Tour de Ruhr:
Experiences and a Concept for Future Electric Vehicles

Klaus Brinkmann, Wolfgang Köhler

Abstract

This paper presents in a *first part* an overview and description of the event 'Tour de Ruhr', which was, already from the very first beginning, supported and participated by members of the Chair of Electrical Power Engineering from the FernUniversität in Hagen. This includes not only organising and technical advice activities, but also active participation with self made experimental or modified vehicles. During these nearly ten years, many valuable experiences were made and systematically analysed. Basing on this, a scope of a concept proposal for future battery powered electric vehicles is presented in a *second part*.

Keywords: sun energy, energy consumption, battery, range, simulation.

1 Introduction

The 'Tour de Ruhr' is a competition for Electric Solar Vehicles, which takes place annually in the region of the river Ruhr in middle Germany. This so-called 'Ruhrgebiet' is one of the most traditional industrial districts in Germany. The responsible organiser of this rally is the 'Initiative Solarmobile Ruhr e.V.'. This association was founded 1990 in Dortmund and has now more than fifty active members. Aim of this initiative is to increase and to promote the usage and development of electric vehicles, which batteries are powered by renewable energies like solar energy, wind power or aqua power. The renewable way to produce electrical energy, for example with the help of photovoltaic plants, has the great advantage, that there are no CO_2-emissions with negative effects on climate conditions [2]. Because nowadays, nearly 14% of the world wide CO_2-emissions are produced by general traffic activities, as shown in figure1. In Germany this emission rates approximately 20%, with 2/3 from the individual traffic part.

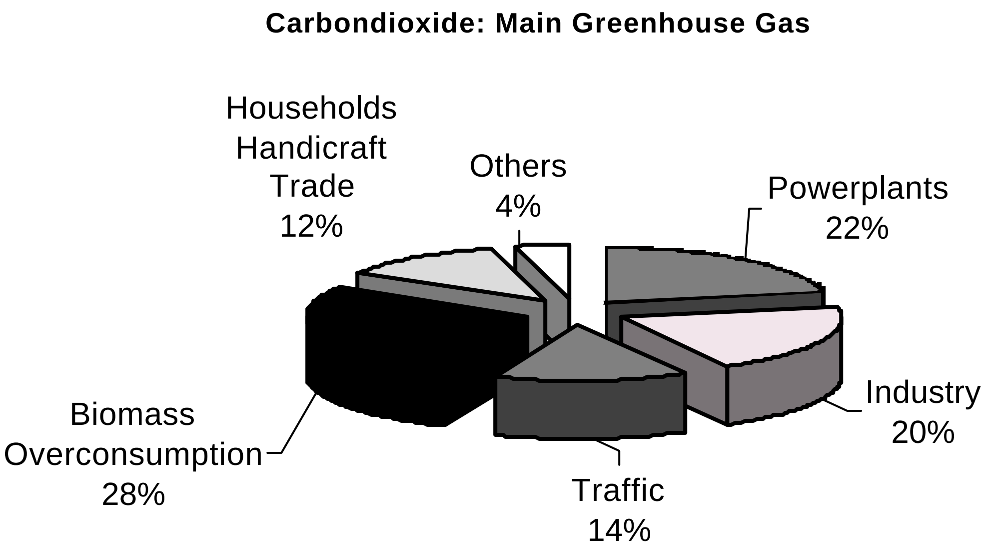

Figure 1: Partition of the world wide CO_2-emissions with respect to the mean sources [1]

The analysis of encapsulated air bubbles in the ice of glaciers, as well as direct measurements during the last decades, show an increase of the atmospheric CO_2-concentration from 280 ppmv at the beginning of industrialisation to now 358 ppmv, as demonstrated in figure 2. This means an increase of 25% in a very short time, compared to geological dynamics. Some prognostics approximate the future increase of the world wide traffic CO_2-emissions to 60% up to the year 2030.

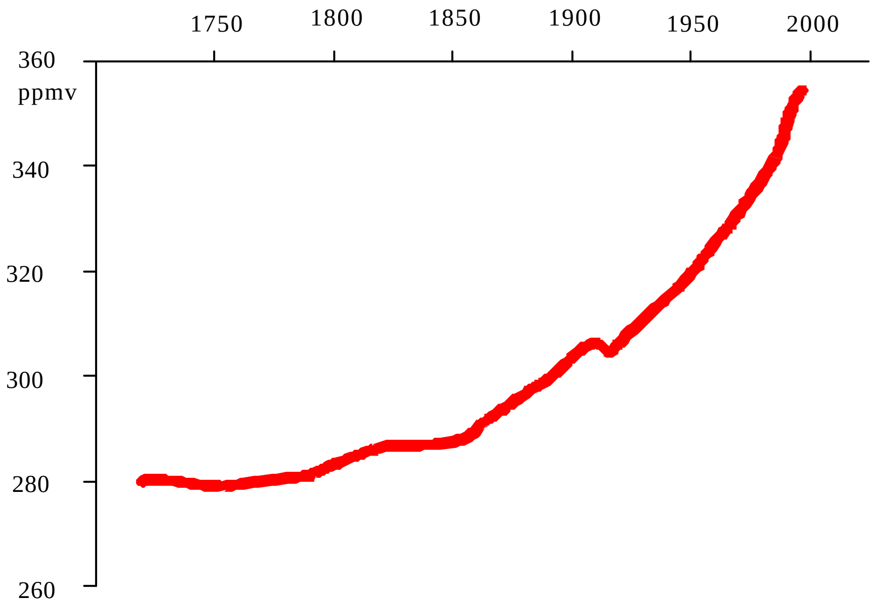

Figure 2: Increase of the atmospheric CO_2-concentration [1]

In contrast to the "never-ending" renewable energy resources, fossil primary energies like oil, gas and coal are limited. Nowadays, nearly 60% of all oil-products are consumed by the automobile traffic [6].

