Developing a diffusion model of competing alternative drive-train technologies (cadt-model)

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Strategic measures for global ecology and security of energy supply particularly affect road traffic, as a main originator of greenhouse gas emissions by use of fossil energy. The introduction of several alternative, eco-friendly drive-train technologies in the automotive fleet leads to a competition with the existing petrol and diesel engines as well as with each other. A system dynamics model is developed to understand the fundamental competing forces driving the market penetration of the new technologies, and to derive policy implications and strategies potentially contributing to their successful introduction. A conceptual model is presented to examine different diffusion patterns between competing technologies. First results show, that reaching a critical market share in time is a decisive factor. This is demonstrated for the case of Switzerland, that represents a demand driven market without an autonomous automotive industry.

Keywords: technology diffusion, market share, alternative drive-train, system dynamics, competition, social norm, critical mass, potential

1 Introduction

These days the worldwide per-capita energy consumption averages 18000 $\frac{kWh}{a}$, which corresponds to an average power of 2100 W. In Switzerland about 5000 Watt per capita is spent, i.e. 2.5 times more than the global average (novatlantis – Nachhaltigkeit im ETH Bereich, 2005). The vision of "novatlantis – Sustainability in the ETH-Domain" (novatlantis – Nachhaltigkeit im ETH Bereich, 2005) is the so-called "2000-Watt-Society" (Energie–Spiegel, 2007), aiming at a reduction of the per-capita consumption to the current global average of some 2000 W, which is considered as a contribution to the establishment of a balance between the industrial countries and the developing world. Facing global climate change – boosted by accumulated greenhouse gas emissions, especially CO_2 – and the oncoming shortage of fossil resources, it is necessary to reduce overall primary energy consumption and to advance a sustainable development towards more eco-friendly, renewable energy sources and energy efficient technologies. Emanating from a consistent progression in all sectors, the energy consumption in the Swiss light duty vehicle sector in particular has to be reduced from about 6.8 GW in 2005 towards a 2.7 GW landmark (Bericht des BFE, 2004). For the biggest effect possible of this envisioned reduction path, alternative fuel technologies need to be promoted, since they are still sparsely represented in today's carfleet. This spread of one or more new drive-train technologies throughout society represents an innovation diffusion process (Rogers, 1969), which is needed to achieve long-term climate and energy policy goals.

To answer the overarching research question of how to reach a successful introduction of new drive-train technologies resulting in an required fuel split in the car fleet, several steps have to be performed. The purpose of this paper is to develop and analyse a cadt-model (competing alternative drive-train technologies model) that illustrates the effect of a critical mass. This has big relevance for those who are interested in the potential or the spread of new drive-train technologies, as for instance fuel suppliers or governmental authorities at different levels. Learning about the critical quantities or significant leverage points in the system is fundamentally important to exert influence on the development of the system. System understanding gives insights that form the basis for the development of implementation strategies and a long-term policy.

The aim of this paper is to point out an adapted methodology of describing and explaining the diffusion rates of new drive-train technologies with a simulation model. To realise an adequate technology path leading to the adoption of the new technologies, the most important factors and processes favouring or retarding this path must be identified. The basic relations applied in our model show the important role of a critical market share, which determines success or failure of the diffusion process. Because of the competition between different alternatives the single developments will be the result of interdependent dynamic processes.

2 System analysis

First of all it is necessary to describe the system represented by the model. Building on our case study in Switzerland we are illustrating the case of a small industrialised country without any autonomous automotive industry. Several aspects can be adopted from Janssen (2004), whose work is to be continued and expanded by the current study. According to the system analysis of Janssen (2004) three main groups of stakeholders interact in the market of our system: The customer sector, the car import and retail sector and the fuelling station sector. Fig. 1 shows a sector model of the system with the three groups mentioned in the centre.

Stakeholders of these groups experience basic conditions like technology availability, performance, fuel price, car purchase price, taxes etc. Their options basically consist in adopting or not adopting new drive-train technologies, and their actions have an influence on the decisions of other stakeholders within their own as well as in other sectors. The distinction of all customers into private ones and fleet carriers has not yet been incorporated into the model, but seems to be important in an early market implementation phase (Nesbitt und Sperling, 1998).

A second point concerns the distinction between endogenous (‘customers‘, ‘fueling stations‘, ‘car import, retail and service‘) and exogenous stakeholders, defining the model boundaries of the system dynamic (SD) model. In contrast to the first group mapped with an SD model, the latter have to be treated with a different approach. In order to simulate realistic behaviour it would be preferable to have a framework making different scenarios reasonable and putting the model parameter values in a major context. They should be deduced from strategies of policy-making stakeholders, acting rather like players than as a homogeneous mass. The initial position with different individuals or parties pursuing different interests forms a conflict situation, characterised by interaction of all parties involved in terms of rational statements about the participants, their possible options,

