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Reducing the Energy Consumption of Electric Vehicles

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Abstract. Currently more and more attention is paid to energy consumption and it is especially noticeable in electric vehicles. Generally, when thinking about the idea of reducing the energy consumption in an electric vehicle there are two methods. The first one is introducing new technical solutions in the design for reducing energy consumption. The second way is driving and performing other maintenance tasks in a manner that reduce energy consumption. A special case of the use of these methods is with vehicles built specifically for energy efficient racing, where the criterion of energy saving is much more critical than in the ordinary, commercial vehicles. The task of ensuring minimum energy consumption during driving is quite demanding and the decisions taken as early as at the vehicle concept stage can have a great impact on the final result. The paper presents the experience of the Silesian University of Technology team gained while constructing the high-performance electric vehicles designed for Shell Eco-marathon, beginning with the selected methodology for the design of such vehicles by solving partial design issues for some components of the vehicle as well as studies carried both on test stands and on the racetrack . Special attention was paid to the method of dealing with the determination when reducing the interaction of design features to evaluate their influence on the energy consumption. The second part of the paper deals with the evaluation of the driving strategy during the race and its impact on reducing the energy consumption. The method to determine the outcome of the set strategy and how to select the race strategy is presented along with the optimal strategy in specific structural and environmental constraints. The paper summarizes a few year experience in the design and testing of two vehicles built for Shell Eco-marathon, which is world famous competition for Prototype and UrbanConcept electric battery powered vehicles.

Keywords. Efficiency, energy consumption, race car, optimisation, simulation model, design, driving strategy

Introduction

Shell Eco-marathon, which is the biggest race of energy saving vehicles, is held annually in three different places in Europe, Asia and North America [1]. The task is to cover a given route in a given time using the smallest amount of energy. The results are given in a form of a number of driven kilometers per energy/fuel unit.

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The organizers of the Shell Eco-marathon determine the schedule for test measuring rides. As part of the competition, each team has several attempts within three days to take a test within several hour time span. There is a division to several categories and classes. There is UrbanConcept category where vehicles resemble small city cars, and Prototype class. The course of the competition is different for these categories: in UrbanConcept type, the vehicles are required to stop at a certain time (approx. 1.6 km) to simulate city driving, while the prototype vehicles are allowed to continue ride freely. Additionally, there is division depending on the drive unit. In each class the following drives are distinguish: Gasoline, Hydrogen, Battery Electric, Diesel, Alternative Diesel and Ethanol. The competition is tough for the drivers because there is always a large number of vehicles on the track and in addition each of the vehicles has its own strategy thereby there are vehicles driving at different speeds causing continuous overtaking of each other. Consequently, it increases the danger of collisions and significantly impedes the implementation of the preplanned strategy.

The prototype electric-powered vehicle (MuSHELLka) was designed and built by members of the Student Scientific Association of Machine Design [2], at the Institute of Fundamentals of Machinery Design at the Silesian University of Technology in Gliwice. The vehicle was designed and built within one academic year by a team of a dozen of people, students and academics of the Faculty of Mechanical Engineering at the Silesian University of Technology. The vehicle has been designed according to the strict race regulations for the class prototype vehicles and battery electric category. In the last three years, it took part in the European edition of the competition with the score of 487.3 km/kWh in 2014.

Apart from the vehicle in the prototype category the team also competed in the category of UrbanConcept battery electric (Bytel) and the team is currently preparing a vehicle for UrbanConcept Hydrogen.

1. Planning development tasks

The vehicle shown in Figure 1 is a tricycle structure monocouque type and the outer layer is made of sandwich composites structure based on epoxy resin and carbon fiber, aramid and glass fabric [3].