2 Tour de Ruhr

The event ‘Tour de Ruhr’ started for the first time in 1992 and was repeated every year at the beginning of the summer holidays. This competition is a rally over a distance of nearly 250 km and takes three days, to test and to compare the everyday abilities and energy demand of the different electric vehicles; nearly 50-60 vehicles every year.

2.1 Categories of Electrical Vehicles

These vehicles were divided into different categories regarding the rules of the ‘Bundesverband Solarmobile (BSM)’ as follows:

a) Self-Sufficient Solar Vehicles
b) Purpose Design (B1)
c) Conversion Design (B2)
d) Commercial Vehicles
e) Transport Vehicles
f) Light Vehicles (2- and 3 wheelers)

In our analysis we regard all vehicles, which are possibly able to be used in the city area, concerning their every day abilities and energy efficiencies. These are mainly the types from b) to e). Additionally we made experiences with our own vehicles belonging to class c). Racing cars and two wheel vehicles were not part of our investigations.

All four categories are designed for the transport of persons, as well as of additional baggage, to be used in city areas for usual purposes. Some of these vehicles have three wheels instead of four, and others have the possibility of an additional foot-pedal drive as an energy saving alternative.

2.2 Every Day Ability of Electric Vehicles

Before a vehicle gets the allowance to start at the tour, each vehicle of the participants has to take part in an official check procedure regarding their technical security.
In order to get a fair evaluation and comparison of the different vehicles regarding their energy consumption during the competition, the masses of the vehicles, driving persons as well as their baggage are to be registered. This is especially necessary, to compare and evaluate the vehicles at the end of the event concerning the efficiency of their electrical energy consumption.
To test the every day ability, the organisers found some routines, which are to be absolved, for example parking exercises, slalom-parcours forward and backward, ability to take baggage like suitcases and packages and to withstand rainfalls [4].

2.3 Battery and Charge Control

The range of the electric vehicles amounts usually 40 to 80 km. After this, they have to be recharged. For this procedure the participants get a time of approximately 3,5 hours. Therefore some of the used battery sets are afterwards only partially loaded.

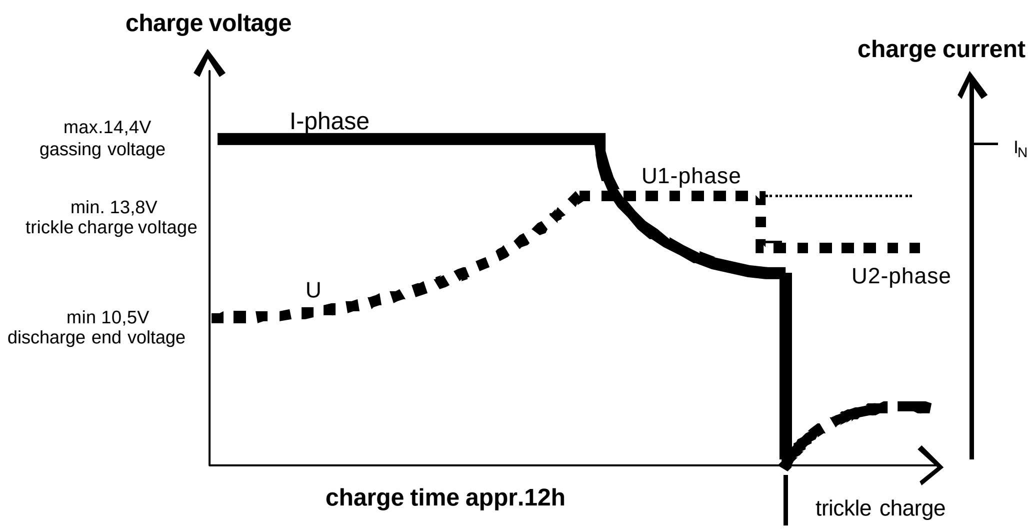

Figure 3: Principal charge characteristics of a lead-jelly battery

The main reason is the limited charge current of the different charge management systems of the individually used charge controller.
The following types of batteries were mainly used in vehicles at the Tour de Ruhr competition:

i) Lead / Acid Batteries
ii) Lead / Jelly Batteries
iii) Lead / Fleece batteries
iv) Ni / Cd Batteries

One of the most used type is the lead / jelly battery. The energy evaluation at the tour depends on the consideration of a battery capacity concerning a C5 characteristic. This means a discharge during five hours.

2.4 The Electrical Driving Motor

Similar to the batteries, also different variants of electric drives were realised. The next list shows the main concepts:

i) Permanent-Magnet DC Motor with Simple Control
ii) Disk Wheel Motor with PWM Control
iii) Asynchronous Motor with Three-Phase Inverter in Four-Quadrant Operation
iv) Synchronous Motor with Power Control
v) Synchronous Wheel Hub Motor

An important criteria for the choice of a special driving system with control, would be the reachable degree of the system efficiency, as well as the possibility of recuperation. The recuperation gives the ability to charge the batteries partially during gear processes and valley passages with surplus energy. This may reduce the energy consumption.