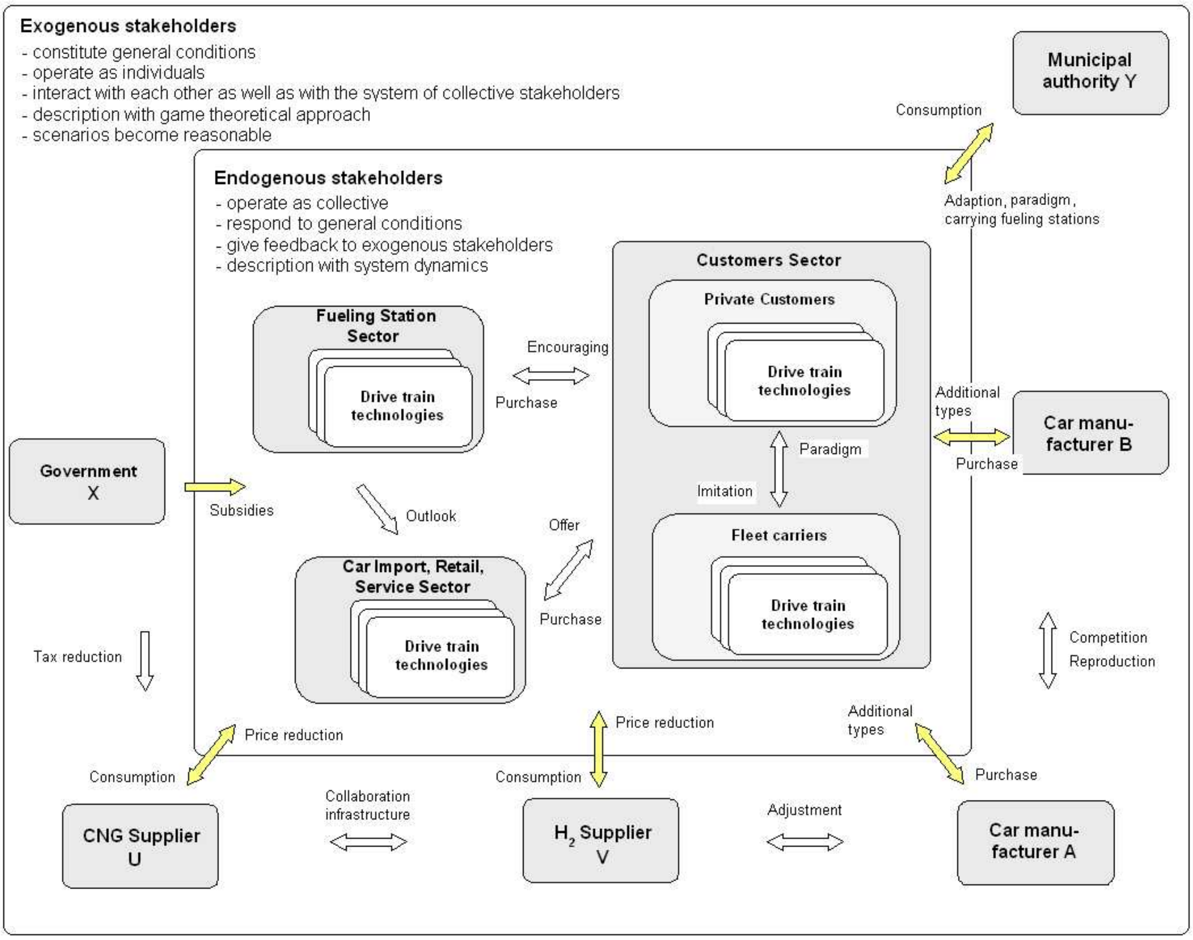

Figure 1: Box diagram, showing the model boundaries and the different subsystems.

their strategies and mutual information exchange. The analysis of such situations is the quintessence of game theory (cf. Manteuffel und Stumpe, 1977; Krabs, 2005). The model structure is therefore extended by an outer framework for policy making stakeholders. The coupling would lead to a combined model comprising a system dynamical as well as an explaining game theoretical part. However, this step still needs further research.
So far there are three different sorts of policy making stakeholders in the system: Fuel suppliers, car manufacturers and municipal and governmental authorities. It is them who determine the the basic conditions of the market. The options they can use to influence the market are described as follows:

Subsidies on alternative vehicles are a one-time financial support given directly to the customer and reducing the purchase price of such vehicles. This instrument makes the investments smaller and therefore increases the attractiveness of new technologies. Subsidies can be **granted by the government or the fuel industry**, for example in the context of a bonus malus system as discussed in Switzerland.

Fueling station subsidies work in an analogue way as the subsidies on alternative vehicles, but relating to the installation or construction of filling facilities for corresponding fuels. Like for vehicles we are dealing with a one-time subsidy, lowering the fueling station managers invested capital and therefore raising profitability. This sort of financial support can be **granted by the government, the fuel industry**

or together with car manufacturers[1].

Fuel tax advantages can be given to fueling station managers, who can shift a certain amount to the customers by a reduction of the end user fuel prices. The tax reductions are to be seen in comparison to non-leaded petrol[2]. Tax advantages are **granted by the government**.

Information spread has an influence on the fraction of possible adopters that effectively adopt a new technology. The estimation of the effect of information is very difficult and needs a measure for its effectiveness, which depends on the total amount invested in information spread. This measure is **taken by the government, car manufacturers and the fuel industry**.

Technology improvement as a result of research and development is supported by the state. Its time dependent behaviour is difficult to estimate over the models time horizon of up to 100 years. Technology improvement is **based on investments made by the government, car manufacturers or the fuel industry**.

Fuel marketing measures comprise cost-free or price-reduced fuel. The offer can hold for the initial purchase of a promoted car, and can be extended, if the customer agrees on using his car as an advertising medium. An example is the natural gas campaign “Aktion Naturgas“ (Erdgas Zürich, 2006) of the regional gas supplier *Erdgas Zürich* in Switzerland. This sort of support is **granted by the fuel industry**.

Car marketing measures comprise publicity, price reductions on cars or an increase in product diversity, improving customer-friendliness. This sort of support is **granted by car manufacturers**.

Today‘s almost exclusively used fuels in the Swiss passenger car sector are petrol and diesel for internal combustion engines (ICEs). Following the manufacturers of the ten best sold car makes in Switzerland, bifuelled natural gas vehicles (NGVs) driven by an ICE operating with petrol/diesel and natural gas, and ICE/electric hybrids (HEVs – hybrid electric vehicles) are the most promising alternatives. The hydrogen fuel cell vehicle (FCV) is commonly seen as an optimal long term option. An important issue is the competition between all four alternatives and its consequences on fueling infrastructure built up. Some developments may hinder or delay the emergence of hydrogen technology, while others could support it due to technical and social spill-overs.

The Swiss federal statistical office calculated the average age of passenger cars to be 7.4 years in 2004 (Bundesamt für Statistik, 2004), with increasing tendency. Some future technologies such as hydrogen powered fuel cell vehicles will enter the mass market only in some 20 years. Therefore the time horizon to perceive relevant changes in the passenger car fleet should at least be 40 to 50 years. If we want to analyse behaviours with delayed technology diffusion we have to extend the time horizon up to 100 years. It is clear that the reliability of the model forecasts will decrease towards the time horizon.

Although we are primarily interested in the development of the light duty vehicle fleet referring to Switzerland, our basic characterisation of the system should also apply to most industrial countries. The Central questions to be answered are:

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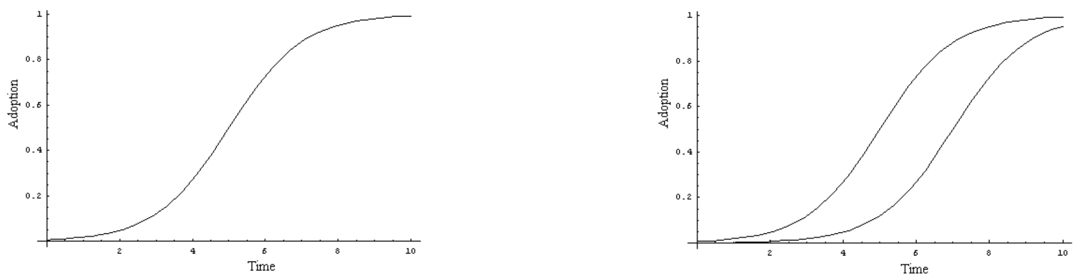
[1] See for instance Clean Energy Partnership (CEP) (2006).

[2] Diesel has therefore a negative tax advantage in Switzerland (Eidgenössische Zollverwaltung (EZV), 2006).

- Which processes can influence the share of alternative technologies, and under which conditions?
- When does a critical mass occur and what is its effect?
- What influence does the competition between different alternatives have?