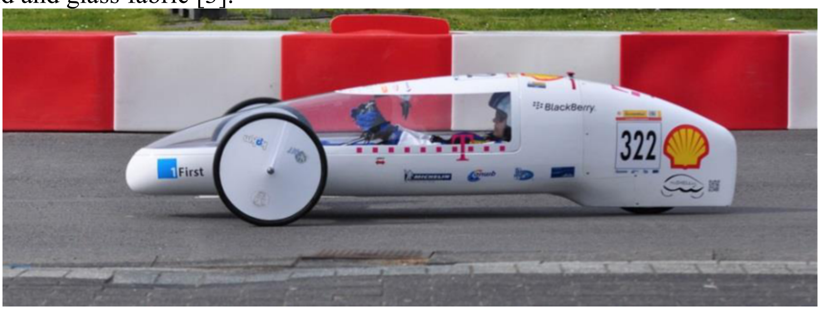

Figure 1. MuSHELLka vehicle – prototype, battery electric.

Designing a vehicle for such specific racing applications is an extremely difficult task because the most important design decisions are made at the beginning of concept phase. It is very difficult to assess their impact on the final outcome and even more to choose optimal solution. The aim of the designers is to minimize energy consumption in certain race conditions. Since the beginning of work on the various concepts it was thought how to evaluate the vehicle concept and individual systems up to date. In other words, how to transfer the current assessment of general ideas and a more detailed design solutions to a formal optimization problem so that at any time during the design process you can choose from a set of proposed best solutions. The solution is to use a simulation model designed for the analysis of the vehicle in the conditions of the race track. So from the very beginning of the work on a multi-vehicle racing, the simulation model was built. It should be emphasized that the degree of complexity and confidence to the results of the simulation model is adequate to the level of development of the vehicle and the level of team knowledge on the race and the car. The original model built in the first moments of the project work is so incompatible to the current advanced the simulation model. The assumption of continuous development of the simulation model had a significant impact on the assumptions about the general form of the model i.e. modularity so that the particular parts can be developed separately and if necessary replaced.

Modelling and simulation of hybrid and electric vehicles is in the focus of interests in last few years. The need for modelling and simulation of electric and hybrid vehicles was described in [4]. The authors presented especially physics based modelling. In [5] the other point of view is presented. This paper considered REVS (Renewable Energy Vehicle Simulation) environment which is a simulation and modelling package developed at University of Manitoba. REVS is composed of several components such as electric motors, internal combustion engines, batteries, chemical reactions, fuzzy control strategies, renewable energy resources and support components that can be integrated to model and simulate hybrid drive trains in different configurations. Seref Soylu in his book [6] have been investigated modelling and simulation of electric vehicles and their components. Mathematical models for mechanical and control devices and their components were proposed to make this reference a guide for everyone how want to prototype electric vehicles.

During the project realization the following stages of the development of the model have been assumed:

- Development of a preliminary version of the simulation model
- Improvement of the individual parts of the simulation model
- Verification and tuning of the model based on the results of test rides on the target racetrack in Rotterdam
- Improving simulation model based on the results of the verification research in specialized studies
- Improving the modeling and optimization methods and further tuning of the model parameters
- Customizing the simulation model to changing environmental conditions

The original form of the model was based mainly on the mathematical description of physical phenomena of a moving driven mechanical system subjected to external forces such as aerodynamic drag, rolling resistance, etc. In the further stage, the individual modules of the model were developed, based on the research results from the bench stands and preliminary test drives. For the purpose of this verification special bench test stands have been created - engine test bench, the bench drivetrain [7] etc. Based on these results, the model parameters have been fine-tuned to increase the accuracy of operation. A series of verification tests with the use of specialized equipment have been carried e.g. the study of vehicle aerodynamics at the Institute of

Aviation in Warsaw. The results of the studies were integrated into the system simulation model. This allowed a significant increase in confidence in the performance of the simulation model as opposed to preliminary results which were perceived with high degree of uncertainty. The next step was to tune the simulation model based on the results based on test drives in conditions similar to the race [8]. As there is no possibility to access the racetrack on the streets of Rotterdam for testing apart from the competition, a loop track was organized on the test track of FIAT automotive company in Tychy, Poland. In the subsequent stages, it is planned to adapt the model to changing driving conditions on the track as well as various vehicle parameters and different types of vehicles. The simulation model is developing in MATLAB environment and details of simulation model are described in [8,9].

