRA. The driver brakes over approximately 3 meters and tries to turn away, but it is impossible to avoid a collision on that short distance. He smashes into the right side of the van with an angle of approx 45 degrees and swings against it.



During the braking the speed is reduced to approx 30 km/h. The left wheel and suspension is crushed and the fairing, roll bar and left side of the frame yield a few centimeters in an elastic-plastic deformation. The LEITRA is then thrown sideways away from the van, and the right wheel and suspension is crushed against the street and the kerb.

The driver suffered no injuries, not even a small scratch or blue mark. Knowing the collision speed, with a velocity component  $V = 20 \text{ km/h}$  ( $5.55 \text{ m/sec}$ ) perpendicular to the van, and assuming a deformation of  $s = 0.3 \text{ m}$ , we can estimate the deceleration  $G$ , which the vehicle has been subject to

$$G = V^2 / s = 100 \text{ m/sec}^2 \text{ or } 10 \text{ g}$$

This value assumes a perfect elastic deformation. In reality a considerable part of the deformation is plastic. Therefore, the g-forces will probably be less, since a perfect plastic deformation will give

$$G = V^2 / 2s = 50 \text{ m/sec}^2 \text{ or } 5 \text{ g}$$

## Conclusion

Safety is an important, if not the most important, aspect in the design of practical velomobiles. Some experience and inspiration can be found in car design, but there are also big differences in the design philosophy.

We can not build heavy machines with big bumpers, safety belts, air bags etc. to make the driver survive a crash. Such a vehicle will never get off the ground with human power. In aircraft design, safety must be considered without adding a lot of extra weight - and this is also the conditions when designing velomobiles.

Therefore, we must adopt a multi-function philosophy, which means that the different components of a velomobile: frame, seat, fairing, wheels etc., should serve more than their primary function - not least the purpose of crash protection.

## References:

- 1) John Schubert: The LEITRA M1 Recumbent: A Practical HPV. BIKE TECH (USA), Feb. 1983, p. 13.
- 2) C. G. Rasmussen: The Design of an All-weather Cycle,. BIKE TECH (USA), Feb. 1983, p. 14.
- 3) C. G. Rasmussen: Completing the Paris-Brest-Paris Rally After a Crash. Les Resultats du 11e Paris-Brest-Paris.

## DESIGN FOR FUN

*by Søren Bendtsen  
Bendtsen Design, Copenhagen.*

It was a foolish thing to do, calling my lecture 'Design for Fun'. It's certainly no joke trying to be entertaining in a foreign language that I do not master to well.

And trying to do so about something that happens to be my profession – I am an industrial designer – that is even more stupid.

Anyway, what I am going to show you now is actually pretty close to my normal way of working. You may wonder, but so it is!

When you are designing a product incorporating quite a lot of functional demands, you can easily get yourself into severe troubles when you – all the way through the project – eagerly try to find the best possible solution.

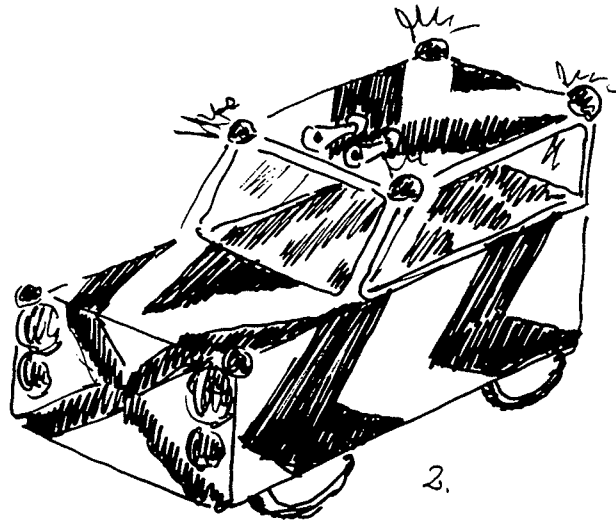
It generates conflicts, because the best possible solution for one aspect of the product may very well be the worst possible for some of the other aspects.

You have to make some compromises, whether you like it or not. And making compromises certainly is a problem in itself. (Take a quick glance at our politicians, for instance. Doesn't it look like they are loosing sight of their initial goals during 'the compromising process' now and then?)



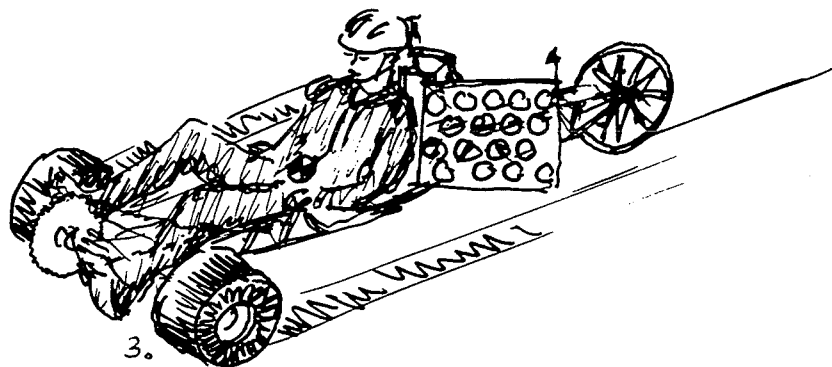
I have, never the less, tried to come up with some kind of comic strip in which I caricature, to a certain extent, the different functional demands that a bicycle-concept consists of, starting with the 'safety first'-parametres. I.e.: the parametres that make people survive in nowadays traffic.

One of the first and most important matters in that respect is simply being able to see everything around you. And the best solution – in my opinion – is the velocipede with the rider perching atop of it. You will notice his reflex-free coat, the miner's helmet with built in light, mirrors and – very important indeed – the riders lofty position that gives him a fine survey.



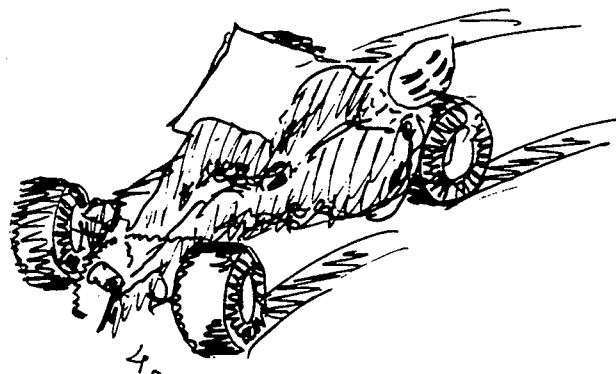
But it is, off course, of equal importance to be seen by other drivers. So the next drawing symbolizes the highest degree of visibility that I could imagine.

It is of great importance to look huge, primarily because it indicates that you are not far away – and consequently ‘potentially dangerous’.



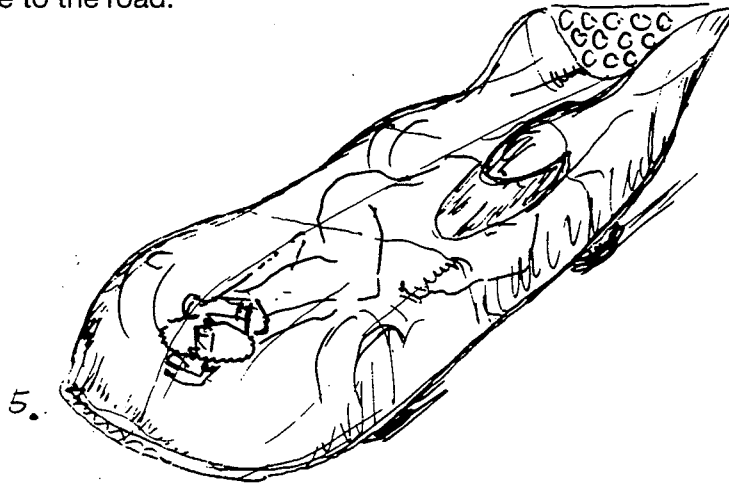
Having ensured the drivers survey, you will have to make sure that the vehicle can stop as fast as possible.

This time I have chosen a kind of ‘inverted dragster’ with the front wheels being go-kart slicks with a very high capacity of friction. The vehicle has an air-brake too, and the centre of gravity is positioned very close to the ground, plus as much as possible of the total weight is placed over the wheels fitted with brakes.



Well, sometimes you can't just brake you out of the problems. Instead you will have to cling to the handlebars and steer your machine round the obstacles.

This figure intends to show how a vehicle, capable of going fast round a corner, looks like. – Please notice, that now you have got four go-kart slicks and furthermore the possibility of leaning yourself towards the centre of the curve, enabling you to transfer a maximum of transversal force to the road.



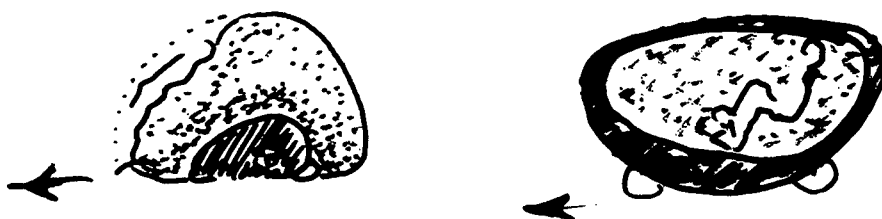
Important, too, is a negligible cross-wind-sensitivity. In order to keep that down to a minimum I have placed the driver lying down on one side in order to minimize the side-area – so that the wind has less to push at. – I have also equipped the vehicle with an air-brake, actually used as a kind of drag anchor, that keeps stability.

Air resistance may be useful for some purposes !

But even if you can avoid being pushed out of line, are fully able to stop, have a good survey as a driver, and have a high visibility – accidents might happen anyway. You can hit somebody or something, for instance.

If you hit somebody, he/she will be thankful if you and your vehicle are light and soft. It is also important that the vehicle has a very little ground clearance (so that it does not squeeze the victim between the vehicle and the road).

On the other hand: what if a massive, two tons truck drives right out in front of you? – Well, then it is very useful to have as much and as stiff material in front of you, ready to hit the truck and, thereby, protecting yourself.



A 50-tons Centurion tank, for example, is very suitable. – And don't forget to fill it up with nice, impact-absorbing material inside to protect your vulnerable body.

Now you have heard something about shape and weight. Next thing to be discussed will be dimensions.

First something about the acceleration. The g-forces should be understood as the degrees of acceleration that the body can take (without being severely overloaded) – and that the tyres can transmit.

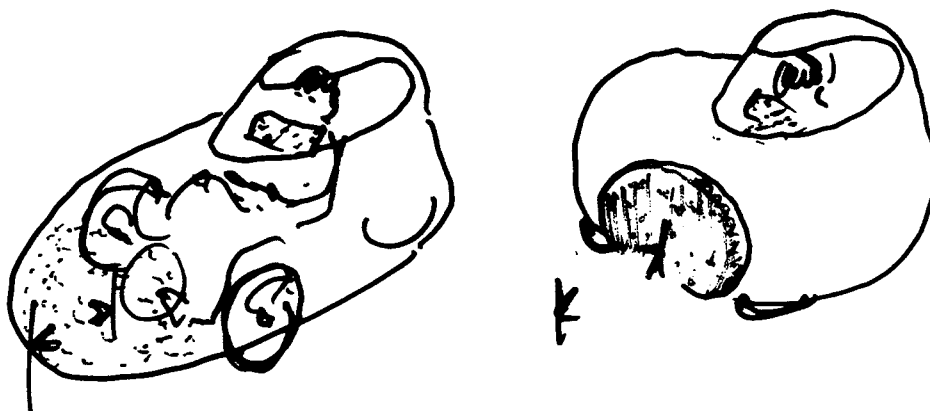
40-50 gs are considered to be very close to a mortal dose for a human being. That is if you are properly protected against damages by means of seat belt etc.