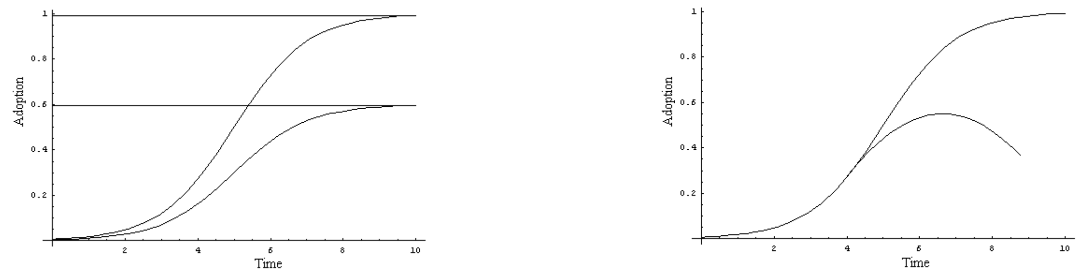
3 Diffusion of drive-train technologies

A simplified, idealised innovation diffusion (Rogers, 1969) in general follows – at least until a certain point in time – a sigmoid form, as it is shown in figure 2.a. The graph shows the number of units for a certain technology plotted against time (x-axis). We will refer to a successful development, if the curve follows a sigmoid form that reaches a desired level within an acceptable time span depending on the goals being set for the development of the system. Possible failures in this sense would be "extended diffusion time" (diffusion takes more time than acceptable, fig. 2.b), "limited growth" (diffusion does not reach an acceptable level, fig. 2.c) or "unstable development and decline" (strong fluctuations with subsequent disappearance, fig. 2.d).



a) Successful development

b) Extended diffusion time



c) Undersized growth

d) Instable development-path

Figure 2: Comparison of four different fundamental behaviours of the sigmoidal diffusion curve. These curves should be considered as qualitative. In theses graphs adoption is normalised to 1, and the time axis has arbitrary units.

Curves with a completely different outcome show a similar behaviour at the beginning. Success or failure can possibly not be distinguished in the starting phase of the diffusion process, and the difference in early observable numbers may lie below precision of measurements. Once collapsed, a diffusion process can hardly be re-initiated. This shows why a better understanding of the early implementation phase is needed to anticipate unwanted development in an early stage.

Following the definition of Rogers (1969) the introduction of alternative drive-trains and their corresponding fuelling infrastructure in a car fleet is a process of technology diffusion. The way for the diffusion of the innovation‘s hardware is paved by communication. For a successful introduction of alternative technologies in the Swiss car fleet corresponding with a 2000-Watt-vision, stimulation and support of an optimal technology development path is of fundamental importance. The timing and the sequence in which different technologies appear can be very crucial for a further development. Technical spill overs for example can foster the diffusion by saving expenses, or customised features of certain systems can eliminate handicaps and lead to the emergence and the approvement of new technologies. However, lock-in effects for certain technologies (cf. e.g. Arthur, 1989) have always the consequence of locking out competing technologies, what might especially not be preferable in the case of alternative drive trains and fuels.

Likewise Leydesdorff (2001) is speaking about a “point of no return“, meaning a stage in the diffusion process, where established standards lead to an exclusion of alternatives. According to Leydesdorff a break-out of a lock-in situation and a return to equilibrium remain possible, but changes in parameters in the order of magnitude are possibly needed. Considering the lock-in as a grown state, the result of a “selection over time by an emerging system“ as Leydesdorff says, we can look at today‘s passenger cars‘ drive-train technology as a lock-in of the internal combustion engine (ICE) and all its corresponding systems, such as fueling infrastructure for example. In this sense the challenge with introducing new drive-train systems is not the diffusion of a new technology, but replacing an existing one with the same purpose and of excellent performance, at least from a customer‘s point of view. This means that a break-out must happen first to reestablish the possibility of a shift in direction. Furthermore, where we are facing the problem of substitution as in our case, the “point of no return“ denotes the time when the decision in favour of one of the competing technologies is being taken. This is not directly related to the overall success of the chosen technology’s diffusion, which can also have sort of a “point of no return“. It is still able to fail, even if it has prevailed in the market against other alternatives, but not against the predominant system.

Similarly Rogers identifies a “point of no return“ in a diffusion process. It becomes manifest in the number of adopters of the concerning technology, the critical mass (Rogers, 1969, p. 343ff.), that is needed for the further rate of adoption to become self-sustaining. This means that we get a process where stimulating measures become redundant. Following Rogers (1969) the critical mass is a fundamental concept that expresses the social nature of the diffusion process. Assuming the critical mass exists, two questions – from our point of view not yet answered in literature – immediately arise: How large is the critical mass? And what are the conditions to reach it in the diffusion process?

As we will see below the critical mass is not always accessible by means of a model, although being a very important quantity regarding policy considerations. However, using a system dynamics model together with Rogers‘ characterisation of “reaching the critical mass“ as the “moment when the adoption rate experiences an acceleration“, the amount of the critical mass can be estimated. Gassmann und Ulli-Beer (2006) show a criterion to determine whether a critical mass exists for a given model, and they show that the widely used Bass model does not map this important concept. The critical mass coming of our cadt-model depends on the norm building process, actually on its nonlinearity.

4 Model description and setup

The purpose of the cadt-model is to explain the chronological sequence of the diffusion rates of alternative drive-train technologies. Its main function is therefore to link the single technology layers and describe the transfer between them. The effect of certain policy measures and strategies is to be analysed in different scenarios, which are not described in this paper.

4.1 Modelling approach

The dynamics underlying the system and the treatment of several quantities like e.g. customers, number of fueling stations or vehicles as aggregated clusters, indicate a differential equation based modelling approach. System dynamics (cf. Sterman, 2000) provides a method and a language to build and communicate such differential equation models. Graphical interfaces assist in dealing with causal structures, while the normally complex system of coupled equations is being solved with numeric integration by means of Euler or Runge-Kutta methods.

In system dynamics, variables representing quantities of our system are subdivided into three groups (Sterman, 2000): endogenous, exogenous and excluded, i.e. dynamically tied up variables, given variables from outside the model and variables not being considered. In the following we will further talk about stocks of different technologies, meaning cumulative quantities in the system belonging to a certain drive-train technology, and flows, which are the rates defining the transfers between the stocks. The flows are determined by a number of factors discussed below. Other variables than stocks and flows exist and influence the rates, possibly being time dependent. The entirety of variables associated with the same drive-train technology are designated as a technology platform. The idea of different technology platforms was developed and implemented into a model by Struben (2004a), and is used in our case in a similar, slightly modified manner. Together with the stakeholders interacting in the market – referred to as the endogenous stakeholders – we get the following subsystem shown in figure 3.

4.2 Model structure

The basic model structure is generic and could be applied to other single or regions of multiple countries (e.g. Europe) and different drive-train technologies after few modifications. While Janssen (2004) developed a model with only one alternative drive-train technology and worked out the relationships between car stocks, import and infrastructure within a technology platform, our model is primarily aiming at the interactions between different platforms.