2.5 The Evaluation of the Energy Efficiency

With respect to practicability, the kind of charge control and battery type, as well as the electric drive system are not part of the evaluation procedure. Only the weight of the vehicles including their batteries, the maximum load with driver, assistant driver and additional baggage, the maximum total weight of the vehicles and at last the capacity of the battery set have to be registered at the competition's beginning. When they start, the batteries are considered to be fully charged. The necessary charging processes on the route were managed with the help of a mobile charging station, provided with an equipment to count the energy units for each vehicle.
In order to find a fair comparison method of the vehicles, depending on their category to which they individually belong, a formula was created to calculate a so-called evaluation factor.

The calculation formula for the *evaluation factor* concerning the rules of the BSM is given by:

$$Evaluation\_Factor = 0{,}8 + 0{,}2 \cdot \left(\frac{load}{75} \right) + 0{,}2 \cdot \left(\frac{load_{\max} - load}{150} \right) \tag{1}$$

with

$load$ [kg] = *weight at start* [kg] *minus weight empty* [kg]
$load_{\max}$ [kg] = *maximum allowed total weight* [kg].

Example:

Driver $\hat{=}$ $load$ =85 kg, weight empty: 280 kg, $load_{\max}$ =400 kg $\Rightarrow$

$$Evaluation\_Factor = 0{,}8 + 0{,}2 \cdot \left(\frac{85}{75} \right) + 0{,}2 \cdot \left(\frac{35}{150} \right) = 1{,}072\,.$$

With the help of this evaluation factor, the measured energy consumption off each vehicle has to be corrected, to allow a most possible fairness for the comparison. This is done in the following way:

$$Energy_{total} = Capacity_{battery} + Energy_{counted} \tag{2}$$

$$Evalution\_Points = \frac{Energy_{total}\,(100km)}{evaluation - factor} \tag{3}$$

Example:

Vehicle A: $Energy_{total}\left(100km\right) = 5700\,\text{Wh},\ Evaluation\_Factor = 1{,}072 \quad \Rightarrow$

$$\frac{5700}{1{,}072} = 5317 \ \text{ Points}$$

Vehicle B: $Energy_{total}\left(100km\right) = 8720\,\text{Wh},\ Evaluation\_Factor = 1{,}480 \quad \Rightarrow$

$$\frac{8720}{1{,}480} = 5892 \ \text{ Points}$$

In this energy consumption based evaluation system, the vehicles have to be ranked with respect to decreasing *evaluation-points*. The lower the evaluation points are, the better is the ranking. The following figure 4 gives an overview of the energy consumption of electric vehicles, which took part at the Tour de Ruhr for at least three times:

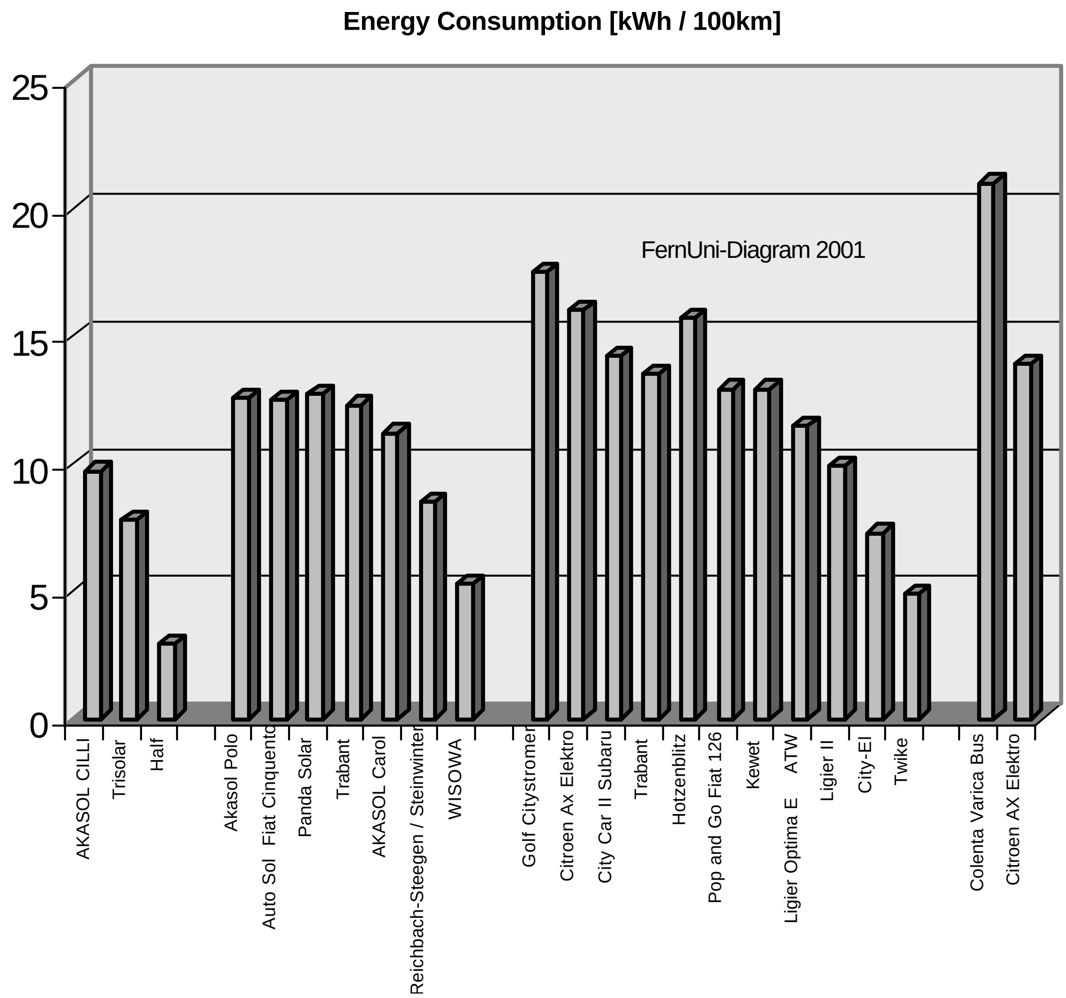

Figure 4: Average energy consumption of some electric vehicles for 100 km at the Tour de Ruhr

This can be seen in comparison to Figure 5, where the same vehicles are listed concerning their empty weight. It can obviously be seen, that the energy consumption correlates to these data. The energy consumption of the light vehicles like "Half" and "Twike" could be influenced by additional contributions from the drivers, who are able to drive also muscle powered with pedals.

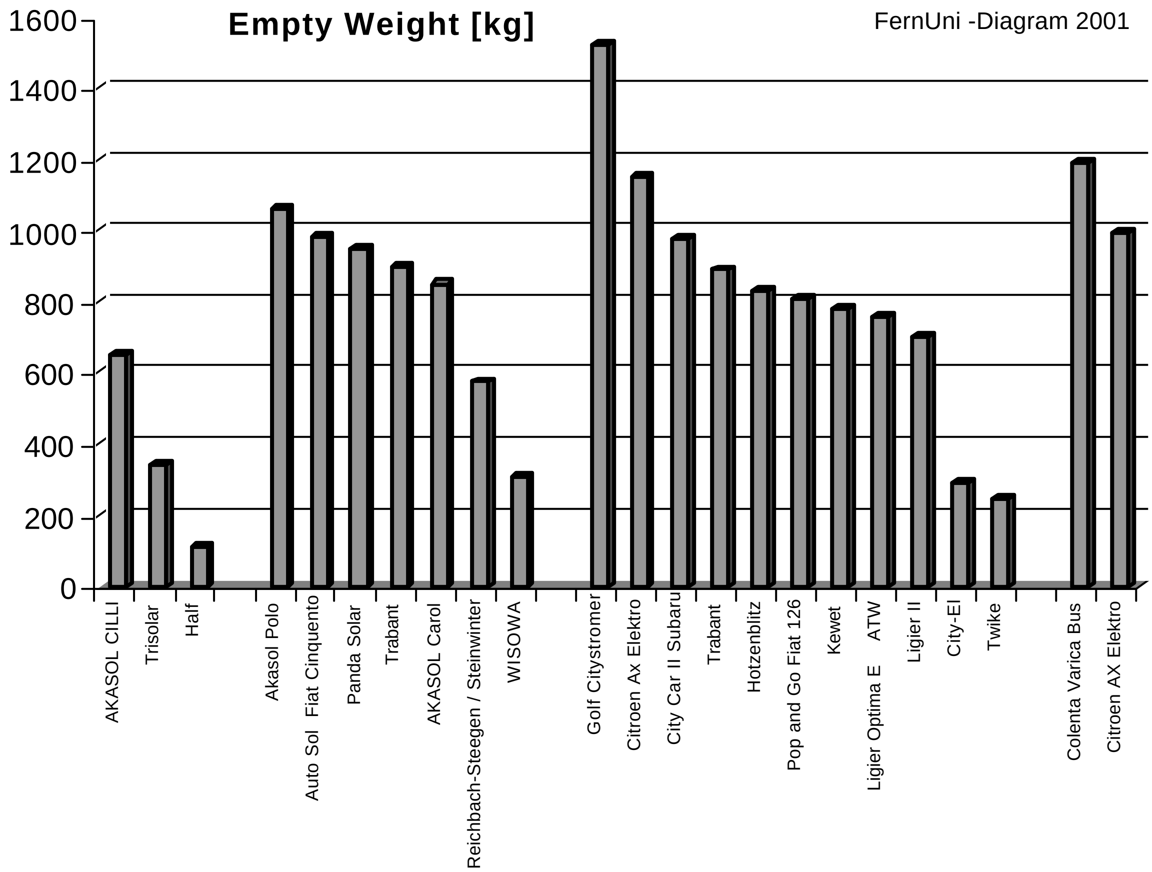

Figure 5: Empty weight of electric vehicles at the Tour de Ruhr

2.6 Experimental Vehicle: "Sunrunner" as a City Car

At the University of Hagen, in co-operation with WISOWA Hagen, we developed an experimental vehicle, the so-called "Sunrunner", which took part at different events like Hanse Solar, EVA and Tour de Ruhr in Germany [4],[5].