In the other end of the scale, about 1 g is what a normal car and 0,5 g what a bicycle will expose you to now and then. Both values representing an easily tolerated load.

	40g	30g	20g	10g	1g	0.5g
100 km/t	0.96	1.29	1.93	3.86	38.6	77.2m
75 km/t	0.54	0.72	1.08	2.17	21.7	43.4m
50 km/1	0.24	0.32	0.48	0.96	9.65	19.3m
25 km/t	0.06	0.08	0.12	0.24	2.40	4.8m

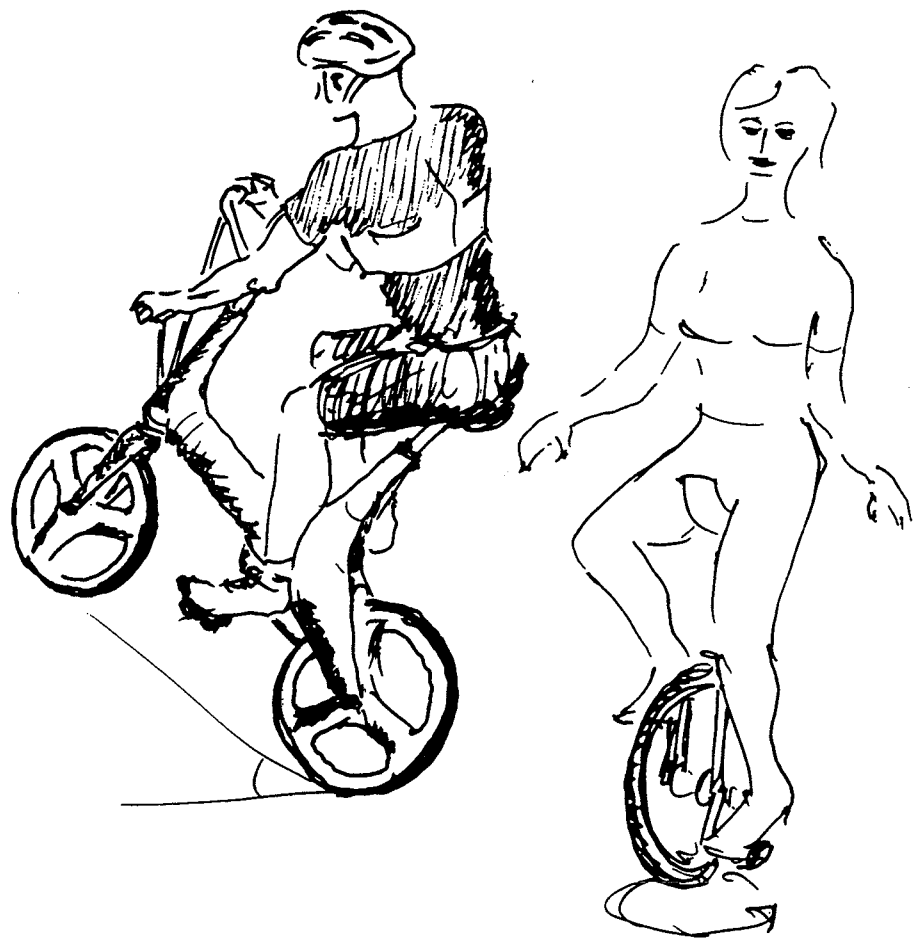
You can see from the table that the gs are related to speed and braking distances. If the constructions (as mentioned in the tables) does not include such a braking distance, the gs will exceed tolerable values. It is of great importance, though, that the deformation zone has a sufficient lenght, so that the energy of motion of the car can be absorbed.

Enough about visibility, braking distances, and accidents!

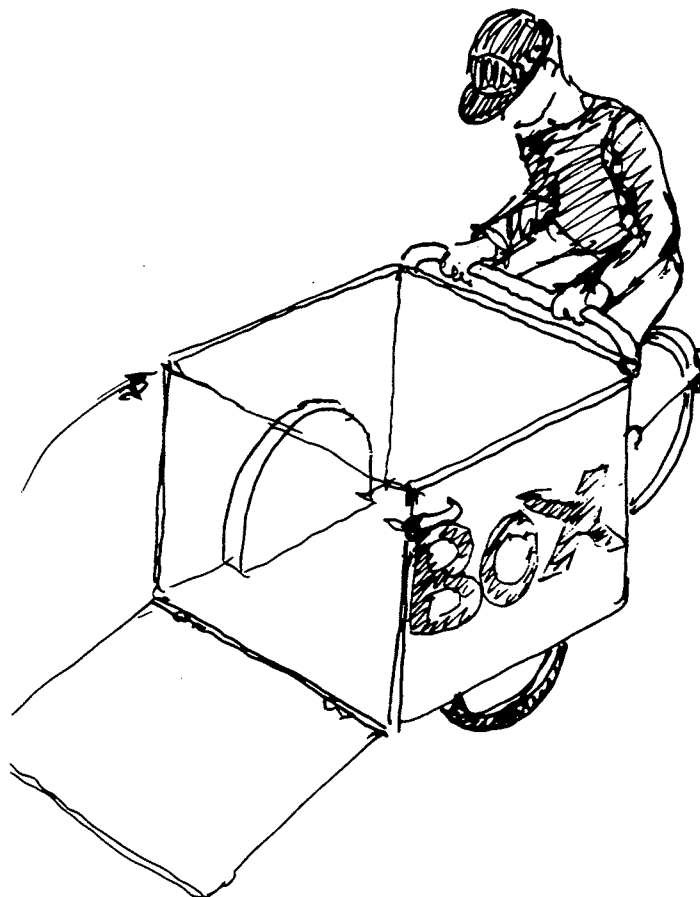


In addition to survival in the traffic, there will be a good deal of other qualities to focus on.

For example the capability to climb steep hills is useful, which means low weight. The little, featherweight carbon-fiber bicycle with it's tiny carbon-fiber wheels and the use of both arms and legs for propelling the rear wheel driven vehicle – that is my best shot for a hill-climber.



Another important quality to possess is a high degree of manoeuvrability. And if you also want a vehicle that takes up as little space as possible while parking – a mono-cycle is the choice.



Then again, if your need to move half a cubic meter of assorted stuff during holidays – or just shopping for a big family – only a three-wheeled carrier cycle with a trunk up front will do.

Some luxury might be given a chance, though. – What about a black leather sofa, protected against the weather, and with nice, soft springs. Something that floats gently, the road underneath rubbing smoothly against the tyres. – Wouldn't that be nice for automobile-addicts, wanting to change to Human Powered Vehicles – just as a transitional stage?

Have I forgotten something?...Oh yes: As you have possibly seen in magazines concerning automobiles, acceleration is very often stressed as a prime safety factor. – Every other time when you are out there in the overtaker lane you'll need some more power in order to speed

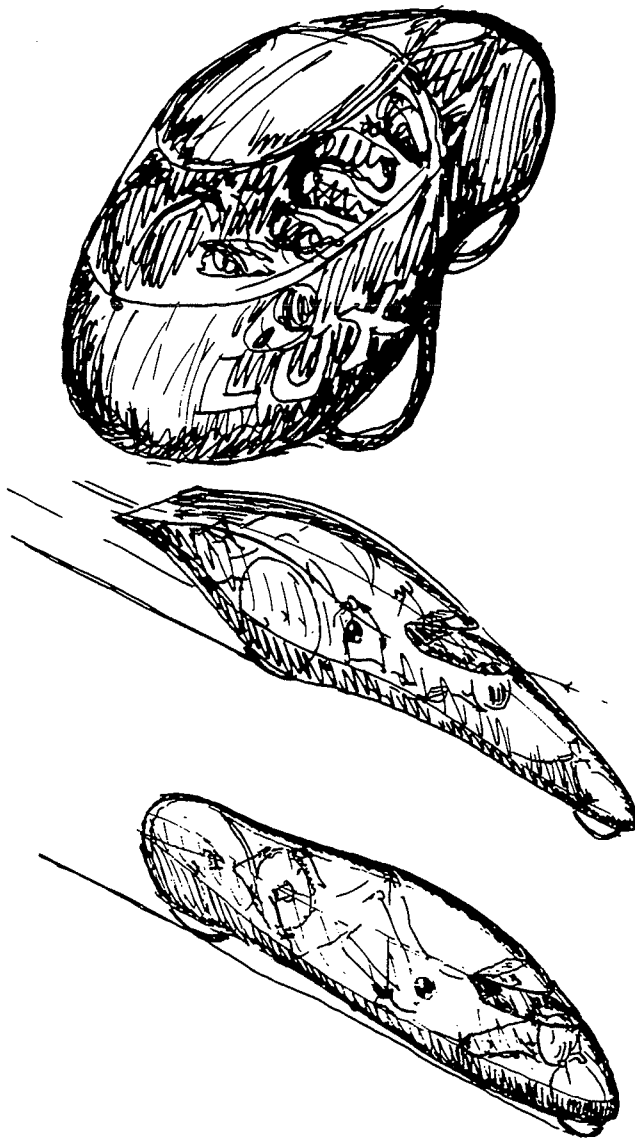
yourself out of the dangerous situations.

It certainly also feels good to be number one at the usual cross-roads 'green light-tests'!

For such purposes I have designed the little, red vehicle.

It has the centre of gravity very close to the driving wheels, the smallest possible front area and low weight. The driver is placed on his back with his head pointing forward (thus giving the shortest possible transmission-system and smallest front area). – He is using a periscope in order to see the road in front of him.

This configuration is also used when the best possible stream line shape is wanted – for high speed purposes. In these cases the issue is no longer to have the centre of gravity over the driving wheel, but to have the centre placed aerodynamically correct to ensure stability at high speeds.



Now, that was what I intended to tell you about the design – based on (more or less) functional requirements.