The following table on page 7 gives an overview of the variables so far considered in the model, where market forecasting, filling facility cost, fleet aging and mileage have been omitted for the time being:

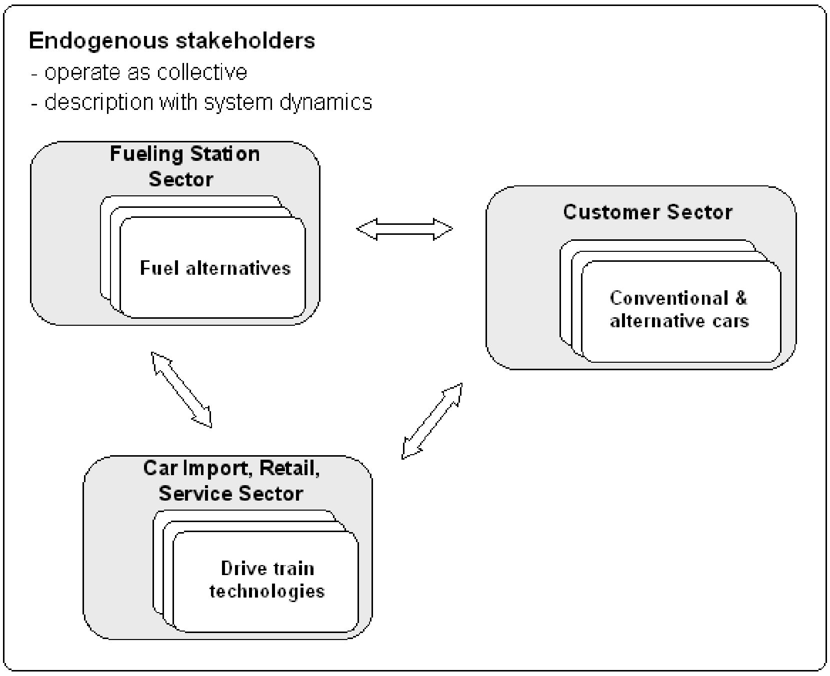


Figure 3: Box diagram showing the model structure: The simultanous handling of more than one alternative fuel technology with the resulting competition can be realised by the introduction of different coupled platforms, similarly structured within the same sector.

Classification	**Variable**	**Description**
Endogenous	Car stocks	Numbers of petrol or diesel cars etc.
	Social norm	The strength of the social norm (acceptance of a drive-train technology)
	Comparative attractiveness	Based on financial incentives for adopting a certain drive-train technology
	Perceived attractiveness	Product of social norm and comparative attractiveness
	Customer satisfaction	Degree to which customers are satisfied with a technology ($\in [0, 1]$)
	Adopter potential	Product of customer satisfaction and perceived attractiveness
Exogenous	Median lifetime	The time a car is registered
	Fleet growth	Annual fleet growth rate
	Availability	Degree to which a technology is available for customers ($\in [0, 1]$)
	Fueling stations	Numbers of fueling stations providing dedicated fuels
	Type spectrum	Diversity of car types offered
	Fuel price	Fuel price per litre petrol equivalent
	Purchase price	Purchase price of a typical car for each technology
	Inherent attractiveness	Basic attractiveness during start-up phase

In our present model stocks are defined as number of cars. Technology substitution occurs when a car is scrapped and replaced by a new one of the same or another drive-train type, while the total size of the fleet remains constant. All stocks are linked to each other by flows in a symmetrical way. This allows a customer to replace his car after scrapping by one of any of the four chosen drive-train technologies. There we assume that a car is scrapped and replaced after an average lifetime of 12 years. The time horizon is set to 100 years (see above).

The options for the policy making stakeholders – like e.g. subsidies and tax reductions – are not explicitly included in the model yet. They are implicitly manifest in the variables "comparative attractiveness", "customer satisfaction" and "availability". These are influencing the purchase decision of the customers and determine the flow rates between the stocks and therefore the technology substitution. The variable "comparative attractiveness" consists of a constant basic and a time dependent part. The first one corresponds to an attractiveness a technology always has, for example on innovative persons. The second one is accessible by means of the policy measures discussed in section 2.

The dynamic hypothesis of the model is illustrated in figure 4. The causal loop diagram shows the whole decision-taking structure, which counts for all technology platforms, but with different stock values and input parameters.

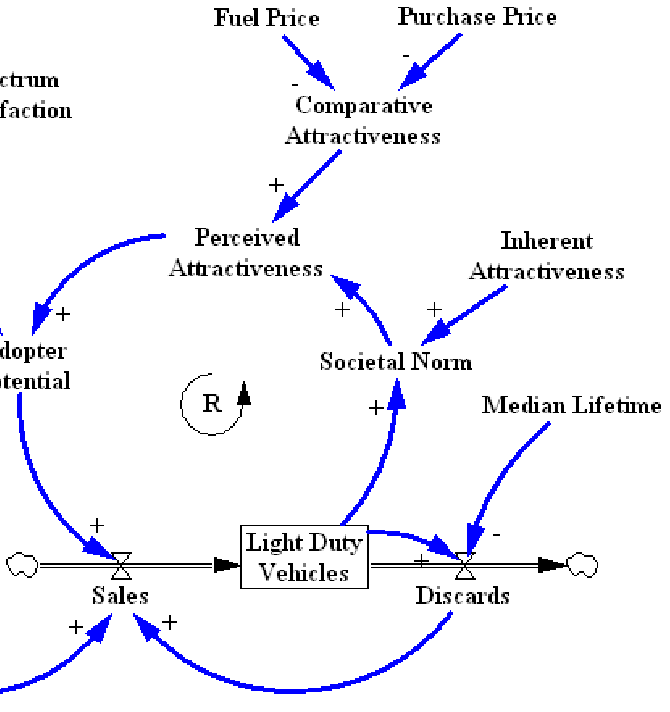


Figure 4: Causal loop diagram of the current model, showing the decision-taking process.

In this work the new sales are set to zero in order to point out the effect of the decision process more clearly, and particularly the effect of the social norm. The interpretation of the normalised adopter potential as the probability of purchase allows the multiplication of all flow rates with this number, considered as the percentage of adopters.

An alternative way to look at the model is exemplified in figure 5, taking three different drive-train technologies into account. This illustration shows the competition much more clearly, and the way the different drive-train platforms interact with each other. There is theoretically no limitation on the number of technologies considered, although there is certainly a limitation by the market itself.

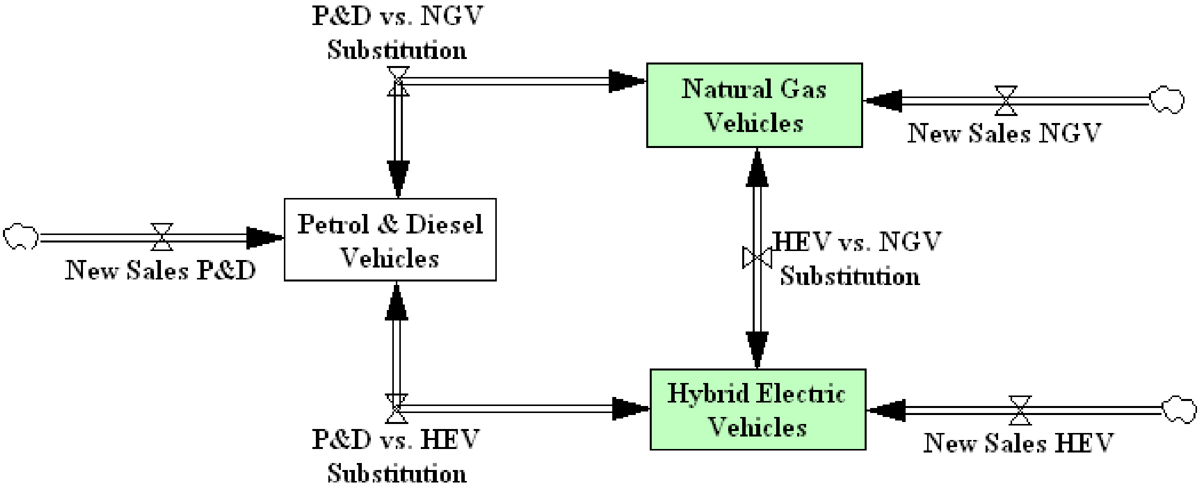


Figure 5: Stock and flow diagram, showing the basic model structure for three different car stocks. The structure can be extended to more than three technology layers.