2. The choice of design approaches

Choosing the right design approach is the most important factor influencing the sporting outcome and performance of the vehicle. It should be realized that the solutions adopted at the beginning in most cases can no longer be changed and have an additional impact on other vehicle systems. Other factors such as a chosen strategy or current preparation of the vehicle, which also affect the outcome, can be changed to the existing conditions in a given time limit. The assumption of using a model simulation to evaluate design decisions determined the direction of constructors steps from the very beginning. The first preliminary calculations showed the impact of different design characteristics on resistance forces (Figure 2).

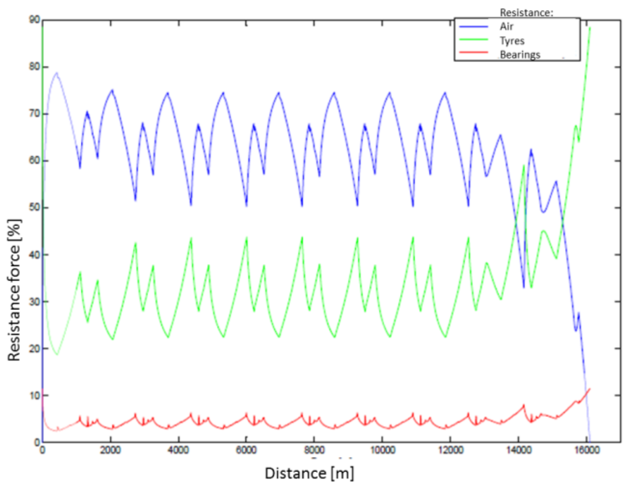

Figure 2. Comparison of various types of characteristics on vehicle resistance forces.

For this type of vehicle and scenario, by far the largest impact on energy consumption is air resistance, however, it is also important to take into account the rolling resistance of the wheels. In contrast, the resistance of the bearings used in the vehicle is negligible at the preliminary design stage, assuming regularity of bearing arrangements. As a result, it is surprising that the weight of the vehicle taken into account in the latter two categories is not the primary factor influencing the outcome.

2.1. The choice of shape of the vehicle

It is hardly possible to describe all the aspects of the selection of design features. For purpose of this paper example, based on the selection of the shape characteristics of the vehicle, the methodology of selection of these characteristics will be described. Choosing the right design solution and its features is always specific for a given feature. The choice of different aspects of the MuSHELLka vehicle design was described in detail in other papers [10], [11], [12]. During design Knowledge-based Engineering methods was used [13] utilizing CATIA Knowledgeware.

The fundamental decision on the concept of the shape was taken on the basis of statutory regulations, planned and published by the organizers. Amendments to the regulations allowed, inter alia, a gradual reduction in the required turning radius, the ban on rear wheel for steering. As the consequence, the concept previously used by most teams did not meet in the future the basic requirements of driving stability. So far, most of the teams have applied the structures already built a few years ago and integrated all wheels to the body resulting in a significant reduction in air resistance. In order for our team to be in line with the planned requirements, we have decided to eject the wheels off the vehicle body which resulted in worse outcomes than the other teams. But our destination in mind was racing in 2014. Since, aerodynamic drag force

$$F_x = c_x S_x \rho \frac{V^2}{2} \tag{1}$$

depends on two design factors - shape coefficient (c_x) and the area of vehicle face projection (S_x) and one operational – velocity (V) while looking for solutions the main goal was to minimize the face and the shape. While minimizing the face, the greatest influence were the ergonomic factors. First, drivers that meet the requirements of the regulations were select with the best geometrical parameters, then their body shapes were modeled and the minimum necessary shape for their safe driving was chosen (Figure 3)