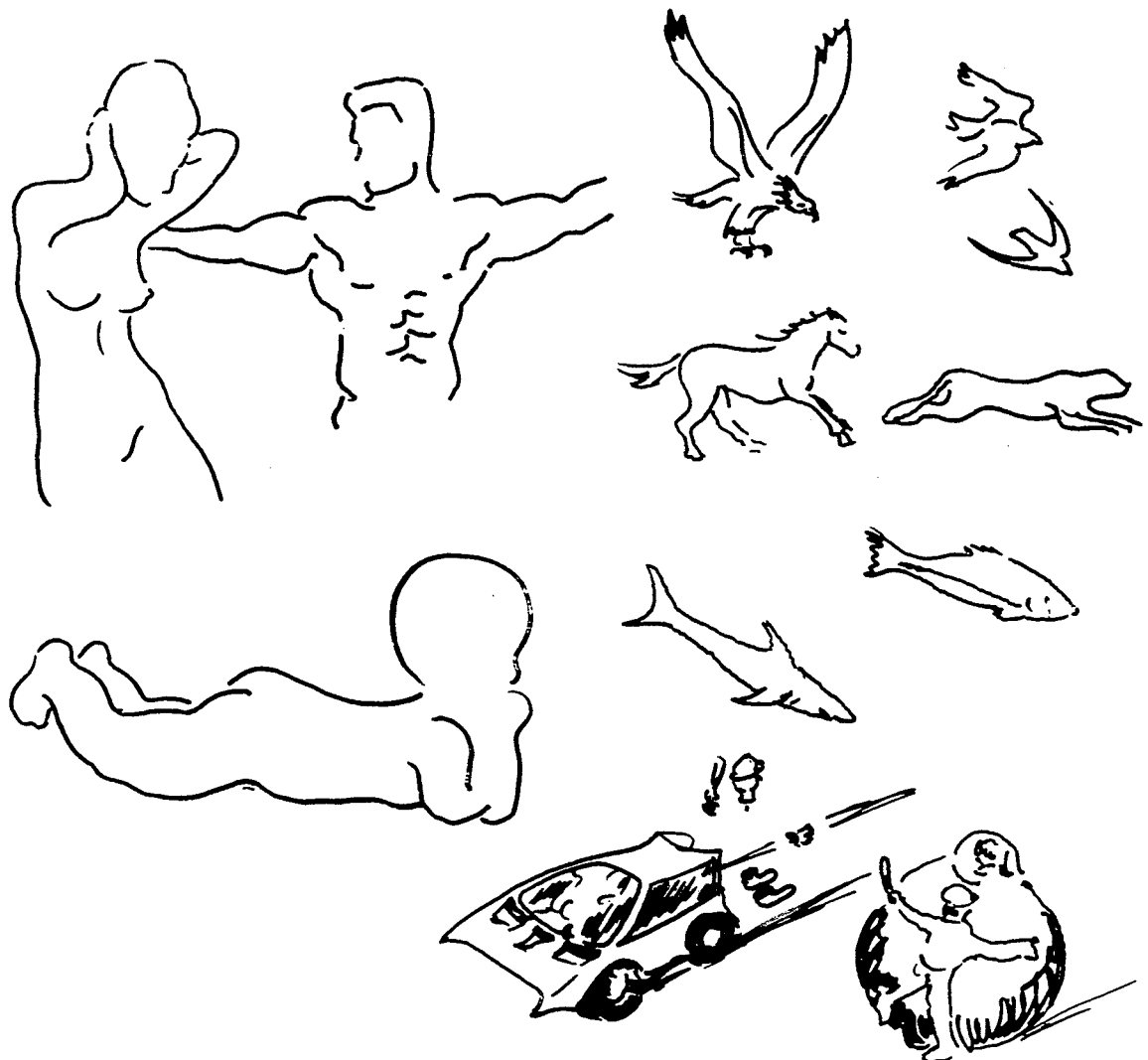
But we're not quite through yet.

Because: There are some psychological aspects to be considered, too, I think.

That is: Would you be happy simply by possessing a vehicle – or would you rather like to identify yourself with it? – That depends on, primarily, whether it is 'the centaur-feeling' or 'the possessor-desire' that is your predominant trait.

If it happens to be the latter it should indicate – for male buyers – that you would prefer a somewhat feminine, smooth and soft design. Whereas the man, who identifies himself with the vehicle, most likely is going to buy himself an expensive, fast, aggressive muscle-machine.

The design of cars, which do not only look aggressive and destructive, but certainly were so too, can be exemplified by referring to Cadillac, who – years ago – excelled in big, sharp tailfins.



Those fins did not only result in severe damages for bicyclists. It is also reported that a kid on a tricycle once died after hitting such a tailfin with his head.

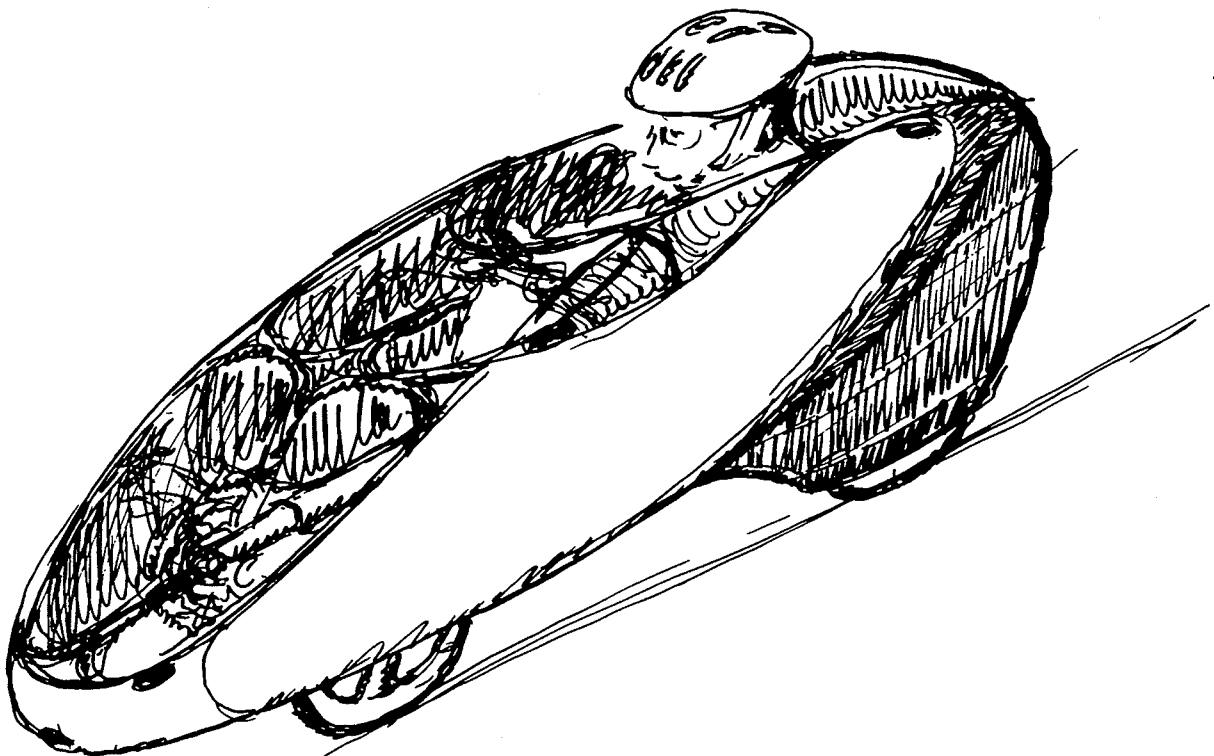
I don't know the actual speed of the tricycle, but let us assume that it has been limited.

When, eventually, you are trying to unite all the highly different – and (more or less) incompatible – psychological, physiological, and functional characteristics, you will have some troubles trying to combine these aspects.

I know very well that it would be appropriate at this time to come up with a nice weighting-diagram, displaying a common denominator that compasses the entire subject.

But – being a designer, not necessarily being a philosopher, and certainly not a mathematician – I will instead show you some overhead-drawings you have already seen during the last fifteen minutes – but this time stacked so that you see (hopefully) all of them at the same time.

And from the kaleidoscope appears: the Bendtsen Design vehicle.



## PLEA FOR A GOOD TYRE

*By Thomas Senkel, Dept. of Physics, University of Oldenburg*

How fast you ride a bicycle depends firstly on your power and secondly on overcoming the resistive forces.

If it is a question of non-accelerating riding on level ground, then it is rolling- and air-resistance which absorb your energy, since friction losses in the transmission can generally be considered negligible.

There are two categories of cyclists. The first want to ride as fast as possible, the second, with as little effort as possible.

These both boil down to the same thing, namely the reduction of the sum of the resistances, although the former category, the racing cyclists, are most interested in the air resistance, to which much research has been devoted and about which a great deal has been written.

Up to a speed of about 4.5 m/sec (16 km/h) the rolling resistance is, however, greater than the air resistance, and therefore of far greater interest to cyclists using their bicycles for daily transport and recreation.

Particularly when riding with a trailer or with bicycles for the transport of heavy goods, the rolling resistance is by far the most important part of the total resistance.

In diagram 1, the full drawn curves give the attainable speeds with a given power input for two different tyres.

The dotted curve shows the percentage increase in the speed, which can be obtained from a given power input, when the rolling coefficient is reduced from  $C_r = 0.00568$  to  $C_r = 0.00160$ .

This range corresponds roughly to the range in rolling resistance coefficients from the poorest to the best tyres of the size 20 inch at 5 bar, that we have measured so far.

With a power input of 75 W (the power of an average bicyclist over long time) you would be able to ride 12 % faster.

Even with a 200 W input, the increase in speed would be about 6 %.

The development of bicycle tyres has so far, in the main, been the preserve of the industry. One of the few exceptions is the Leipzig engineer Paul Rinkowski, who has developed and manufactured his own hand-made radial tyres (5).

A few tyre manufacturers measure the rolling resistance of their tyres on laboratory test beds and draw on their results in their optimization.

Rolling resistance is seldom used as a sales argument and figures are not available. This could be due to the differences in measuring techniques, which makes direct compari-

Rolling Resistance Coefficient Cr for different tyres.

The values given in the Tabel are  $Cr \times 10^5$ .

300 kPa	500 kPa	700 kPa	Size	Type
<hr/>				
669	436	378	47-305	Conti Tour de Sol (Spezialanf.)
614	-	-	47-305	Schwalbe Standard GW, HS159
-	416	-	47-406	ACS RL-Edge
-	514	-	47-406	Avocet Fastgrip Freestyle
392	-	-	47-406	Continental Nylon S, US Type, weiR
782	596	-	47-406	Continental Nylon S, beige
219	160	-	47-406	Rinkowski Gürtelreifen, Typ 1
261	195	-	47-406	Rinkowski Gürtelreifen, Typ 2
-	568	467	32-406	Schwalbe City Jet
685	-	-	47-406	Schwalbe Standard SK, HS188
526	-	-	47-406	Schwalbe Standard GW, HS188
455	-	-	47-406	Schwalbe Standard GW, HS159
-	394	-	47-406	Tioga Competition mit Mittelsteg
-	419	-	47-406	Tioga Competition mit Stollen
-	534	-	28-440	Michelin Standard
-	446	360	32-451	Hudyn HPV
408	-	-	47-507	Schwalbe Standard GW, HS159
-	267 *	-	47-559	Continental Avenue
504	370	-	44-559	Continental Goliath
696	643 *	-	50-559	Continental Super Cross
332	-	-	47-559	Schwalbe Standard GW, HS159
513	361	-	32-622	Avocet Slik
596	402	349	28-622	Avocet Slik
-	477	376	20-622	Avocet Slik
-	351	-	28-622	Continental Super Sport
-	278	-	32-622	Continental Top Touring Skinwall
448	341	-	37-622	Continental Top Touring (weiR)
-	480	417	30-622	IRC Tandem
-	381	313	35-622	Michelin Highlight Tour
-	537	-	25-622	Panaracer Tour Guard
446	351	-	47-622	Schwalbe City Jet HS257
522	362	-	37-622	Schwalbe City Jet HS257
573	389	321	25-622	Schwalbe Blizzard HS190
-	432	342	22-622	Schwalbe Blizzard HS190
-	496	405	18-622	Schwalbe Blizzard HS190
-	397	-	44-622	Schwalbe Hurricane
-	474	-	32-622	Schwalbe Marathon
336	-	-	47-622	Schwalbe Standard GW, HS159
-	393	-	28-622	Semperit Long Life
600	474	414	35-622	Trek Invert K
-	319	-	37-622	Vredestein Monte Carlo
-	312	-	25-622	Vredestein Runner

The relative standard deviation is  $< 2\%$ .