Figure 6 shows the general formation of the substitution rates. The rates back to the stock of conventional ICEs are treated later.

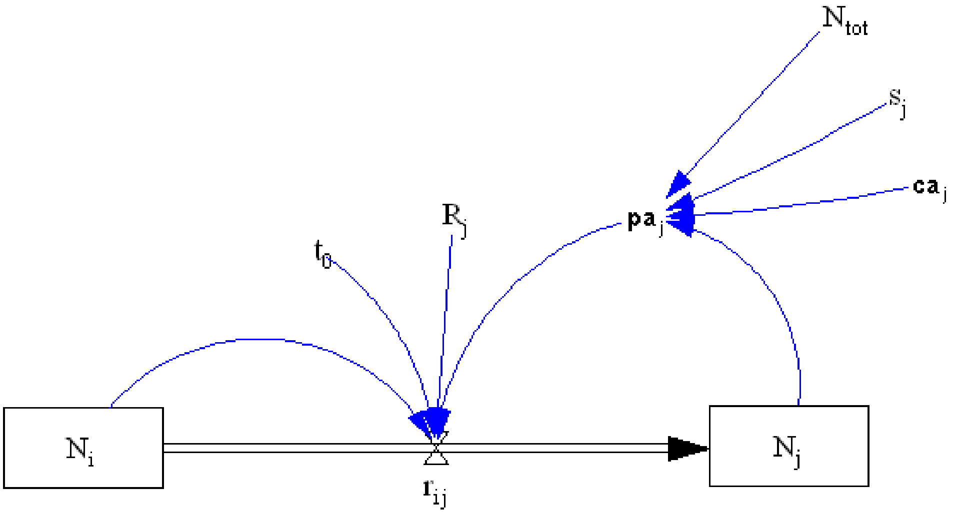


Figure 6: General structure of a flow rate. All rates in the model, excepted the flows back to conventional ICE vehicles, are built with this structure.

The calculation performed for the flowrate of stock N_i to stock N_j reads as follows:

$$r_{ij}(t) = \frac{N_i(t)}{t_0} \cdot pa_j(t) \cdot A_j \tag{1}$$

with

$$pa_j(t) = C_j \left(\frac{N_j(t)}{N_{tot}} \right)^2 \cdot s_j(t) + ca_j(t) \tag{2}$$

where C_j is a constant factor and weight of the normbuilding process, and

$r_{ij}(t)$: substitution rate
$N_i(t)$: car stock i
t_0 : median lifetime
$pa_j(t)$: perceived attractiveness
$s_j(t)$: customer satisfaction
N_{tot} : number of vehicles on road
$N_j(t)$: car stock j
t : time
$ca_j(t)$: comparative attractiveness
A_j : availability

Let us first consider equation (1). The fraction $\frac{N_i(t)}{t_0}$ on the right hand is the average number of cars with technology i that are replaced per time unit, because they reach the end of their lifetime, t_0. This fraction is multiplied with a technology-specific “perceived attractiveness“ pa_j (c.f. equation (2)) which is explained below. This attractiveness of technology j is interpreted as the percentage of cars that are substituted by this technology. Since the sum of all cars that are replaced in N_i is limited to $\frac{N_i(t)}{t_0}$, the sum over j with $j \neq i$ of all perceived attractivenesses pa_j must have a maximum of 1. The final factor A_j is a potentially limiting factor with the range of 0 to 1. It represents the fact that a substitution will not take place instantly, because there may be a delay for several reasons, like delivery problems or a lack of infrastructure for instance. It is standardised to today‘s ICE standard, being considered relatively to this technology and its infrastructure. It is not likely that alternative technologies would have better retail and service attributes etc. than ICEs.

In equation (2) it can be seen that the perceived attractiveness is determined by two additive terms: The first term in brackets is a product of the “customer satisfaction“ s_j with the square of the fraction of cars belonging to technology j. s_j is a perceived satisfaction in relation to today‘s standard technology’s supply of needs – of ICEs in our case – which is assumed to be the maximum. The norm factor $(\frac{N_j(t)}{N_{tot}})^2$ describes the measure of perception (cf. Rogers, 1969, p. 352f.) of technology j. The second power has been chosen to fulfil three simple conditions to the effect of the social norm: The norm must disappear if N_j is zero, and it should grow slowly with N_j in the beginning but faster with increasing N_j (cf. Gassmann und Ulli-Beer, 2006). C_j is a weighting factor for the norm, describing the societal desirability of technology j. It is standardised in the same way as A_j. The second summand $ca_j(t)$ represents a given basic attractiveness of technology j, but has also a time dependent part which is added. This value is associated with the potential to launch the technology substitution process. In the current model it has to be ensured during runtime that the sum of the attractivenesses mentioned above does not exceed 1, which still has to be improved, for instance by introducing a normalisation.

Flow rates from any car stock back to ICEs are formulated slightly different. All the flows back to conventional ICEs could shrink independently on their comparative attractiveness or norm over time due to the assumption, that petrol and diesel will decline with the future lack of crude oil resources. Furthermore A_{ICE} as well as C_{ICE} equals 1 because of the standardisation and can therefore be omitted. Figure 7 shows the formation of such a rate.

The appropriate calculation for the flow rate N_i to stock N_{ICE} reads as follows:

$$r_{i,ICE}(t) = \frac{N_i(t)}{t_0} \cdot pa_{ICE}(t) \tag{3}$$

with

$$pa_{ICE}(t) = \Big(\Big(\frac{N_{ICE}(t)}{N_{tot}}\Big)^2 \cdot s_{ICE}(t) + ca_{ICE}(t)\Big) \cdot S_{ICE}(t) \tag{4}$$

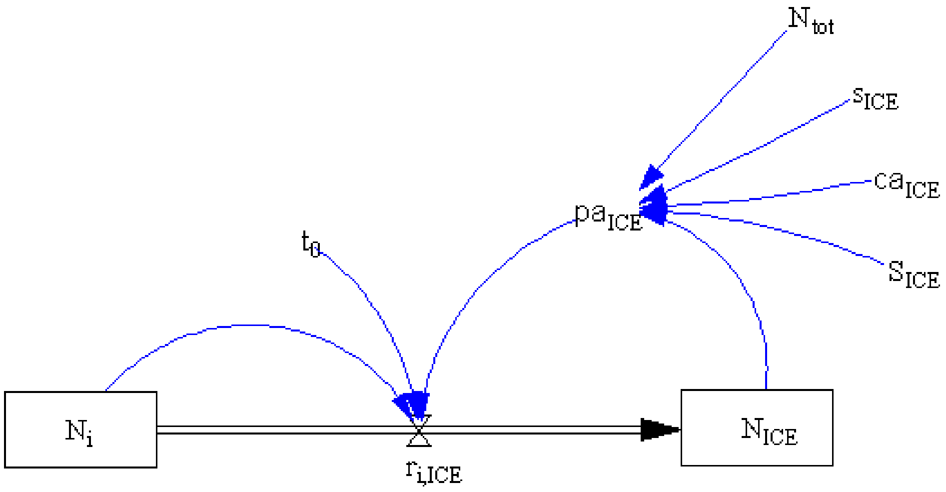


Figure 7: Structure for a flow rate back to conventional ICE vehicles. The availability factor A_j is set to 1, according to its definition (see below). However, there is an additional factor S_{ICE} appearing in the definition of the perceived attractiveness, describing the decreasing availability of crude oil.