Aim of the technical development of an own experimental vehicle was to modify a commercial light weighted two seated vehicle, to drive it electrically instead of the usual combustion engine. This in a manner, that the energy demand would be as low as possible, without a significant loss in the every day ability. Tests concerning the durability and reliability of this electric vehicle followed.

For the driving system, we choose a three-phase asynchronous motor with a bi-directional inverter, to allow recuperation with the help of a four-quadrant control system. The electric motor is directly connected to the drive gear via a tooth cone belt.

For the Batteries, lead /acid as well as lead / jelly were used and tested. The charge control is able to manage the batteries single and complete, even in cases of recuperation. The usual charge station for this vehicle is the solar charger of the University of Hagen, which is supplied by a 6.000 Wp grid connected photovoltaic plant at the roof of our buildings. An integrated display informs the driver every time about the charge capacity of the batteries.

Additionally a software package was developed. With the help of a notebook, it is possible to get important data to optimise the driving technique, especially to help the driver during the competition of the Tour de Ruhr to save energy.

During this research and development activities, many differentiated valuable experiences with the construction of an electric vehicle and driving system, as well as with the practical usage of such a vehicle, were made. Depending on these experiences and gained insight knowledge, we thought about concept proposals for future electric vehicle designs.

Some of these experiences are already documented in different German publications [2], [3], [4]. Video productions in co-operation with the ZFE of the University of Hagen were shown recently in the German TV (WDR) [5], [6].
The following figure 6 shows the principal scheme of the realised driving system of our experimental electric vehicle "Sunrunner".

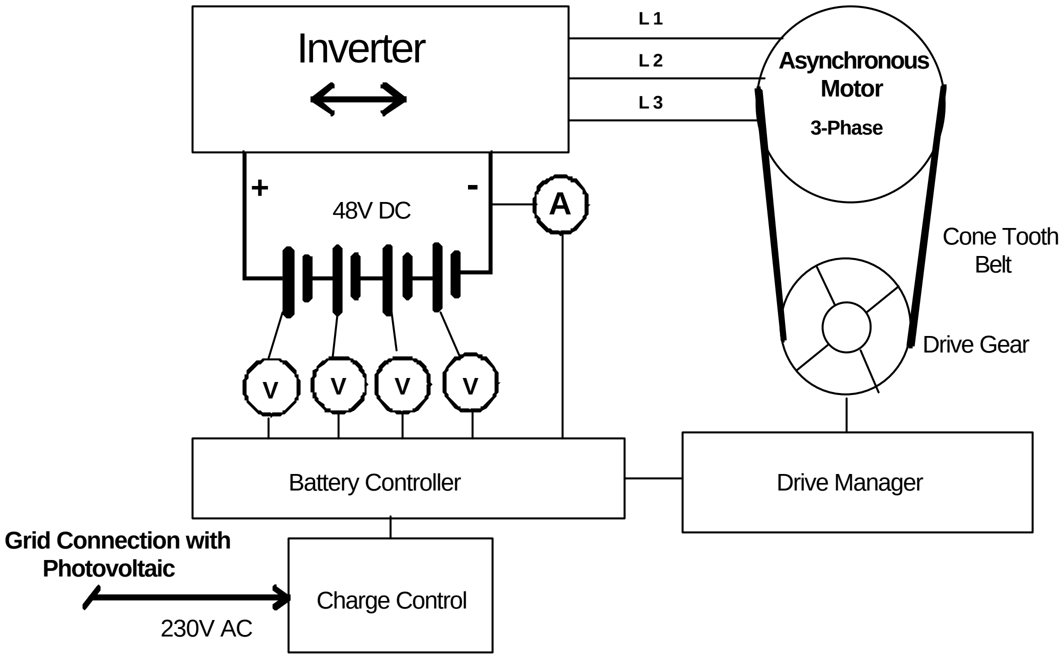

Figure 6: Driving system concept for electric vehicles

3 Concept Proposal for Future Electric Vehicles

We used the experimental and theoretical experiences for critical analysis of the existing technologies and strategies for electric vehicles. As a consequence, we worked out a concept for the construction and optimising of electrical vehicles in order to minimise the energy demand. This concept regards the individual demands on an electric vehicle, like range, speed, amount of passengers, transport capacity etc., in interaction with the correlated physical conditions of the construction and the characteristics of the average type of roadway [2],[3].

3.1 Individual Demands

Aim of the following explanations is to demonstrate a way to gain criteria for a general optimisation procedure for the design of electric vehicles. First of all there are the wishes of the individuals.

Table 1: Technical demands from the consumer

Individual "Wishes"
• Range [km] • Maximum Speed [km/h] • Average Speed [km/h] • Maximum Amount of Passengers • Maximum Load [kg]

The leading parameter for the optimisation is the energy efficiency. Naturally, the first step is to find out and to take into consideration the consumer's individual wishes, as listed in table 1.

3.2 Route Classification

Additionally, there exist typical demands, which follow from the individual daily driving route. If one takes into account only statistically usual routes, it may be possible to classify them roughly in the following categories.

Table 2: Rough classification of usual driving routes

Route Class	
i)	Flat Plane
ii)	Highlands
iii)	Mountains

Especially of course of the limited range of electric vehicles, this classification is an important step to determine for example the necessary battery capacity.
As a simplification, it would be sufficient for an optimisation procedure to calculate only with a distance-height-profile of a representative route from the above classification. This means approximately a linear model, neglecting effects of radial forces:

$$h = h(s) \equiv height\,, \quad s = s(t) \equiv distance\,, \quad t = time\,. \tag{4}$$

The figure 7 shows exemplary how such a profile looks like.