Values with \* are measured at 450 kPa (4.5 Bar).

sons of data difficult. Moreover, it seems to be the appearance of the tyre, from the heavily treaded to the slippery slicks, which takes the consumers fancy.

The bicycle research group at our university decided to form the basis of a theory for bicycle tyres through an experimental investigation of as many different tyres as possible.

More than two years ago, in the framework of a thesis, we perfected a measuring system, which enables realistic measurements, with great precision, on any road surface whatever(1).

### **The coasting method**

Measurements are carried out with a specially constructed tricycle. The ORM (Oldenburg rolling resistance measuring equipment) is started by hand and then rolls freely over a measured distance. With the help of a pocket computer, the time for each wheel revolution, during free wheeling, is measured and stored. From the time difference between two wheel revolutions, the deceleration and, hence, the total resistance can be calculated. The measurements are repeated and averaged out to increase accuracy.

Since the air resistance and the rolling resistance of two of the wheels on the tricycle are known from calibration, the rolling resistance of the third, unknown, wheel can be calculated.

In order to compensate for the influence of the height profile of the measuring track, measurements are made in both directions, and the paired values are assessed.

The load on the measured wheel was approximately 55 kg, which represents the usual wheel load on a two wheeler. For accurate evaluation, the wheel circumference, the load on the wheel, the moment of inertia and the air density must be known. Moreover, the influence of air movements should be as small as possible. Therefore, we carried out the measurements in a closed hall, on a PVC-surface laid on top of a heavy load bearing concrete floor.

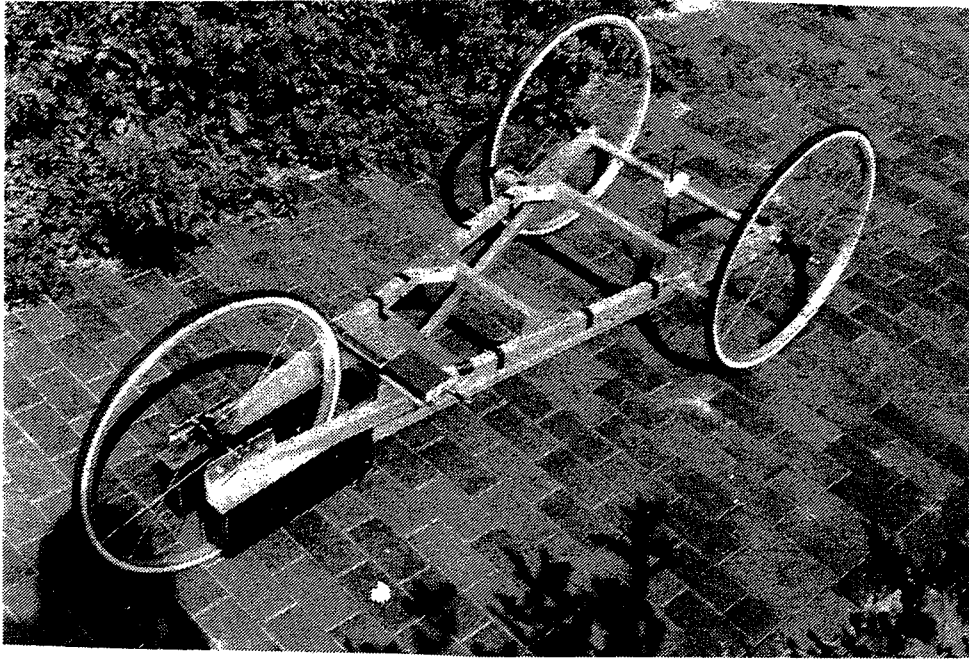
### **How rolling resistance arises**

The rolling resistance of a tyre is given by

$$F_r = C_r m g$$

The higher  $C_r$ , and the heavier the load ( $m g$ ) on the wheel, the heavier it runs. There is no guaranteed theory of how the rolling resistance in tyres arises, though it is assumed to stem mainly from two components : the rolling resistance of and the flexing force.

The rolling resistance arises because the contact between the wheel and the road surface is



The ORM test vehicle, a tricycle without drive.

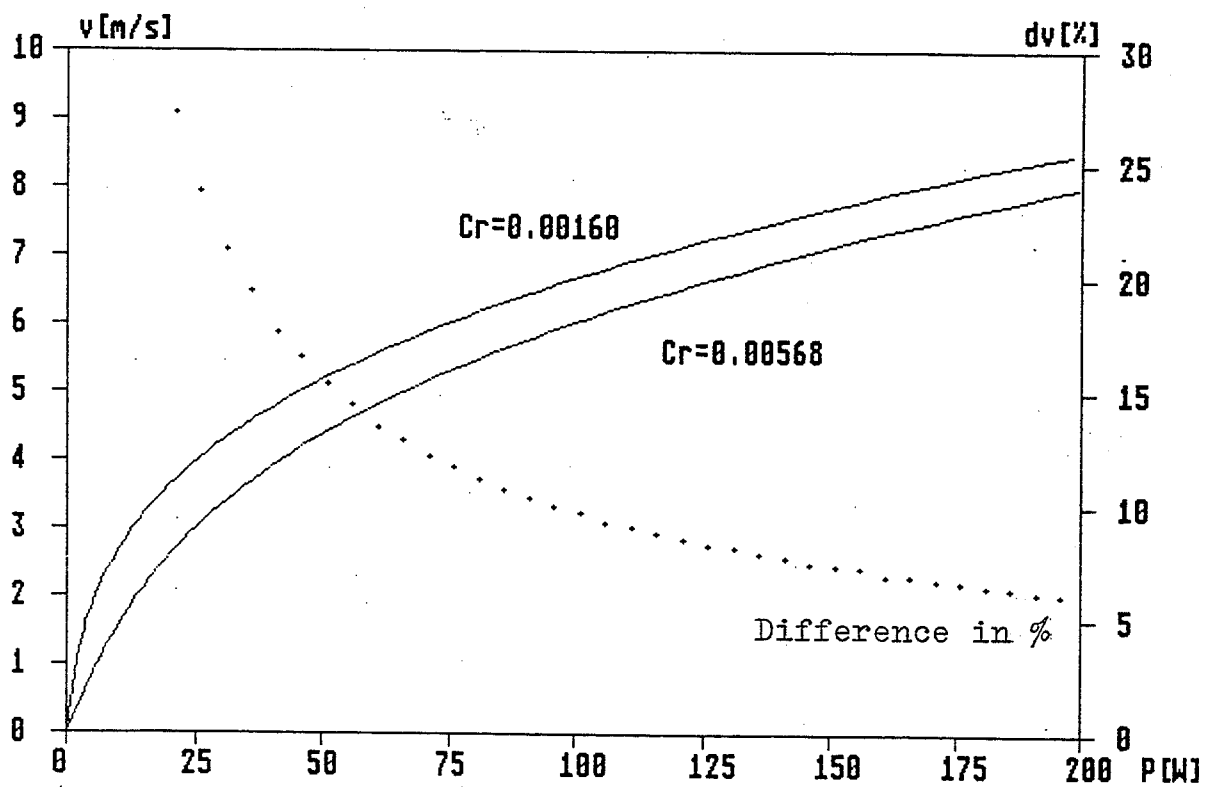


Diagram 1: Speed increase due to better tyres.

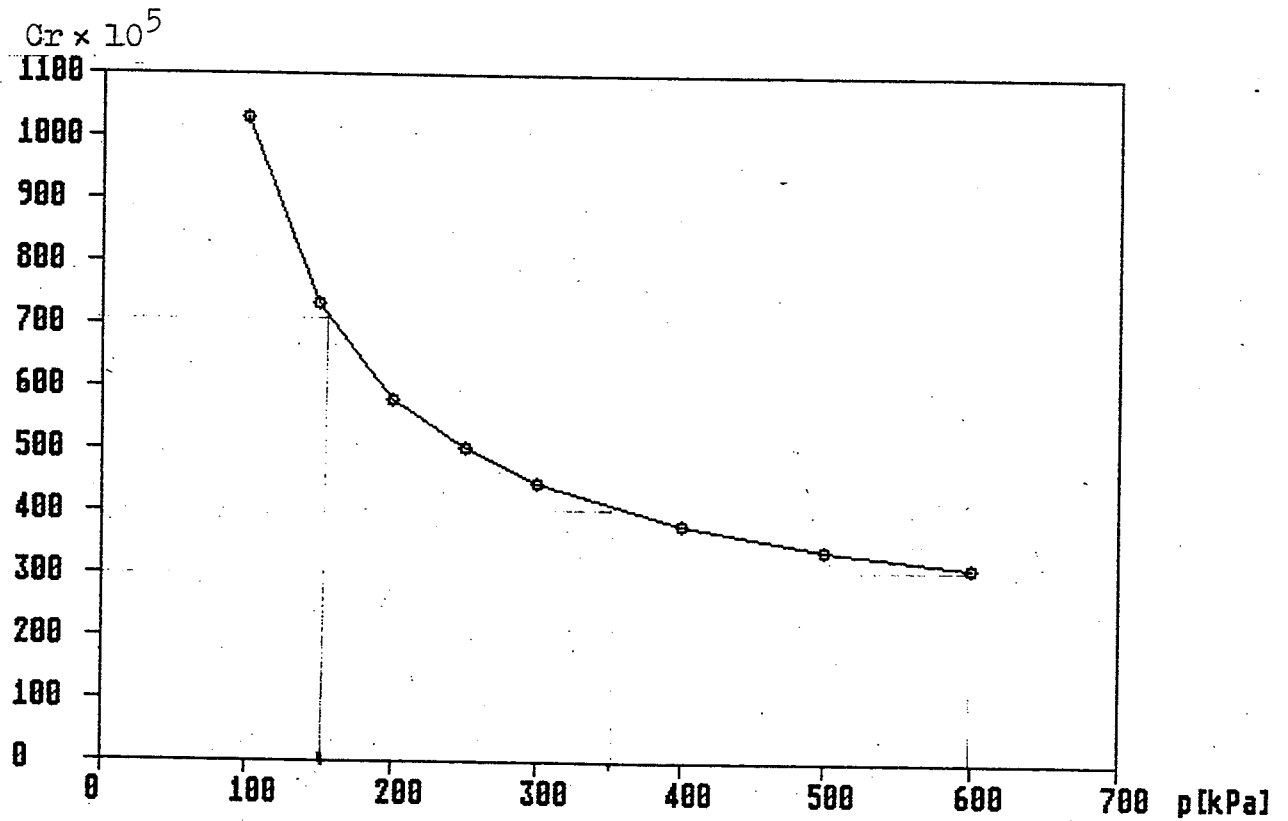


Diagram 2 : Rolling resistance as a function of pressure.