where

$$S_{ICE}(t) \quad : \quad \text{shortage of resources}$$

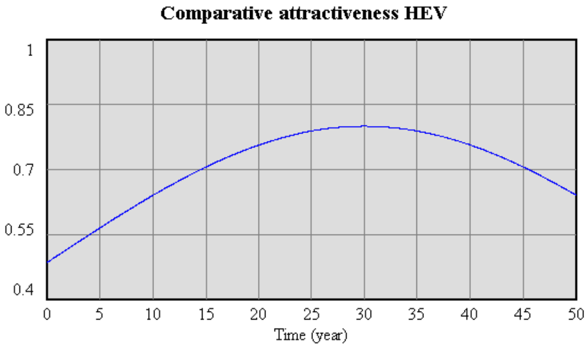
The other variables and parameters are equally defined as in equations (1) and (2).
The additional factor $S_{ICE}(t)$ in equation (4) represents the mentioned possible disappearence of fossil fuelled drive-train technologies due to decreasing resources. This would cause a general loss of attractiveness, although the corresponding drive-trains could still be technologically attractive.
It is important to remark that the exogenous variables ca_j,A_j,s_j and S_{ICE} can be time dependent. This has a great influence on the model behaviour. To keep it simple these variables are chosen to be functions like gaussian or sigmoid curves. Of course these simple functions are incapable of reproducing complicated and detailed look-up curves as model input, but on the model's level of aggregation they are adequate to investigate the most important and characteristic behaviours. The great advantage is the controlling of the functions‘ behaviour by only few parameters. The following example illustrates the simplicity of this approach:
The time dependent part of the comparative attractiveness of hybrid vehicles ca_{HEV} might grow in the near future, because they become more economic and ecologic than conventional ICEs. However, since they still need liquid or gaseous fuels for their combustion engine in addition to the electric power train, their consumer satisfaction might peak after a certain time and eventually decrease again due to certain taxes or perhaps a complicated handling compared to future standards. This behaviour can qualitatively be reproduced by the following gaussian function:

$$ca_{HEV}(t) = c_{max} \cdot e^{-\frac{(t-\mu)^2}{2\sigma^2}} \qquad (5)$$

where

c_{max} : determines the maximum value achieved
μ : denotes the point in time where c_{max} is taken (mean value)
σ : is the standard deviation

The shape of the curve can easily be determined by adjusting these three parameters. Figure 8 shows a numerical sample.



with parameter setting:

c_{max} : 0.8
μ : 30 a
σ : 30 a

Figure 8: Numeric example of a gaussian function (5) used for the qualitative behaviour of the time dependent part of ca_{HEV}.

5 First results

In this section we will discuss some preliminary, qualitative comparative scenario results, achieved with the rather simple model structure described in the last section. As an example we will focus on two interrelated model runs. We choose initial values for the stocks comparable to the present situation in Switzerland: Some 3.8 million conventional ICEs, about 2000 NGVs and 200 HEVs respectively. To keep it clear, only the three technologies chosen above were kept and taken into account for these exemplary model runs. Both runs have been performed with a time horizon of 100 years. Our interest lies on the resulting characteristics of the development of the NGV and HEV stocks, which is shown in the following graphs. The curves for the ICE stock have been omitted, but can be reconstructed from the difference to the total amount of cars in the model. All parameters have been set to constant values: Customer satisfaction is highest for HEVs, and the comparative attractivenesses are at 2% for HEVs and NGVs, and 5% for ICEs. Only the comparative attractiveness of HEVs ca_{HEV} shows a slightly varying characteristic: It grows to a maximum of 0.03, decreases over a period of about 20 years, and eventually levels off on 0.02. The coupling constants are chosen to increase the visibility of the effects by the critical mass, hence the model is not yet calibrated. Finally, the availabilities, customer satisfactions as well as the ICE‘s shortage of resources are all set to 1 for simplicity.

Figure 9 shows a behaviour where both, HEVs and NGVs end up at the same level, which is a stable state of the model. Although HEVs have a quite strong rise at first, they eventually decline again after not having reached their critical mass. Their market share was too small to establish a norm. This means that most cars discarded are replaced by conventional ICEs in this scenario, and both alternatives just go into a niche market. We now change the situation for HEVs. Their comparative attractiveness will now peak to a higher value of 0.195 and decrease again to 0.02, but in a slower manner. The

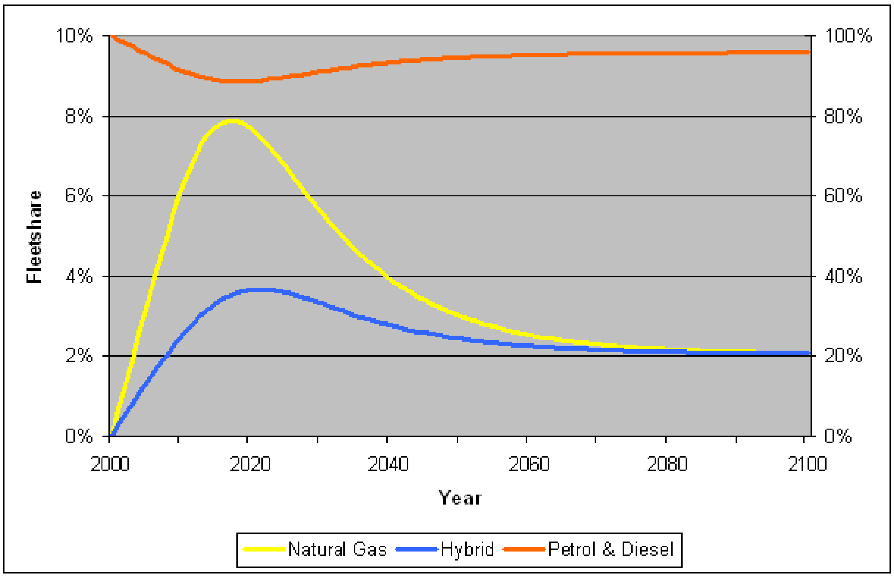


Figure 9: Development of the three stocks of ICEs, NGVs and HEVs reaching an equilibrium.

consequence is that HEVs reach a critical number of cars, before their attractiveness shrinks again. The norm building effect is already strong enough and leads to a self-sustaining growth behaviour as shown in figure 10. We see that the HEVs move beyond the tipping point. The NGVs end up with a small number comparable to that in figure 9.