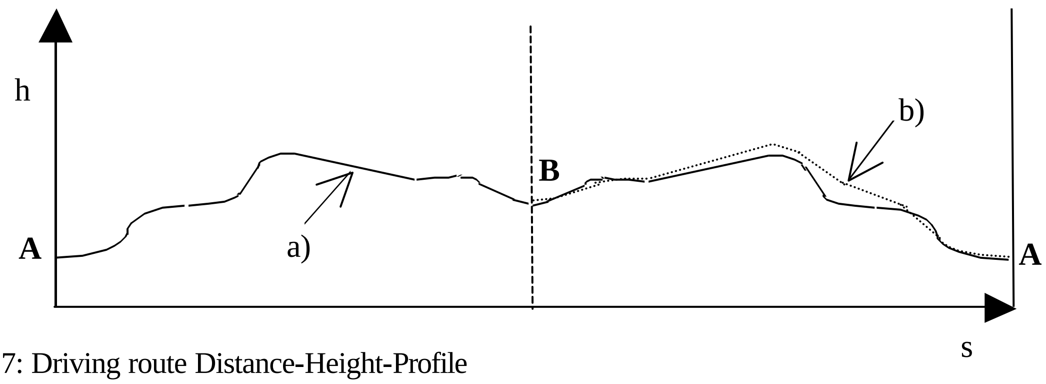

Figure 7: Driving route Distance-Height-Profile

This could be the daily way to the working place. In this case A means the starting point at home and B the working place. The way a) from A to B is not necessarily identical with the way back b) from B to A. But the total daily route could be considered as to be periodically done in time. This implies the idea to describe the route functional with the help of a Fourier's series (harmonic analysis).
The functional connection between the physical raising angle and the mathematical deviation is then given by:

$$\frac{dh}{ds} = \frac{\tan a}{\sqrt{1+\tan^2 a}}\,. \tag{5}$$

Beside this distance-height-profile, the statistically averaged velocity-profile, as demonstrated in figure 8, is also a necessary information for optimising purposes, because of the acceleration work.
During the optimising process, one can consider, that the consumer tries to reach the velocity limits of the route as fast as it is technical possible. For the acceleration processes (positive as well as negative), usual values should be taken, which are compatible with the humans comfortable feelings.
Basing on these ideas, it would perhaps be possible to generate three sufficiently representative test routes, available with the help of an analysis of statistical data concerning usual daily driving routes.

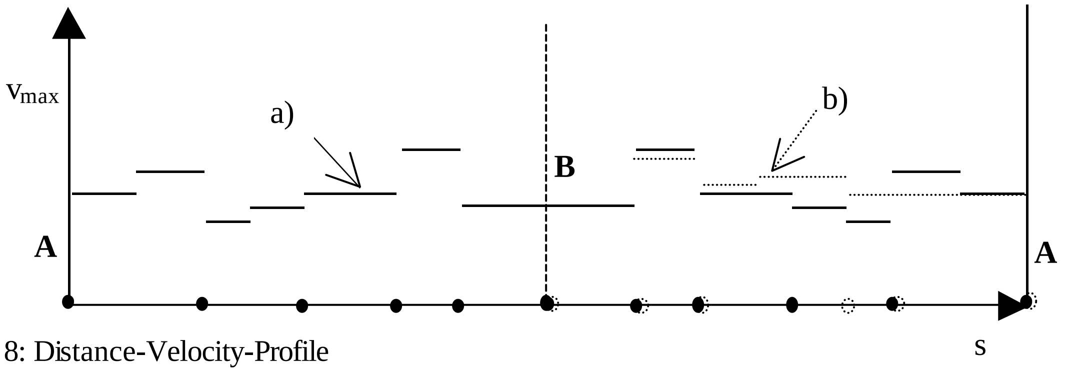

Figure 8: Distance-Velocity-Profile

The lines and dots in the figure 8 above indicate the maximum possible velocity in dependence of the distance, which could be given from technical as well as from regulatory traffic rules.
In order to find an optimisation procedure, these technical demands from the distance profiles have to be correlated with the individual wishes as shown in table 1.

3.3 Foundations of the Optimisation Concept

The function $h(s)$ in figure 7 could be divided into a limited amount of partial intervals with continuous and monotone behaviour, so that the Dirichlet's condition is fulfilled, which is necessary to get Fourier's series with well defined coefficients. But it could not be expected, that the functions were available in an analytic form, so an approximation should be done in the following way:

- Divide the total route S_{total} n sufficient $2 \cdot m$ equal parts
- Therefore results the supporting points (s_0, h_0), (s_1, h_1),... (s_{2m-1}, h_{2m-1})
- Calculate the coefficients:

$$a_0 = \frac{1}{2m} \sum_{i=0}^{2m-1} h_i \,, \tag{6}$$

$$a_n = \frac{1}{m} \sum_{i=0}^{2m-1} h_i \cos\frac{n \cdot i}{m} \quad \text{for} \quad n = 1,2,...,m \,, \tag{7}$$

$$b_n = \frac{1}{m} \sum_{i=0}^{2m-1} h_i \sin\frac{n \cdot i}{m} \quad \text{for} \quad n = 1,2,...,(m-1) \,, \tag{8}$$

- With these coefficients the following approximation is valid:

$$h(s) \cong a_0 + \sum_{n=1}^{(m-1)} \left(a_n \cos(n \cdot s) + b_n \sin(n \cdot s)\right) + a_m \cos(m \cdot s) \,. \tag{9}$$

The velocity-profile in figure 8 has to be correlated to the height-profile $h(s)$ in figure 7 with

$$v_{\max}(s) = u_i \quad \text{for} \quad s \in [s_i, s_{i+1}] \text{ and } \quad i = 0,1,...,k \,, \quad s_i \le s_{i+1} \tag{10}$$

and $u_i \le$ technically possible maximum speed of the vehicle.