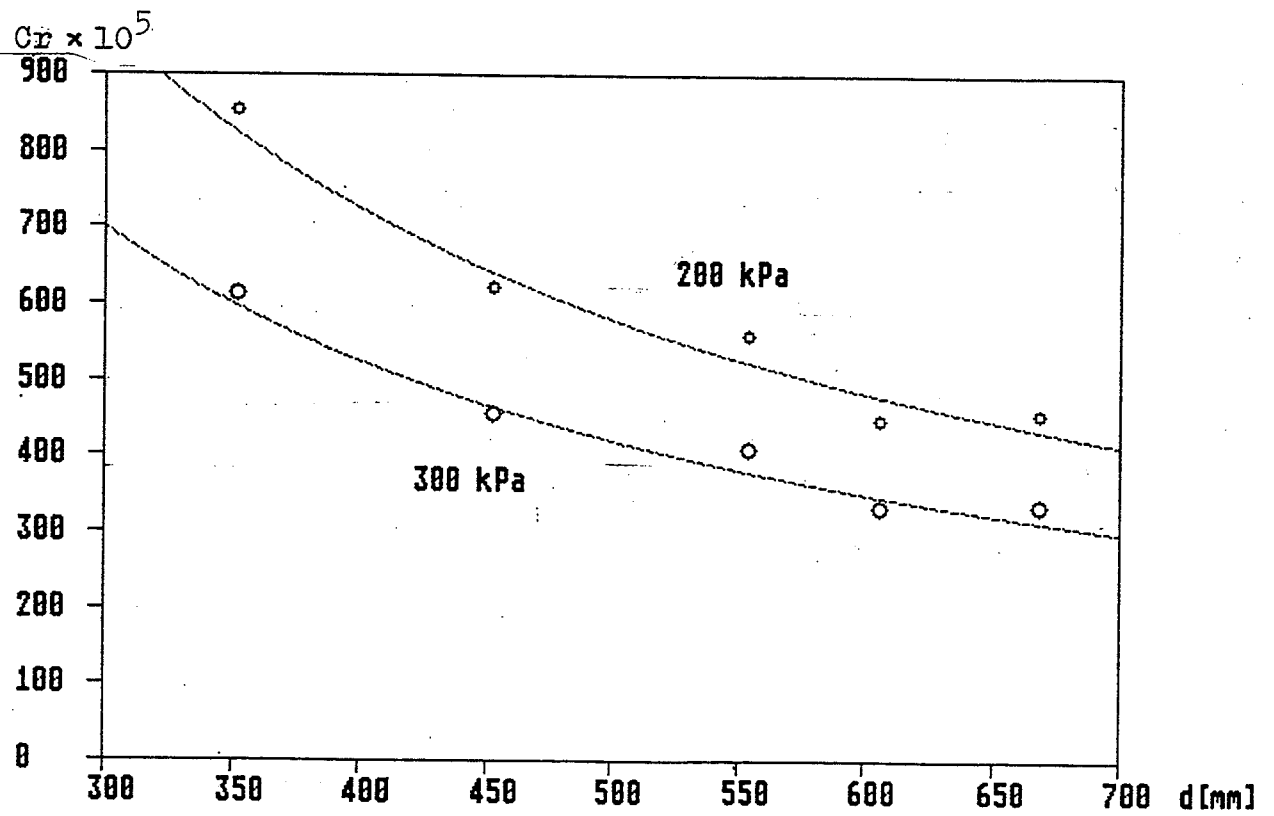


Diagram 3 : Rolling resistance as a function of wheel diameter.

not a mathematical point, but rather an elliptical surface. The rolling process can be thought of as a continuous tilting over a virtual edge across the contact surface area. The longer the contact surface, and the smaller the wheel diameter, the higher the rolling force.

The flexing force can be explained as follows.

When rolling, the tyre constantly thrusts out a rubber bead on the leading edge of the contact surface. As the wheel revolves, the tyre is kneaded, which gives rise to losses. Due to the damping effect in the tyre material the energy absorbed by the deformation of the tyre is not completely restituted. The damping losses are directly proportional to the flattening (2).

### Experimental results

Table 1 shows the rolling resistances measured so far, arranged according to the tyre size. One sample of each tyre is measured and the results are given with a standard deviation smaller than 2%.

Whether the results apply to all tyres of the same type is open to question, since the variation within a production batch is unknown. Also, the age and the wear of the tyre have an effect on the rolling resistance. Almost all the tyres measured were new. The selection of tyres is, of course, largely fortuitous and far from adequate.

When buying a tyre, the rolling resistance should be taken into consideration together with other important qualities such as

- Resistance to punctures
- Life span
- Springing properties
- Ride dynamics
- Road holding
- Price

Diagram 2 shows the dependance of rolling resistance on tyre pressure for a Continental Top Touring 37-622.

Starting from a low pressure, the effect of increasing the pressure is much more noticeable than from a higher pressure.

Lightly pumped up tyres offer good springing but have an appreciably higher rolling resistance than at the specified pressure. On the other hand, with high pressure tyres, the difference between, e.g. 800 and 900 kPa (8 and 9 bar) is virtually insignificant.

As regards the dependance of rolling resistance on tyre diameter we can take the Schwalbe Standard GW tyres with profile HS 159, since they all have the same construction and the same width, namely 47 mm.

Diagram 3 shows that rolling resistance is inversely proportional to tyre diameter.

Quite unexpectedly, and worth noting, is the finding that – with roughly similar construction and similar parameters – wide tyres have a lower rolling resistance than narrow tyres (see Table 1).

This seems to run contrary to normal human understanding, but can perhaps be clarified by a closer look:

With the same pressure the area of the contact surface is also the same. With wide tyres, however, the ellipse is shorter and broader, which results in a lower rolling resistance.

In racing, narrow tyres have taken over, first and foremost because of their lower air resistance and lower weight.

For the same reason, until recently, no high quality wide tyres for high pressures have been produced.

The rolling resistance naturally depends too on the road surface. For the usual cycle tracks, made of cement blocks or asphalt, the rolling resistance is approximately 20-50% higher than on PVC surfaces.

With very soft surfaces, such as grass or sand, the deformation of the soil is the main factor in the rolling resistance, which then becomes several times higher than on a hard surface.

In this way, the hierarchy of the tyres can change considerably, so that for soft ground, Table 1 no longer has any bearing.

In order to obtain as low a rolling resistance ( $C_r$ ) as possible on hard ground, the tyres should possess the following characteristics:

- Good elasticity
- Short contact area
- Large diameter

To obtain a small contact surface, you need:

- High strength to withstand high pressures
- Wide tyres
- Great rigidity in the tyre walls
- Positive profile effect

These characteristics seem partly contradictory, e.g. an elastic tyre is also less rigid (2).

## Conclusion

The values measured show that tyres have very different rolling resistances, from which we may conclude that they hold out a considerable potential for research and innovation.

In particular, the experiments of Rinkowski with radial tyres of small diameter and great width can perhaps show the way – not least for the tyre industry – to adopt new construction principles, since despite the poor production conditions, the rolling resistance of these tyres is only half that of conventional radial tyres.

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## AFTER THE CENTURY OF EXPLOSIONS

*by Andrej Detela*

*presented by Riko Jerman, Ljubljana.*

The expression Century of Explosions denotes this very period of history, in which the human civilization has been led almost to the extreme rim of its existence by exhausting the non-regenerative treasures of the Earth, by the "nuclearity" and a linear development. The human race is slowly becoming aware of this process.

The invention of the internal combustion engine has played an important role in this destructive period.

The new generation of electric motors could be a stimulus to change the human understanding of the world – by its "cyclicity", non-aggressiveness, smoothness, and not least economy.

### **The ideal electric motor**

The development of the European electromobile tends towards a light, economical car, affordable for the masses. An optimal solution seems to be: A car whose four wheels are simultaneously the rotors of special electric motors.

In the light of nowadays needs for a lively, highly economical electromobile, this almost 100 years old idea can be realized only with motors, which are characterized by a very high torque per motor weight and a high efficiency at the same time.

These are above all synchronous DC motors with electronically commutated coils in the stator and permanent magnets in the rotor.

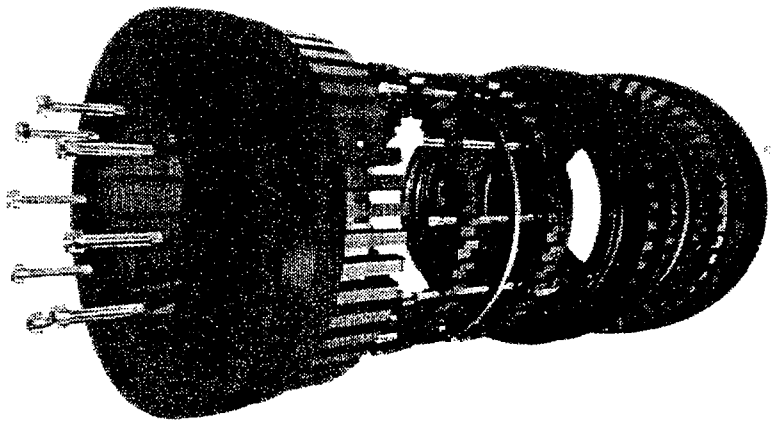
In Slovenia we are also aware, that all possibilities have not been exhausted yet and, therefore, we are developing a new design concept based on a completely new configuration of permanent magnets and electronically commutated coils.

The result is a motor with outstanding specifications:

- exceptionally high torque in spite of low motor weight,
- high efficiency (90 %) in a wide range of velocity and torque,
- simple and inexpensive construction.

A F4T type motor has the form of a ring with a peripheral rotor connected with the wheel rim. Two permanent magnets and two coaxial coils form the basis of the motor.

In each of two phases of the motor there is a coil and a magnet in configuration of the so called "magnet cross".



*Model of the hub-motor intended to be used on a moped. A smaller version for bicycles and velomobiles will be less complicated, less expensive and with maximum power of 400 W. It's weight will be only 1.6 kg.*

During the rotor movement the magnetic flux flows alternatively along two different but symmetrical routes.

The flow through the coil alternates, while simultaneously the flow through the magnet remains constant. Due to a special form of the coil, special position of the magnets and high quality materials, the losses are very low, while the construction itself is more than simple.

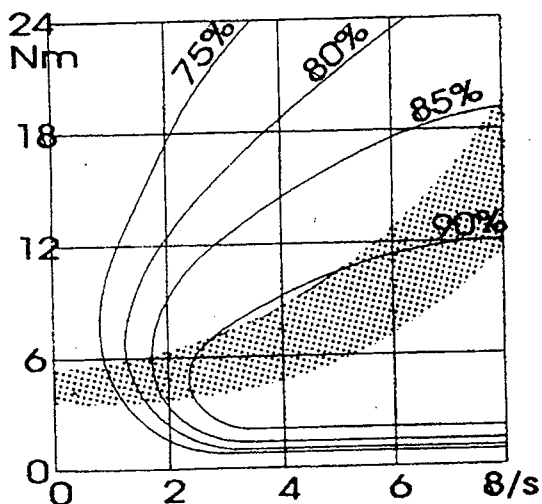
It is expected that the motor will be quiet.

The motor does not require any special maintenance, its service life should be extremely long due to a minimum of wear.

The F4T type motor will be developed in different versions for different applications.