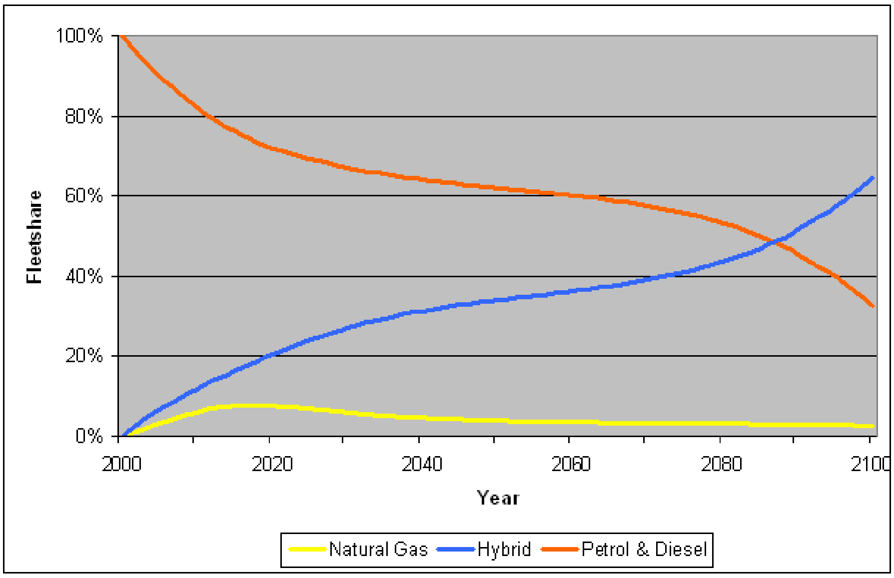


Figure 10: Same situation as with figure 9, but now with a higher peak and a slower decline of ca_{HEV}.

The final states achieved in both cases become apparent as the only possible solutions for the development with the parameters given, which can be predicted. Reaching the critical mass implies a self-sustaining process, that cannot be stopped offhand in this model. The reason for the existence of a critical mass in this model is the nonlinearity of the normbuilding term in equation (2).

6 Discussion

Equation (2) shows, that for small stocks, as it is the case in our example for HEVs as well as NGVs for small t, the perceived attractiveness is almost fully determined by the comparative attractiveness. The term $\frac{N_{HEV}(t)}{N_{tot}}$ in pa_{HEV} is too small during the whole run to have a substantial influence. Therefore, the stock of HEVs in our first case increases with ca_{HEV}, the comparative attractiveness, and eventually reaches equilibrium. In the second situation, the peak in ca_{HEV} is high and broad enough to let the stock grow to a certain extent which enables $\frac{N_{HEV}(t)}{N_{tot}}$ to contribute essentially. Beyond that it compensates the subsequent decrease of ca_{NGV} and leads to a strong rise of the stock. The normative effect becomes strong enough after reaching a critical mass and make the diffusion of HEVs become self-sustaining.

Even if now the influence of the critical mass on the development becomes tangible in this model, corresponding to the description of Rogers (1969, pp. 343ff.), it would be difficult or almost impossible to determine its size by trial and error. In the following paragraphs an analytical method is used to access the critical mass of the model. It will further allow to determine the stable equilibriua and finally help us to answer the questions at the end of section 2 (page 5).

The diffusion process in our model can reach stable states of equilibrium which can be calculated and predicted. This is shown using the method developed by Gassmann und Ulli-Beer (2006). They use the dynamics of a light ball moving downhill and compare it to a system dynamics model. A model with two stocks and a constant sum of their elements can be reduced to one rate-equation $\frac{dx}{dt}$ with only one variable x representing one stock. This equation can be written in the same form as the dynamics of the mechanical analogon, with x corresponding to the ball‘s position on a coordinate axis. Then a potential V can in some cases be found, determining the system‘s behaviour by means of the equation $\frac{dx}{dt} = -\frac{dV}{dx}$ of the approximated mechanical dynamics. The potential gives information about the states of equilibrium, the critical mass etc. Each minimum in the potential is a stable state, while in one dimension (two stocks) the maxima point out the critical masses. This method of analysis is very useful to answer two of the main questions of this work. It allows to calculate the critical masses, and further the potential shows the maximum forces needed to push the system in a desired direction.

In our situation with 4 stocks, we have 3 coordinate axes, and also 3 independent rate-equations. As in the results shown we omit the FCV stock, which plays only an ancillary role in many scenarios, and normalise the stocks with the total number of vehicles: $\frac{N_j}{N_{tot}}$. We identify x with ICEs, y with NGVs and z with HEVs, and note that $z = 1 - x - y$. This leads to two independent rate-equations:

$$\frac{dx}{dt} = -r_{x,y} + r_{y,x} - r_{x,z} + r_{z,x} \tag{6}$$

$$\frac{dy}{dt} = r_{x,y} - r_{y,x} + r_{z,y} - r_{y,z} \tag{7}$$

By applying equations (1) to (4) (with again the availabilities as well as the ICE‘s shortage of resources all set to 1), we get

$$\frac{dx}{dt} = \frac{1}{t_0}\Big(- (s_x + s_z)x^3 - 2s_z x^2 y - (s_y + s_z)xy^2 + (s_x + 2s_z)x^2 + \\ 2s_z xy - (s_z + ca_x + ca_y + ca_z)x + ca_x\Big)$$

$$\frac{dy}{dt} = \frac{1}{t_0}\Big(- (s_y + s_z)y^3 - 2s_z xy^2 - (s_x + s_z)yx^2 + (s_y + 2s_z)y^2 + \\ 2s_z xy - (s_z + ca_x + ca_y + ca_z)y + ca_y\Big)$$

Because of some terms proportional to mixed powers of x and y it is impossible to define a potential $V(x, y)$ satisfying

$$\frac{dx}{dt} = -\frac{dV}{dx} \quad \text{and} \quad \frac{dy}{dt} = -\frac{dV}{dy} \quad \forall\,(x, y) \in \mathbb{R}^2$$

However, an approximated potential V(x,y) would have leading terms of fourth degree in x and y, showing up to two stable states (minima). Though, it is not necessary to know the potential. The sought minima result from the roots of the vector field

$$\mathbf{F} = -\begin{pmatrix} \frac{dV}{dx} \\ \frac{dV}{dy} \end{pmatrix} = \begin{pmatrix} \frac{dx}{dt} \\ \frac{dy}{dt} \end{pmatrix}$$

given by equations 6 and 7. The shape of the vector field $\mathbf{F}$ in $A = \{(x, y) \in \mathbb{R}^2 | x \geq 0, y \geq 0, x + y \leq 1\}$ – the permitted region for x and y – depends on the parameter set. To have a critical mass in the model, at least a potential-wall or a maximum must lie within A. Stable states only exist in the model, when minima lie in A. In case the parameters are functions of time, this can change during the run, but with knowledge of these shapes we can calculate the resulting technology share at the end of the model run. This explains why the model is strongly determined by the time development of the parameter curves, and also why it is difficult to characterise its behaviour by trial and error. Figure 11 shows a vector plot of $\mathbf{F}$ for the allowed region A of x and y, with additionally all s_i set to 1. The state of the system in this graph is given by the two technology shares x and y as coordinates. Scales go from 0 to 1, according to the degree (or percentage) of adoption of the alternative technologies (HEV and NGV), where the conventional technology share (ICE) is given by the difference $1 - x - y$. All three shares added cannot exceed 1. The direction and the strength of the system's development at its particular position is shown by the direction and the length of the vectors. The longer the vector, the stronger the "force" driving the system. The occurring maximum is green, minima red and saddle points are blue encircled. The have been calculated numerically. The system development will always end in one of the attracting minima, which denote stable states.