Then it is possible to calculate the energy demand for the route, described in such a way, for a specified vehicle. In order to realise the individual wishes, in a first step the 'virtual' vehicle has to be composed with all necessary parts, which are conform with them. Doing this, a lot of differentiated technical details and data knowledge are needed. With these detailed information, a first step proposal results in summary in a vehicle mass, which is the main parameter to calculate the energy demand. If there occur discrepancies during the calculation routine concerning the technical data combination, a variation of the responsible parts has to be done, and the whole calculation repeats. In this way, one gets an *iterative routine*, as shown in figure 9, to determine a vehicle with minimum energy demand inclusive all its parts. Therefore a detailed data base with all necessary vehicle parts has to be implemented.

The pure energy demand which would be at minimum necessary to drive the test route with the given velocity profile is determined by the following expression

$$E = \sum_{i=1}^{k} \int_{s_{i-1}}^{s_i} h(s) \cdot F_i(s)\, ds \quad \text{with} \quad F_i \equiv Driving - Force\,. \tag{11}$$

Important for a correct calculation is the efficiency and to regard the fact if a recuperation is integrated or not. This could be considered with the help of

$$h(s) = \begin{cases} 1 & for \quad F_i \geq 0 \\ 0 & for \quad F_i < 0 \quad without \quad \text{Recuperation (Breaking).} \\ h_{rekup}(u) & for \quad F_i < 0 \quad with \quad \text{Recuperation} \end{cases} \tag{12}$$

This expression for the energy demand gives only the energy, which is minimum physically needed to drive the route and would not necessarily be able to regard all the different driving efficiencies and energy losses. Because it is not in all cases possible to achieve detailed information in advance, only the most important forces are to be taken into account like

$$F_{\text{Res}} = F_{ro} + F_{air} + F_{grad} \qquad \text{traction resistance} \tag{13}$$

$$F_{ro} = f_R \cdot m \cdot g \qquad \text{rolling resistance} \tag{14}$$

$$F_{air} = 0{,}5 \cdot \rho_{air} \cdot C_W \cdot A \cdot u^2 \qquad \text{frictional drag} \tag{15}$$

$$F_{grad} = m \cdot g \cdot \sin\alpha \qquad \text{gradient force.} \tag{16}$$

For the resulting acceleration force the formula (17) gives:

$$F_{Acceler.} = F_{Drive} - F_{\text{Res}} \quad \Rightarrow \quad F_{Drive} = F_{\text{Res}} \ \text{case of equilibrium.} \tag{17}$$

If the route gradient is negative, it would be possible to get a negative resulting force. In order to drive the vehicle with constant speed in such cases, one has to break or get the same effect with recuperation. The same thought is valid for speed reducing processes.
To change the speed with respect to the speed profile regard the expressions

$$u = \frac{ds}{dt} \quad \text{and} \quad a = \frac{du}{dt} \quad \Rightarrow \quad ds = a \cdot u \cdot du\ , \tag{18}$$

to evaluate the correct speed for the formulas (13) to (16). In a first approximation, it would be sufficient, to calculate with a set of constant acceleration values.
The recuperation efficiency would be surely dependant from the momentary speed, what could be respected with the help of characteristic curves from the motor-generator data.
In order to minimise the energy demand, the data for the single components of the 'virtual' vehicle are to be changed in a compatible manner again and again until a minimum is achieved. Perhaps this iteration process could not be done complete automatically, so that the constructor has to do some changes with respect to experiences and realisable possibilities, as well as logical principles.
Essentially for a successful implementation this proposed optimisation routine, is the availability of all necessary technical data and characteristic curves of the single components for the vehicle. This means a detailed and differentiated extensive data base to be stored in a computer. As far as possible, proved realistic characteristic curves for example for the driving unit, recuperation, battery charging and recharging etc. should be used. Even constructive experiences concerning the automobile bodies are very important, because they have to be compatible to all the other masses and internal forces. Last but not least, security aspects have naturally to be included. In summary this procedure, fitting one part to another in a compatible way, leads to a set of data which gives a great probability to construct an energy demand optimised vehicle. Further optimisations have to follow on the 'real' vehicle.