F4T100 is the biggest and most powerful, designed for electromobiles.

F4T25 is intended to be installed into the rear wheel of electrocycles and into the wheels of small city electromobiles.



#### F4T100

$M_{max} = 100\text{Nm}$   
 $P_{max} = 10\text{kw}$   
 $m = 8\text{kg}$   
 $\eta = 90\%$

400 DEM (#)

(#) The expected cost of the component parts (without electronic equipment)

#### F4T25

$M_{max} = 25\text{Nm}$   
 $P_{max} = 2\text{kw}$   
 $m = 4.2\text{kg}$   
 $\eta = 90\%$

200 DEM (#)

A shell diagram of F4T25 motor, showing the ranges of rotation velocity and torque when the vehicle is driving horizontally.

A smaller version for bicycles and velomobiles will be less complicated, less expensive and with maximum power of only 400 W. It's weight will be only 1.6 kg.

Doesn't it sound attractive to a velomobile designer, who wants to use assistant power? – I hope so.

My paper is above all an invitation to those, who could and who would like to contribute to the further development and application of this new type of electric motor.

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## VELOCITY – ELEKTROUNTERSTÜTZUNG FÜR VELOMOBILE

*von Michael Kutter, Firma VELOCITY, Basel*

Unter Ihnen bin ich vielleicht so etwas wie ein Bastard. Sie sind alle Anhänger von "pure Human Power". Und ich schlage Ihnen nun etwas ganz anderes vor.

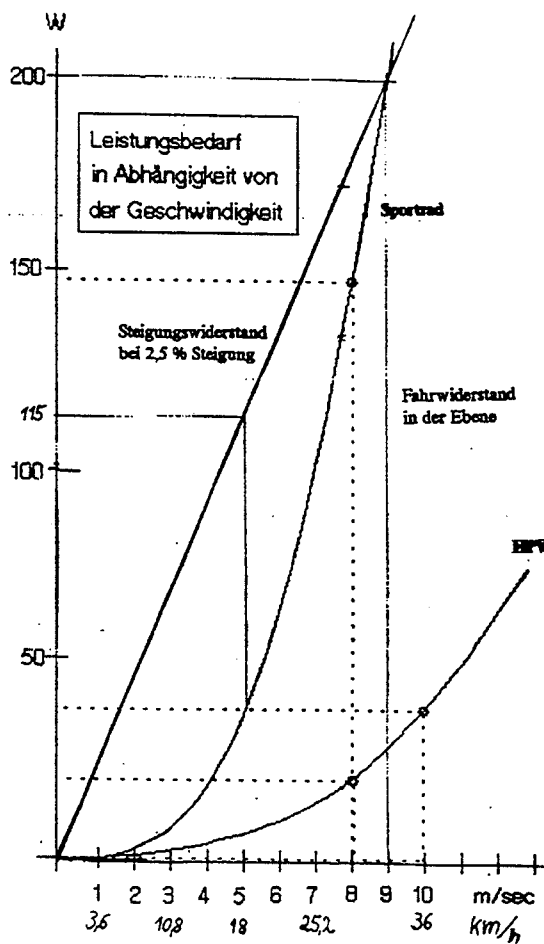
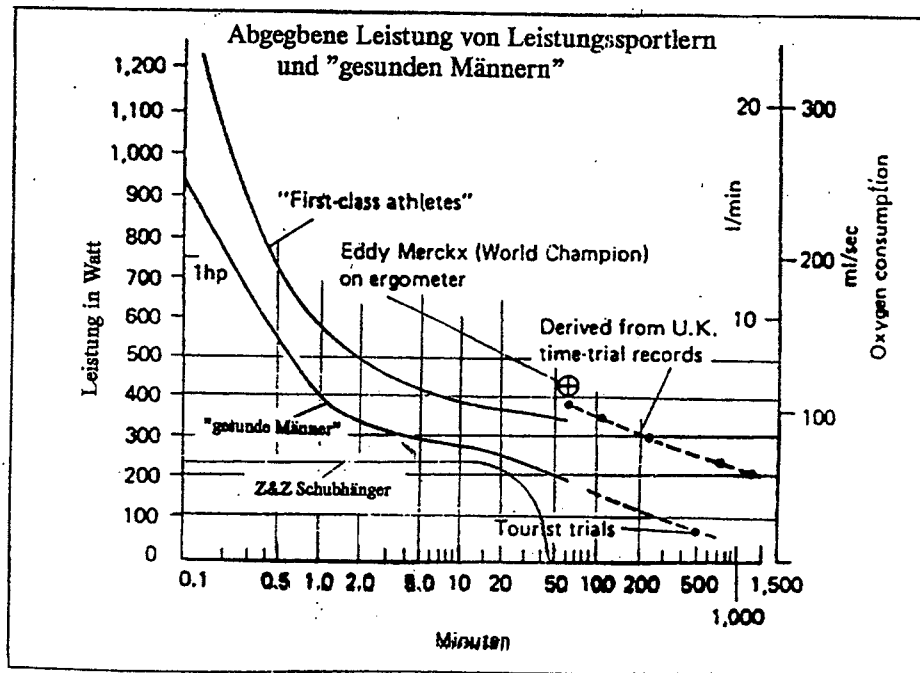
Viele von Ihnen habe ich 1989 an der Tour de Sol gesehen. Ihre enormen Durchschnittsgeschwindigkeiten habe ich vor allem auf Leichtbau, gute Transmission und gute Aerodynamik zurückgeführt.

Ich habe jedoch zusammen mit Freunden das Twike gebaut. Seither sehe ich die Dinge ein wenig anders. Wir waren alle begeistert von einem reinen Muskelkraft-Fahrzeug, das sehr aerodynamisch, jedoch auch sehr bequem und alltagstauglich ist. Ich kann Ihnen auch versichern, dass fahren im Twike, mit 45 km/h aus reiner Muskelkraft in einem so bequemen Fahrzeug daherzurollen sehr grossen Spass bereitet. Regnet es noch dazu so wird das Fahrgefühl noch phantastischer. Aber die Hügel – wir mussten erfahren, dass wir am Berg die auf der Ebene durch die Aerodynamik gewonnene Zeit bei weitem wieder verlieren. Wir mussten das grosse Fahrvergnügen auf der Ebene am Berg oft schwer büssen.

Nun, ich habe einsehen müssen, dass es nicht nur um die Aerodynamik ihrer Fahrzeuge sehr gut bestellt steht, sondern auch um Ihre FITNESS. Ich – bin NICHT so FIT, vielleicht zum Glück. Denn vielleicht bin ich wie die MEISTEN MENSCHEN. Denke ich zurück an all die mühsamen Bergfahrten in gleissender Sonne, so frage ich mich: wie mühsam müssen das Leute finden, die nicht den selben Idealismus und Enthusiasmus aufbringen.

Wir von VELOCITY wollen nicht die Städte umbauen oder die zerstreut wohnenden Menschen umsiedeln, weil wir es nicht können. Wir wollen auch nicht ändern Menschen eine neue Lebensphilosophie aufdrängen. Wir wollen ganz einfach heutigen Menschen, die vielleicht sonst Auto fahren EINE REALISTISCHE ALTERNATIVE BIETEN. Wir wollen Menschen freiwillig vom Auto wegbringen, wir wollen weniger Autos auf der Strasse.

Die Schweiz hat etwa 6'000'000 Einwohner, die ca. 3'000'000 Autos und ca. 3'000'000 Velos besitzen. D.h. Sehr viele Personen besitzen ein AUTO und ein VELO. Die Vermutung liegt nahe, dass viele Autofahrer gerne Velofahren. Wo sind sie alle von Montag bis Freitag? Wo wohnen sie? Wo arbeiten sie? Befragt man solche Personen, weshalb sie wochentags nicht das Fahrrad für den Weg zur Arbeit benützen, so erhält man meist die folgenden Antworten: – Ich wohne ZU WEIT weg vom Arbeitsplatz.



-Der Weg ist ZU ANSTRENGEND, weist GRÖßERE STEIGUNGEN auf. – Eine grosse ANSTRENGUNG TÄGLICH, und vor der Arbeit, ist UNREALISTISCH. – Ich kann es mir NICHT leisten, VERREGNET am Arbeitsort anzukommen.

Also: Um Menschen, die an sich gerne treten, Fahrrad fahren – und das sind sehr viele – mit einer sinnvollen Alternative vom Fahrrad wegzubringen, muss man Ihnen folgendes bieten:

- WETTERSCHUTZ (dessen zusätzliches Gewicht macht Unterstützung beim Treten noch notwendiger.
- HILFE beim TRETEN, möglichst umweltfreundliche und geräuschlos.

Gross ist der Wille vieler Menschen sich selbst fortzubewegen, klein aber sind ihre Kräfte. Um mit einem Sportfahrrad eine Steigung von bloss 2,5 % mit 27 km/h zu befahren ist gemäss dem Diagramm

eine Leistung von 290 W erforderlich. (Steigungswiderstand + Fahrwiderstand in der Ebene.) Das nebenstehende Diagramm zeigt dass diese Leistung über längere Zeit (20 min.) nur von "first class athletes" erbracht werden kann. Beträgt die Steigung gar 7,5% (eine durchaus alltägliche Steigung) so sind bereits 610 W erforderlich, eine Leistung, selbst Eddy Merckx nur über fünf Minuten halten kann.

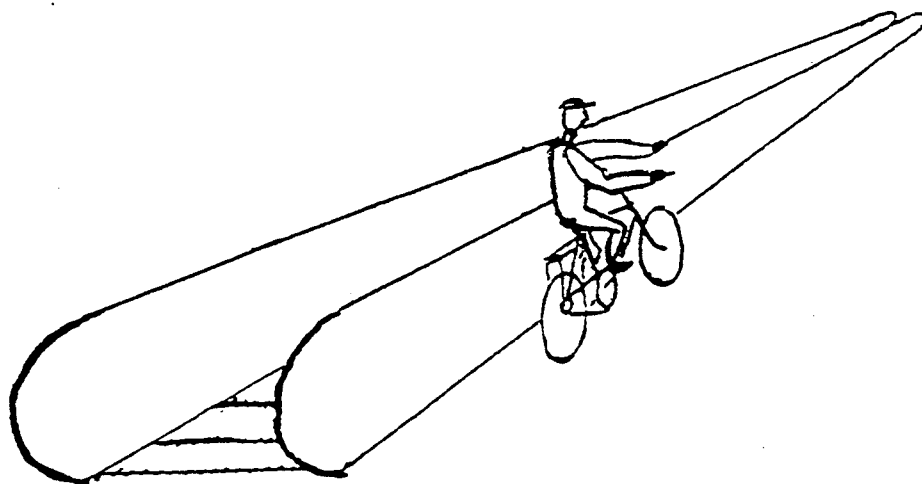
Nun, das gefragte Fahrzeug zeichnet sich klar ab: Ein aerodynamisches HPV mit Wetterschutz und Hilfsantrieb. Sie sind fast alle Konstrukteure von Fahrzeuge, und ich baue den Antrieb dazu. Deswegen bin ich hier.

Wie funktioniert nun ein solcher Antrieb, der zugleich eine stufenlose Übersetzung beinhaltet?