Figure 11 points out, that the critical mass corresponds to certain shares x and y, where a fundamental change of the vector's direction occurs when moving slightly. This is the case along the connecting lines from the maximum to each of the three saddle points, which can be imagined like water sheds, that divide A into three areas. In each area the system will finally end in its related minimum.

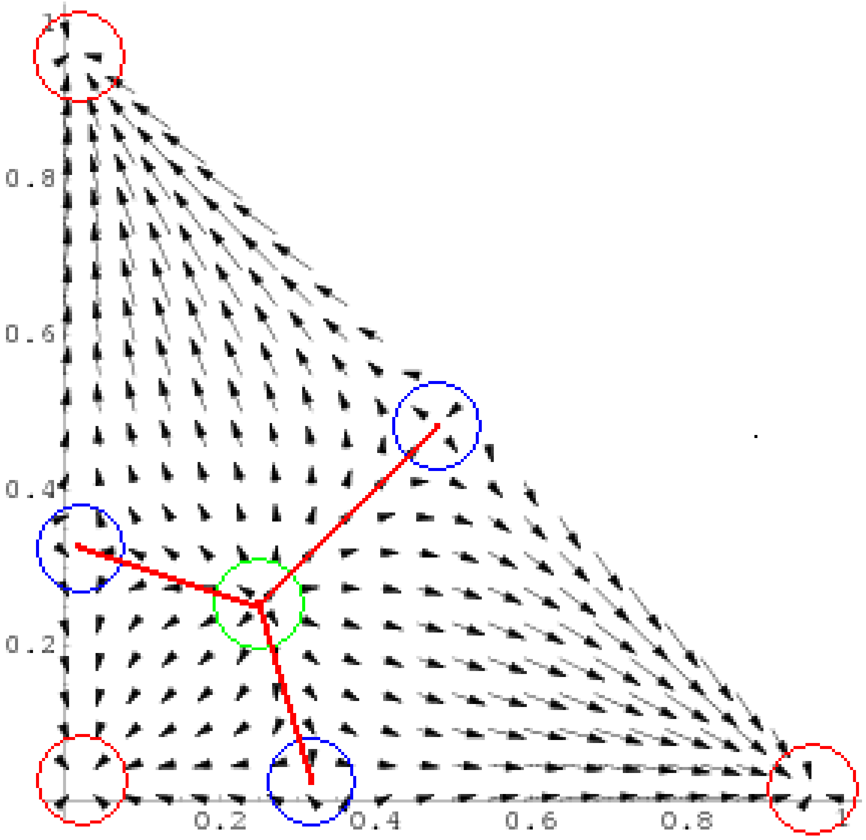


Figure 11: Mathematica-plot of the vector field **F**. The longer a vector appears in the picture, the stronger the "force" at this point. The encircled areas contain critical points: maxima (green), minima(red) and saddle points (blue), which do not coincide with the coordinates.

This brings us back to the questions on page 5. We conclude that the critical mass acts like a water shed, which would not exist, if the norm building fraction $\frac{N_j}{N_{tot}}$ was considered as linear in equation (1), as shown by Gassmann und Ulli-Beer (2006). Further we can see that the critical mass depends on the state of the system, by no means it is constant for one type of technology. As we can see in the picture of the vector field, a certain amount of NGVs diminishes the critical mass of HEVs, but after a certain point it will be increased tremendously. This is an effect of the competition between two alternative technologies.

The processes involved – the norm building effect and the perception of the comparative attractiveness – shape the vector field, and a stand-alone system would follow this shape. Reaching a critical share ("crossing the water shed") could be achieved by forcing the system into one direction by an external force. In our case the time dependent part of the comparative attractiveness can play this role, as we used it to succeed with the HEVs (cf. figure 10). However, this break out of a sort of lock-in situation does not guarantee that the minimum aimed at will lie at 100% adoption of a certain technology, but without exceeding the critical mass it will only reach a niche market.

With this model we can finally conclude, that all this gives no evidence about the time needed for the system to get to a stable equilibrium. It is strongly dependent on the path that is chosen and the measures leading to an increase of the comparative attractiveness of certain technologies and a deformation of the vector field. Finally, the norm building processes is only one among others and contributes to a superposition determining the final model behaviour.

A remark is to be added on the average age of a car. In the style of the word "demography" we could summarise the analysis of development and changes of a car fleet with "stolography" (from Greek $\sigma\tau\acute{o}\lambda o\varsigma$ - fleet), especially when we are talking of quantity and ageing structure. A very important statement of stolography is the average lifetime of a car, which is used in our model to determine the rate of discard. The application of the median lifetime instead of the average is required in situations, where data on vehicle age is given in categories with varying intervals. The median has the two advantages of being more robust against outliers and of being applicable to data in an ordinal scale. Regardless on which value is used, an improvement can be achieved by using a time dependent lifetime, reflecting the expected trend (Janssen, 2004).

Still an open question at the moment is the potential of replacements for liquid fossil fuels, like for example biodiesel as a replacement for diesel, but this could be incorporated into the model in a similar way as the reduction of fossil resources availability. Therefore, and since the environmental impact of such substitutions is not yet accessed, no additional stock for liquid bio-fuels in internal combustion engines is needed at this time.

7 Outlook

The model can be used to simulate the emerging technology diffusion in different scenarios with competition of several alternatives. However, it has not yet been calibrated or empirically approved. This, and also the refinement of the model will be done within an oncoming study about the potential of different alternative drive-train technologies in Europe and their effect on greenhouse gas emissions, mainly CO_2. The study will use a combined model with a part developed by Anup Bandivadekar at MIT (Bandivadekar und et al., 2007). With the new model, impacts on CO_2-emissions for example will base on simulated diffusion rates and not on estimated developments. The European results will be compared to a similar study by Anup Bandivadekar for the USA.

The estimation of the potential of different drive train technologies and the corresponding model specifications could be done with indicators (cf. table 1).

For the time being we defined 12 such indicators being assigned to three categories: attractiveness, potential and system development. Particularly the final two have also diagnostic character. Table 2 finally shows their impact on the model.

Table 1: Indicators by categories. Particularly potential and system development indicators have also diagnostic character.

Category		**Indicator**	**Comment**
Attractiveness	I	ΔPurchase price	Price difference to reference technology, e.g. "Petrol-ICE"
	II	ΔVariable costs	Operational and fuel costs
	III	Stimulating measures	Fiscal impact of fuels, subsidies, CO_2-charge, etc.
Potential	IV	#Private early adopters	Determines early diffusion rates
	V	#LDV	Vehicles with a weight of ≤ 3.5 t, broken down by fuel
	VI	Makes	10 best-selling car makes
	VII	Income	Per capita national income
	VIII	Resources	Access to fuel resources (e.g. fossil resources)
	IX	R&D	Investments in research and development
	X	Coverage	Share of inhabitants with natural gas connection
System development	XI	Fuel share	Share of energy
	XII	CO_2	Tons of CO_2 emitted, broken down by fuel

Table 2: Indicators and their integration into the model.

Indicators	**Influence on...**
I, II, IV, VI	Comparative attractiveness
III	Indicators I&II
V	Initial stock values
VII	Importance of prices
VIII, IX, X	Stimulating measures, scenarios
V, XI, XII	system evaluation

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