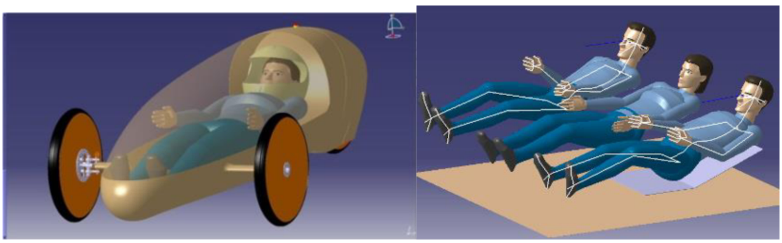

Figure 3. Ergonomic analyses of the body shape.

Another limitation which has proved tricky was an outer shape and in particular unfolding surface shape of the transparent windscreen of the vehicle. Technological and economical aspects played a decisive role in adjusting a glider windscreen, which we received, and shape of the body of the vehicle. Therefore, calculations and the choice of optimal shape of the cockpit were focusing on adapting the upper parts of the body along with the lower part together with flexible beam of the chassis and other details such as hubcaps and steering knuckle. The analysis was carried out using a CFD software (Figure 4).

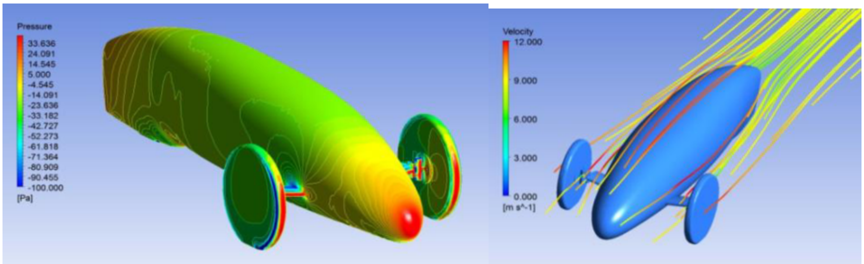

Figure 4. CFD analysis of vehicle body.

2.2. Verification of vehicle shape parameters

CFD analysis results allowed us to select better solutions by means of comparative method [10]. Nevertheless, there were some doubts concerning the final result of the drag. As the wind tunnel tests were planned for a later date, a numerical method was developed to verify the selected design features of the vehicle by using a reverse simulation model which is described in details in [14]. The basic assumption of the method is the use of appropriately adjusted modified simulation model to calculate the value of the selected parameter of a given structural features, eg. C_x drag coefficient based on the known results of test drives. The simulation model by means of optimization methods finds the value of a searched features so that the difference between test drive results and simulation was as little as possible [14]. The final score was additionally verified later in further research in the wind tunnel at the Institute of Aviation in Warsaw [10]. The results obtained by method of reverse simulation model (Cx=0,225) are almost identical with obtained in wind tunnel tests (Cx=0,23).

3. Developing the strategy for driving during the race

Developing strategies for driving during the race includes:

- the elaboration of a simulation model and formulation of optimization task
- verification tests
- development of an optimal strategy for the Rotterdam track