### **Der fliegende Teppich**

Der Titel täuscht, es geht heute nur um den rollenden Teppich, aber gleichwohl um die eine sagenhafte Geschichte.

Wie vielleicht einige schon wissen, befasse ich mich vor allem mit Elektro-Antrieben, welche die Muskelkraft miteinbeziehen. Sie alle kennen, was ich gleich erläutern werde, sicherlich schon aus eigener Erfahrung, denn seit einiger Zeit sind auf den meisten Flughäfen rollende Bänder anzutreffen, auf denen man gehen kann. Und das ist gut so, denn das macht mir meine Erklärung deutlich einfacher. Denn diese Bänder sind eine perfekte, ja die perfekte Verbindung von Elektro-Antrieb und Muskelkraft; den Erfolg spüren sie jedesmal selbst, wenn Sie darauf gehen.



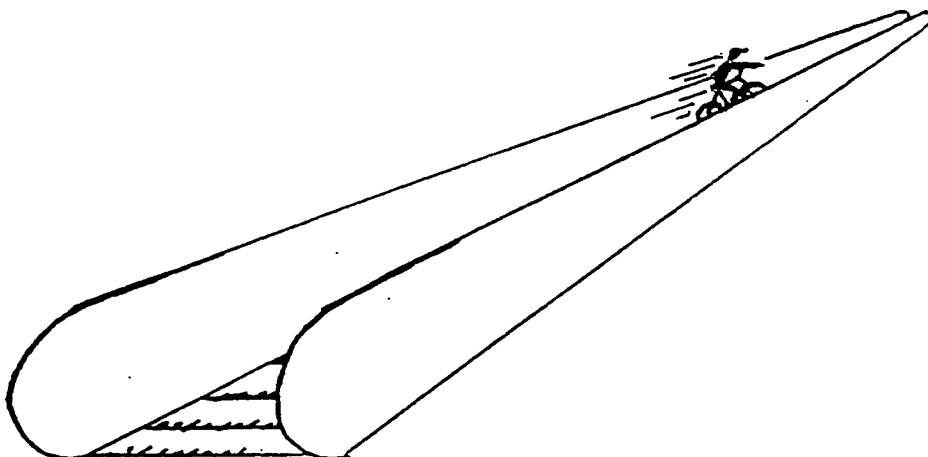
So, was hat das mit Elektro-Velos zu tun? Einiges, aber es kommt vorerst erstens anders, und zweitens als man denkt, und drittens doch so wie man dachte! ElektroVelos haben schon einige gebaut, aber eben anders als Sie nun denken. Wenn ein Velo mit einem elektrischen Hilfsmotor ausgerüstet werden soll, gibt es prinzipiell – auf unser Rollband übertragen – zwei Möglichkeiten: Entweder Sie fahren mit Ihrem Fahrrad neben dem Rollband auf dem Fussboden und halten sich am Handlauf des Rollbandes fest, ein bisschen wie auf dem Kinder-Skilift. Oder aber... – nein, das kommt später.

Sie ahnen es schon, der erste Vorschlag scheint nicht die beste Variante zu sein. So zu fahren ist sicher angenehm, wenn man gar nicht treten will, aber da wir ja treten wollen, bauen wir nicht ein Mofa, sondern "Velocity", das übrigens schneller fährt als ein Mofa.

Nun stellen Sie sich vor, Sie lassen sich noch immer vom Handlauf des Rollbands ziehen, wollen aber mittreten, und Sie werden feststellen, dass Sie durch mittreten gar nicht schneller werden, sondern einfach dem Elektro-Antrieb des Rollbands seine Arbeit abnehmen, ihn entlasten. Irgendwann kommt der Punkt, wo Sie aus eigener Kraft schneller fahren wollen als das Rollband. Wollen Sie hierbei durch das Rollband nicht gebremst werden, so lassen Sie den Handlauf los. Leider helfen Ihnen dann Rollband, Handlauf und Elektro-Antrieb gar nichts mehr; und falls diese dann noch weiterlaufen, ist das eigentlich Stromverschwendung.

Trotzdem wurden bisher alle Elektro-Velos so gebaut. Die schlaueren Konstrukteure haben für den Elektro-Antrieb einen Freilauf eingebaut, der sozusagen automatisch loslässt, wenn das Fahrrad schneller wird als der Handlauf bzw. der Elektro-Motor. Bei anderen Elektro-Velos mit Reibrollenantrieb muss man sozusagen selbst den Handlauf loslassen, indem man die Reibrolle vom Rad wegklappt.

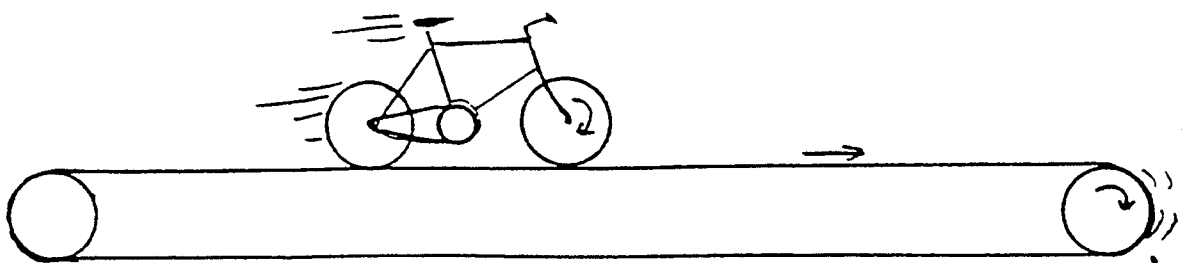
Ich sehe, Sie warten schon ungeduldig, wann ich vorschlage, was doch auf der Hand liegt: Mit dem ganzen Fahrrad aufs Rollband und ab die Post. Dann werden nämlich immer die beiden Geschwindigkeiten von Velo und Rollband addiert, egal wie schnell ein jedes läuft oder fährt.



Beim Rollband liegt das auf der Hand und sieht ganz einfach aus. Die Idee auf ein Elektro-Fahrrad zu übertragen, ohne nun alle Strassen umzubauen, war etwas komplizierter, aber sicherlich weniger aufwendig wie eben alle Strassen umzubauen. (Übrigens wäre ein Velo-Netz mit Rollbändern vermutlich noch lange billiger als Bau und Unterhalt eines Autobahn-Netzes, welches Papa Staat seit eh und jeh stillschweigend finanziert.) Wir haben nun statt sämtlichen Strassen einfach die Hinterrad-Naben umgebaut.

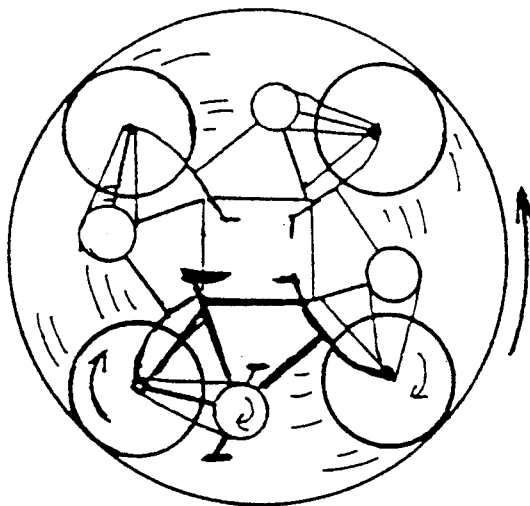
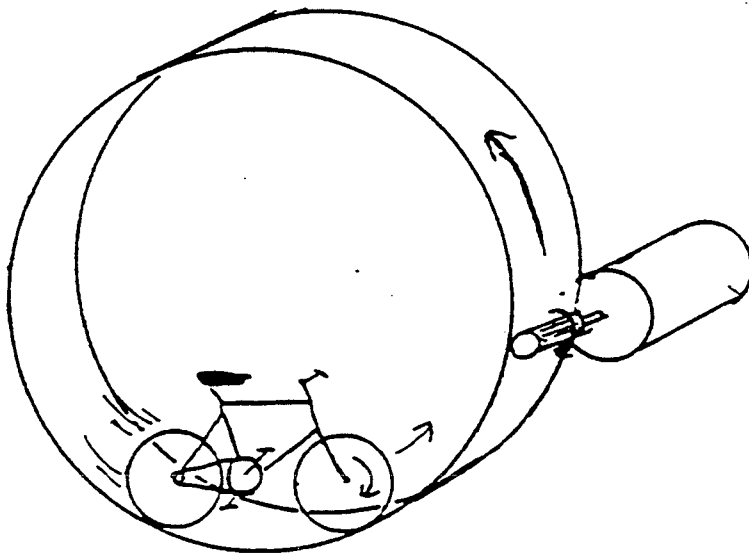
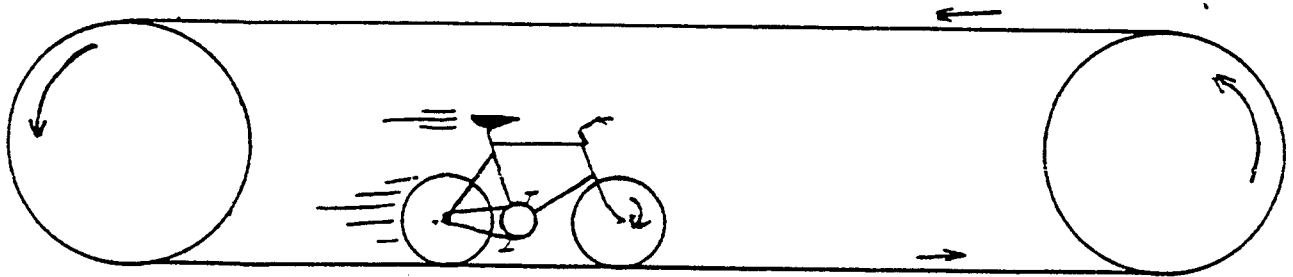
Jedenfalls haben wir eigentlich genau die Rollband-Idee in die Hinterrad-Nabe eingebaut. Endprodukt ist ein Elektro-Velo, das sich exakt so fährt wie Radfahren auf dem Rollband. Nur können Sie die Geschwindigkeit des Rollbandes über den "Gas-Griff" stufenlos regeln von 0-18 km/h. Und das reicht nämlich schon. Denn wenn Sie darauf nur schon mit 20 km/h radfahren, so erreichen Sie bereits eine Geschwindigkeit von 38 km/h, welche sinnvoll scheint für ein solches Fahrzeug. Am Berg, den Sie sonst mit 5 km/h hochkraxeln, fahren Sie zügig mit 23 km/h hoch. Daß nämlich 18km/h für den "rollenden Teppich" bereits reichen, das ist genau der Trick und der Witz der Sache. Gut untersetzt erreicht ein kleiner 200 – 500 W Motor diese 18 km/h problemlos, zieht aber noch immer jeden Berg hoch bis über 20 % Steigung. Mit demselben Motor betrieben, erreicht ein gewöhnliches Elektro-Velo nicht mehr als 18 km/h. Oder, wenn der Motor so untersetzt wird, dass es schneller fährt, kommt es dafür bei grossen Steigungen nicht mehr hoch.

Doch wie versetzt man nun die ganze Rollband-Geschichte in eine Nabe? Ein Rollband, ein Velo. Das Rollband läuft, das Velo fährt. Das gibt zusammen eine grosse Geschwindigkeit: "Velocity" genannt.