3.4 Optimisation Concept

The following scheme gives a scope of the numerical procedure to get optimised design data:

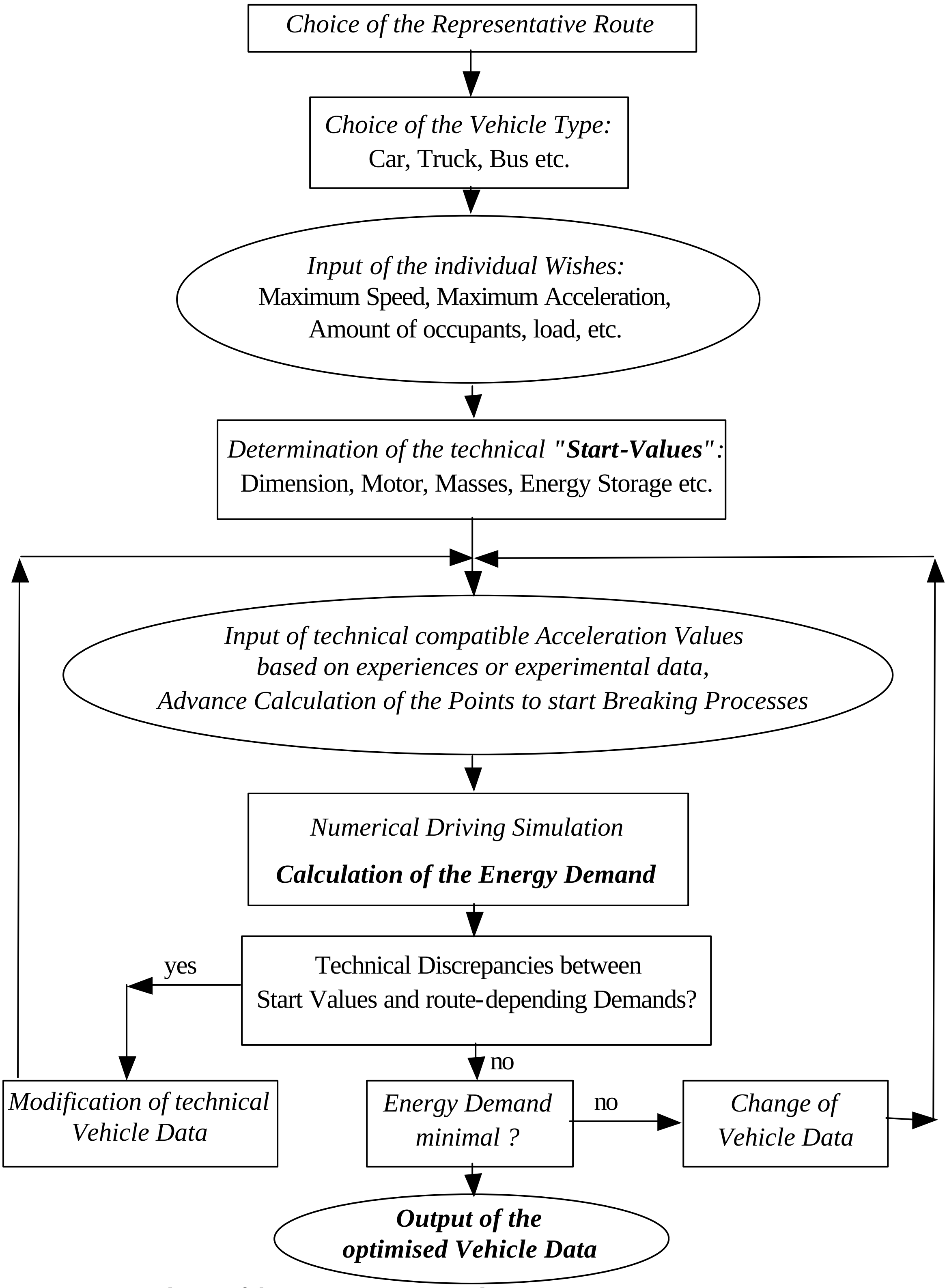

Figure 9: Process Scheme of the Optimisation Procedure

4 Conclusion

Following the basic 'idea' of the Tour de Ruhr, to minimise the energy demand, with respect to a most rational usage of renewable energies, we consequently thought about a method to construct future electric vehicles, which are especially build up with respect to this goal. To reach this, it would be necessary to think about the vehicle as a whole, not only concerning energy saving driving systems.

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Tour de Ruhr:
Experiences and a Concept for Future Electric Vehicles

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This presentation gives in a *first part* an overview and description of the event 'Tour de Ruhr', which was, already from the very first beginning, supported and participated by members of the Chair of Electrical Power Engineering from the FernUniversität in Hagen. This includes not only organising and technical advice activities, but also active participation with self made experimental or modified vehicles. During these nearly ten years, many valuable experiences were made and systematically analysed. Basing on this, a scope of a concept proposal for future electric vehicles is presented in a *second part*.
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Some of these experiences are already documented in different German publications. Video productions in co-operation with the ZFE of the University of Hagen were recently shown in the German television.
We used the experimental and theoretical experiences for critical analysis of the existing technologies and strategies for electric vehicles. As a consequence, we worked out a concept for the construction and optimising of electrical vehicles in order to minimise the energy demand. This concept regards the individual demands on an electric vehicle, like range, speed, amount of passengers, transport capacity etc., in interaction with the correlated physical conditions of the construction and the characteristics of the average type of roadway and driving conditions like possible speed.
In this way, an *iterative routine* was created, to determine at first a 'virtual' vehicle with minimum energy demand inclusive all its parts. Therefore a detailed data base with all necessary vehicle parts has to be implemented. Further optimisations have to follow on the 'real' vehicle.