3.1. Formulation of optimization task

Another significant issue that must be taken into account in designing electric vehicles is to optimize relevant features of every part of the developed system. A comprehensive review on the latest research and development trends in this domain can be found in [15]. Recently, more and more attention has been paid to the second group of problems where advanced control methods were mainly developed. A great number of these methods is strongly connected to the problem of fuel saving. Keulen et al. [16] proposed velocity trajectory optimization for hybrid electric vehicles in order to minimize fuel consumption. Their approach enables fuel saving up to 5% compared i.e. to a Cruise Controller. The authors of the paper [17] present a path and speed planner for automated public transport vehicles in unstructured environments. The proposed method makes it possible to compute analytically a comfort-constrained profile of velocities and accelerations of the electric vehicles. Another path planning method is suggested by Farooq et al. [18]. They used a soft computing method, so-called particle swarm optimization, in order to minimize the length of the path and to meet constraints on total travelling time, total time delay due to signals, total recharging time, and total recharging cost. A very interesting approach is shown in [19]. The paper considered the simultaneous optimisation of either drive train or driving strategy variables of the hybrid electric vehicle system through the use of a multi-objective evolutionary optimiser. In general, the planning of the strategy of the competition can be formulated as the optimization problem (described in details in [8], [9]), in which the best possible trajectory of the linear velocity is sought. As expected, it can be achieved by optimizing the velocity set-points as a function of the distance. The main purpose of the optimization process is to adjust the values of the velocity set-point in different points of the laps in order to minimize a multiple objective function F, which can be formulated taking into account the following criteria. The first criterion is correlated with the total energy consumption. The second one is associated with the required distance that should be covered during a competition. The last objective is connected with the second one and it deals with the set limit value of the travel time that should not be exceeded.

Assuming that all of these objectives are not contradictory, the optimization task can be written as follows [8]:

$$\begin{aligned}&\text{Minimize} \quad \mathbf{F}(\mathbf{v}_c)=[\mathrm{f}_1(\mathbf{v}_c) \quad \mathrm{f}_2(\mathbf{v}_c) \quad \mathrm{f}_3(\mathbf{v}_c)]^T \\ &\text{subject to} \quad v_{ci}^{(L)} \le v_{ci} \le v_{ci}^{(U)} \quad \text{and} \quad i=1,2,\dots,i_{\max}\end{aligned} \tag{2}$$

where $v_{ci}^{(L)}$, $v_{ci}^{(U)}$, are the lower and upper values of the boundary constraints that should be chosen taking into account the properties of the electric vehicle, denotes the total number of parts of a race path that is used to digitize the raceway laps.

The optimization problem that has been described above can be solved in several ways. Generally, multi-objective problems have not a single global solution, and it is reasonable to investigate a set of points, each of which satisfies the objectives f_i. A well-grounded approach to search for an optimal solution is the global criterion method [20,21] in which objectives f_1, f_2 and f_3 are combined in order to form a single function. One of the most general indirect utility functions at this matter can be expressed in its simplest form as the weighted exponential sum:

$$\begin{aligned}&\mathrm{U}(\mathbf{v}_c)=\sum_{i=1}^{3} w_i \,\mathrm{f}_i(\mathbf{v}_c) \\ &\mathrm{U}(\mathbf{v}_c)=w_1\left[1+\varepsilon_{sim}^{\lambda_1}\right]^{-\lambda_2}+w_2\left[\mathrm{H}(d_{cv}-d_{sim})\frac{|d_{cv}-d_{sim}|}{d_{cv}}\right]^{\lambda_2}+w_3\left[\mathrm{H}(t_{sim}-t_{cv})\frac{|t_{cv}-t_{sim}|}{t_{cv}}\right]^{\lambda_2}\end{aligned} \tag{3}$$

where:

H - is the Heaviside step function,

fi and wi - indicate the i-th criterion and its importance (the value of the parameter wi should be chosen arbitrarily from the range [0, 1]) ,

λ_i - the exponent λ_i determines the extent to which a method is able to capture all of the Pareto optimal points for either convex or non-convex criterion spaces,

ε_{sim} [km/kWh] - is an estimator of the efficiency of the system calculated on the basis of the total energy consumption during the ride,

d_{cv} and d_{sim} [m] - is the reference path and the value of the covered distance obtained as a result of the simulation,

t_{cv} and t_{sim} [s] represent the set limit value of the travel time and the travel time calculated on the basis of the simulation,

$\mathbf{v}_c$ is the velocity vector where v_{ci} [m/s] is defined for a certain section of the route (the size of this vector depends on the complexity of the route). The first component of the objective function is responsible for minimizing energy consumption. Two other components are penalty factors being the limitation that is imposed on the average velocity of the race car. Their goal is to ensure that the vehicle will drive an assumed route at the optimum time.