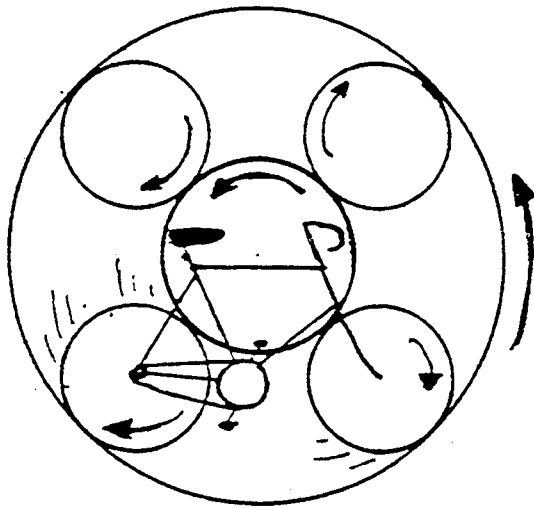
Darmit nun das Velo nicht gleich wieder runterpurzelt, vor allem jedoch, damit ich besser erklären kann, stellen wir ein wenig um. Wir machen das Rollband sehr gross und lassen das Fahrrad auf der Innenseite fahren.

Darmit der Velofahrer nun freie Bahn hat, nehmen wir die Umlenkrolle weg, wählen für das Rollband eine kreisrunde Form – gleich einer grossen Betonröhre. darinnen nun der Radfahrer Loopings fahren darf – und treiben seinen Untergrund, das frühere Rollband von aussen an.



Da alles ja in einer Radnabe Platz finden soll, fangen wir an zu rationalisieren. Unser ursprüngliches Rollband, unsere Betonröhre, wird kleiner, und wir setzen der Symmetrie zu-liebe 4 Velos hinein. Um Räder und Platz zu sparen dient jedoch immer das Hinterrad eines Velos als Vorderrad des Folgenden. Damit sind alle miteinander verbunden und fahren schön ordentlich immer im gleichen Abstand. Wer soll nun pedalen auf diesen 4 Velos, die hier ihre Loopings fahren? Da ist kein Platz für 4 Fahrer. Dieses Problem lösen wir zentralistisch.

Wir treiben alle 4 Räder gemeinsam an durch ein Rad, das wie unsere Sonne im Zentrum steht und um das sich alles dreht. Betrachten wir nun ein einzelnes Fahrrad: Vom Rad im Zentrum, dem Sonnenrad angetrieben, rollt es auf der Betonröhre, dem einstigen Rollband ab, wie eben ein Fahrrad auf der Straße.

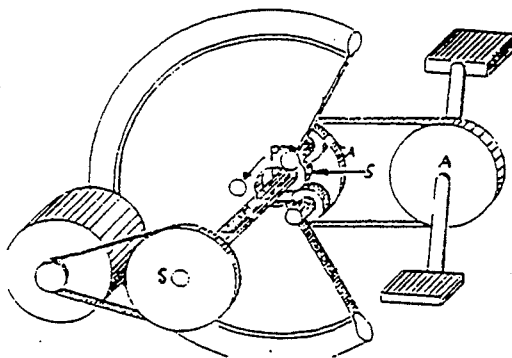


Wenn wir nun auch die Betonröhre, das einstige Rollband, antreiben, fährt unser Velo auf einem bewegten Untergrund, wie auf einem Rollband, und zwar viel schneller, weil die beiden Antriebsgeschwindigkeiten addiert werden. Jetzt müssen wir nur noch diese schnell kreisenden Fahrräder zu fassen kriegen. Aber das ist einfach.

Was wir nun vor uns haben ist eigentlich ein Planetengetriebe. Gewöhnlich wird es – wie hier – angetrieben von einem Rad im Zentrum, Sonnenrad genannt. Und unsere 4 Veloräder – Planetenräder genannt – fahren auf dem Looping-förmigen Untergrund, Aussenring genannt, der normalerweise stillsteht, wie auch unsere Strassen – vorläufig noch.

Das besondere am Velocity-Getriebe ist nun, dass dieser Aussenring – sozusagen die Straße, auf der die 4 Velos fahren – auch angetrieben wird, – wie ein Rollband. Die 4 Räder

der Velos – denn diese vier schnellen Velos interessieren uns ja – sind durch ein spezielles Teil miteinander verbunden, wie hier durch die vier Fahrradrahmen. Und dieses Teil, Planetenträger genannt, ist mit dem Hinterrad verbunden, überträgt also die grosse Geschwindigkeit der 4 kleinen Velos in der Nabe auf das Hinterrad des richtigen gro-



A = Aussenring P = Planetenträger S = Sonnenrad

ßen Velos – unseres "Velocity" – und macht es, wie der Name sagt, sehr schnell.

Vielleicht haben Sie es bemerkt: Ich habe Sie im Verlauf der Geschichte ein wenig betrogen. Ursprünglich war ja das Velo durch die Muskelkraft angetrieben, das Rollband elektrisch. Hier ist es nun gerade umgekehrt. Es war einfacher und vorteilhafter so. Aber ich verspreche Ihnen, dass es kein Betrug ist, wenn ich Ihnen nun sage, dass es überhaupt keine Rolle spielt, wer was antreibt. Die Geschwindigkeiten der beiden Antriebe, Muskelkraft und Elektrisch, werden immer addiert, wie  $2 + 1$  genauso  $3$  gibt wie  $1 + 2$ .

## Ein stufenloses Automatgetriebe

Es gäbe nun noch viel Interessantes und märchenhaftes zu erzählen über dieses sagenhafte Getriebe.

Eines will ich noch verraten: Man kann damit ein stufenloses Automatikgetriebe realisieren und damit wiederum ein Fahrrad der Träume. Sie brauchen nur noch aufzusteigen und loszufahren; Sie treten immer gleich schnell obwohl Sie immer schneller fahren und nicht zu schalten brauchen. Das übernimmt stufenlos und automatisch eine Elektronik.

Inzwischen, nach über einem Jahr Entwicklungsarbeit, die zum Teil durch das Bundesamt für Energiewirtschaft finanziert wurde, konnte dieses Ziel erreicht werden.

Ein kleiner Sensor erfasst jeden vorbeiziehenden Zahn der rotierenden Kettenblätter. Er erfasst damit ständig die Tretfrequenz mit einer Auflösung von 48 Messungen pro Umdrehung. Aufgrund dieser Daten regelt er ständig die Motordrehzahl und damit das Übersetzungsverhältnis zwischen den Pedalen und dem Hinterrad.

Für technisch Interessierte erinnere ich kurz an die Funktionsweise des Getriebes. Steht z.B. der Motor und damit das von ihm getriebene Sonnenrad "S" still, so wird durch die Muskelkraft der Aussenring "A" angetrieben, der mit den Planetenrädern kämmt, die sich wiederum am stillstehenden Sonnenrad abwälzen. Dabei entsteht zwischen Aussenring "A" und Planetenträger "P", also zwischen Tretantrieb und Rad, ein Übersetzungsverhältnis von 3 : 2.

Beginnt nun der Motor zu treiben, bis sich z.B. das Sonnenrad mit gleicher Drehzahl dreht wie der Aussenring, so laufen alle Elemente des Getriebes synchron. Das Drehzahlverhältnis zwischen Aussenring und Planetenträger, also zwischen Tretantrieb und Rad beträgt 1 : 1.

Über die Drehzahl des Motors kann also nicht nur dessen Leistungsanteil, sondern ebenso das Drehzahlverhältnis von Tretantrieb und Hinterrad geregelt werden. Und dies wiederum kann von der Tretfrequenz abhängig gemacht werden. Tritt der Fahrer stärker in die Pedale, so würde sich theoretisch bzw. auf einem normale Fahrrad die Tretfrequenz erhöhen. Dies wird jedoch vom Sensor sofort erfasst und von der Elektronik die Motordrehzahl erhöht. Dadurch vergrößert sich einerseits das Drehzahlverhältnis Pedale/Hinterrad, wodurch die Tretfrequenz konstant gehalten wird. Zugleich erhöht sich aber die vom Motor an die Fortbewegung beigesteuerte Leistung.

Interessant ist bei dieser Lösung, dass allein aus der Information über die Tretfrequenz ein Elektromotor so geregelt werden kann, dass dadurch sowohl dessen Leistungsregelung als auch eine die Tretfrequenz konstant haltende ~stufenlose Übersetzung~ ständig den Wünschen des Fahrers angepasst werden. Erstaunlicherweise können auch die an den Pedalen wirksamen Kräfte ausser acht gelassen werden. Über die Tretfrequenz – nämlich eine geringfügige Erhöhung, wenn das Treten zu leicht geht (und umgekehrt) – werden die an den Pedalen wirksamen Kräfte miterfasst.

Das Velocity-Antriebssystem ist damit zu einem fast unsichtbaren, jedoch sehr muskelstarken, aber überaus leichten Beifahrer geworden, der Ihnen ihre Wünsche nicht von den Lippen, aber von den Waden und Füßen abliest.

Möglicherweise haben wir mit diesem System unwissentlich eine neue Aera der Bedienung eines Fahrzeugs geschaffen.

Das Regeln eines Motor entfällt, obwohl dieser vorhanden ist. Das Bedienen einer Schaltung entfällt ebenfalls.

Allein durch seine Tretbewegung gibt der Fahrer dem System alle für einen mühelosen Fahrbetrieb nötigen Information:

Einfach aufsteigen und treten !

Über das Treten möchte ich noch ein paar Worte verlieren, denn es bildet so etwas wie einen wichtigen Bestandteil unserer Fortbewegungs-Philosophie.

Körperbewegung ist sicherlich eines der elementaren, menschlichen Bedürfnisse. Sich aus eigener Kraft fort-zubewegen ist wohl die älteste und aus heutiger Sicht sinnvollste Kombination zweier elementarer Bedürfnisse: Bewegung und Fort-Bewegung.

Und eigentlich lieben wir ja alle diese sinnvolle Kombination; die Fahrradkaufe (allein in der Schweiz über 500'000 jährlich) belegen es deutlich. Den immer weiteren täglichen Wegstrecken sind aber unsere bescheidenen menschlichen Kräfte (ca. 120 W) einfach nicht mehr gewachsen.

Das Auto, Bösewicht, Sündenbock ... ist hier natürlich mehrfach schuldig: für die Trennung der beiden Bedürfnisse, für die immer grösseren Wegstrecken, und für die schwindenden Muskeln der Menschen.

Die Wege sind weit, die Menschen schwach. "Velocity" will hier einfach helfen, mit zusätzlichen 200 – 1000 W und den bewegungswilligen Menschen etwas unter die Arme greifen.

Als Helfer möchten wir von "Velocity" jedoch möglichst wenig auffallen, einmal äusserlich, ästhetisch und natürlich lärmtechnisch. Unauffällig möchten wir jedoch auch bleiben, was die Bedienung betrifft; sie entfällt einfach.

Wir hoffen, dass dadurch immer mehr Fahrer mehr Mut und Selbstvertrauen schöpfen, immer grössere tägliche Strecken (fast) aus eigenen Kräften zu bewältigen. Wenn sie dabei Ihr "Velocity" vergessen und sich fühlen wie Herkules, so wäre unser Ziel erreicht.