There are various kinds of algorithms that can be applied for solving the problem which has been formulated in the form of (1) or (2). On the one hand, standard optimization methods e.g. gradient/Jacobian/Hessian-based algorithms cannot be effectively employed in this context due to the form of the objective function f_2 and f_3 as well as the non-deterministic parts of the simulation model. Nevertheless, for these types of problems stochastic optimization methods in the classic form e.g. Monte Carlo techniques are very often not able to find an accurate solution which would guarantee polynomial-time convergence. Because of these reasons, the optimal solution (the minimum of the objective function U) is searched using evolutionary algorithms (EAs). EAs are known as methods for solving either single- or multi-objective optimization problems [20, 22]. For the purpose of race strategy planning EA solution described in [8,9] was used.

3.2. Verification tests

As early as the formulation stage of the overall optimization alternative forms of the objective function, calculation methods and specific calculation parameters leading to results as close as possible to reality were considered.

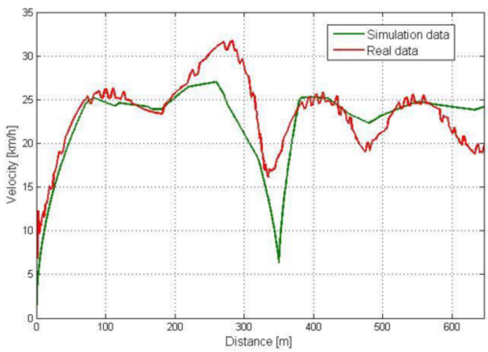

Figure 5. Speed comparison determined through optimization and measured during the test.

Verification of the results of calculations was carried out in a planned way that respects the fundamental limitations such as the lack of access to the target path of the street rack in Rotterdam. Therefore, access to the test track was organized and the geometric parameters of the track and the geometric track parameters were verified in details, including basic weather data records. In addition, the research verification methodology included the driving scenario restrictions limiting driving by the driver and established accuracy of the mapping speed profile during the race. Thus, the race was divided into

3 types of laps i.e. start (1 lap), central (8 laps) and final (1lap) and it was assume that for each of these types of laps separate velocity profile would be implemented. Furthermore, the lap subdivision to pre-established sections with speeds varying linearly between the calculated speeds required at the ends of these segments was assumed. The lengths of sections were selected in experimental way with regard to both the driver's perception and the complexity of the calculations. The Figure 5 shows an example of a graph of vehicle speed on the first lap of the test track. The figure includes the speed which was calculated for the optimal strategy and the speed of travel, registered during the ride when this strategy was being implemented. The correlation coefficient is 0.82.

3.3. Development of an optimal strategy for the race in Rotterdam

The strategy for running the race is selected directly before the race. The race is preceded by a test drive in which the team has developed a previously verified strategy and the final scenario is constructed in agreement with the drivers, who assess the feasibility of the calculated strategy. Strategy elaborated on the basis of numerical simulations and optimization leads to results even twice better than strategy determined by drivers yourself.

4. Conclusions

Reducing energy in an electric vehicle taking part in the Shell Eco-marathon has been included in a specially developed methodology, including the development of a simulation model and reverse simulation model, simulation experiments, laboratory experiments, verification testing, identification and optimization of the design features as well as the design and verification of driving strategies.

Introduced in the project development methodology taking into account the analysis of the impact of decisions on energy consumption. This analysis is done at each stage and allows for a quantifiable answer what is the impact of the planned action /decision on the final outcome of the race. A key element of this methodology is the simulation model. During the works undertaken a series of numerical tests, bench testing and during the race, which confirmed the accepted way of proceedings and preliminary results impact on the final result of the race. The final score is the result of compromises adopted mainly taking into account the planned changes to the regulations and the risk of economic and sport. The possibility of developing an existing structure are limited due to the need for changes in the main components of the structure. After three years of study, the team has the experience and complete vision of the possibilities of improving the result of allowing the building of new structures much better.

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