The effect of multi-incentive policies on the competition of drivetrain technologies

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Facing global climate change and the oncoming shortage of fossil resources, it is necessary to reduce overall primary energy consumption. There is a strong need for action concerning car traffic as a main originator of greenhouse gas emissions by use of fossil energy. For a strong mitigation effect, the technological improvement of today‘s petrol and diesel engines has to be accompanied by the promotion of alternative vehicles, still being sparsely represented in most carfleets. The spread of one or more new drivetrain technologies throughout the transportation sector represents an innovation diffusion process, which is needed in order to achieve long-term climate and energy policy goals. However, there exist no adequate innovation diffusion models that accurately explain the main driving forces between competing alternative drivetrain technologies and their diffusion rate. This work contributes to the understanding of the fundamental diffusion processes by developing, analysing and applying a model for the market penetration of competing alternative drivetrain technologies. Results are presented for competing petrol and diesel internal combustion engines and electric hybrids as well as natural gas vehicles in the French passenger car market.

Keywords: technology diffusion, critical market share, alternative drivetrain, system dynamics, competition, social norm, incentive, policy

1 Introduction

Today‘s worldwide per-capita energy consumption corresponds to an average power of 2100 W, where the country specific values are very different. In Switzerland for instance, more than twice as much is spent, about 5000 Watt per capita (novatlantis – Nachhaltigkeit im ETH Bereich, 2005). The vision of “novatlantis – Sustainability in the ETH-Domain“ 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. Together with a contribution to the establishment of a balance between the industrial countries and the developing world, it is also a step towards the independence from fossil fuels and a sustainable energy supply. 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 the use of environmentally sound, renewable resources and energy efficient technologies. This applies to all sectors equally, but particularly to the transportation sector, being one of the main users of energy and an important source of CO_2-emissions. For a strong mitigation effect on the envisioned reduction path, existing technologies must be improved, and alternative fuel technologies need to be promoted, since they are still sparsely represented in today‘s carfleets. Tapping the full potential of existing drivetrain systems is certainly the first thing to do, but the introduction of alternative propulsion technologies is a required step for a sustainable development in terms of further reducing fuel use and emissions. Although the effect in the early phase of market penetration might still be smaller than that of mere technology improvement in the next one or two decades (Bandivadekar and Heywood, 2004), it becomes crucial for a higher long-term reduction potential.

The spread of one or more new drivetrain technologies throughout society represents an innovation diffusion process (Rogers, 2003), which is needed to achieve long-term climate and energy policy goals. The aim of this work is to point out an adapted methodology of describing and explaining the diffusion rates of new drivetrain technologies with a simulation model under different boundary conditions. This has big relevance for stakeholders who are interested in the potential of the spread of new drivetrain technologies, as for instance car manufacturers, fuel suppliers or governmental authorities at different levels. Learning about the critical quantities or significant leverage points in the market of alternative cars is fundamentally important for policy implementation. To implement an adequate technology path leading to the adoption of new technologies and avoiding lock-in situations, 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, determining the sustainable success or failure of the diffusion process. Because of the competition between different alternatives the system behaviour will be the result of interdependent dynamic processes. The central questions to be answered in this paper are:

- When do stable states and self-sustaining diffusion processes emerge in the system?
- What influence does the competition between different alternative vehicles have?
- Which are the effects and risks of policies promoting alternative vehicles, such as financial incentives or area access permits for example?

2 System description

We will first describe the system represented by the model, comprising different types of interacting stakeholders: customers, retailers and fuelling station owners, referred to as endogenous stakeholders, and car industry, fuel suppliers and governmental authorities, referred to as exogenous stakeholders. These two groups have to be distinguished from each other when defining the boundaries of the model. In order to simulate realistic behaviour, the exogenous stakeholders build a framework making different scenarios reasonable and putting the model parameter values in a major context. Their influence is considered by exogenous parameters of policy measures later described in this paper, such as subsidies, tax reductions or area access permits. The dynamics underlying the interaction between the endogenous stakeholders as well as the consideration of several quantities in terms of aggregated clusters (e.g. number of cars and fuelling stations), indicate a differential equation based modelling approach, such as System Dynamics (Sterman, 2000).

Several aspects can be adopted from earlier work by Janssen (2004), which is to be continued and expanded by the current study. According to his analysis the three main groups of endogenous 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 these three groups in the centre.

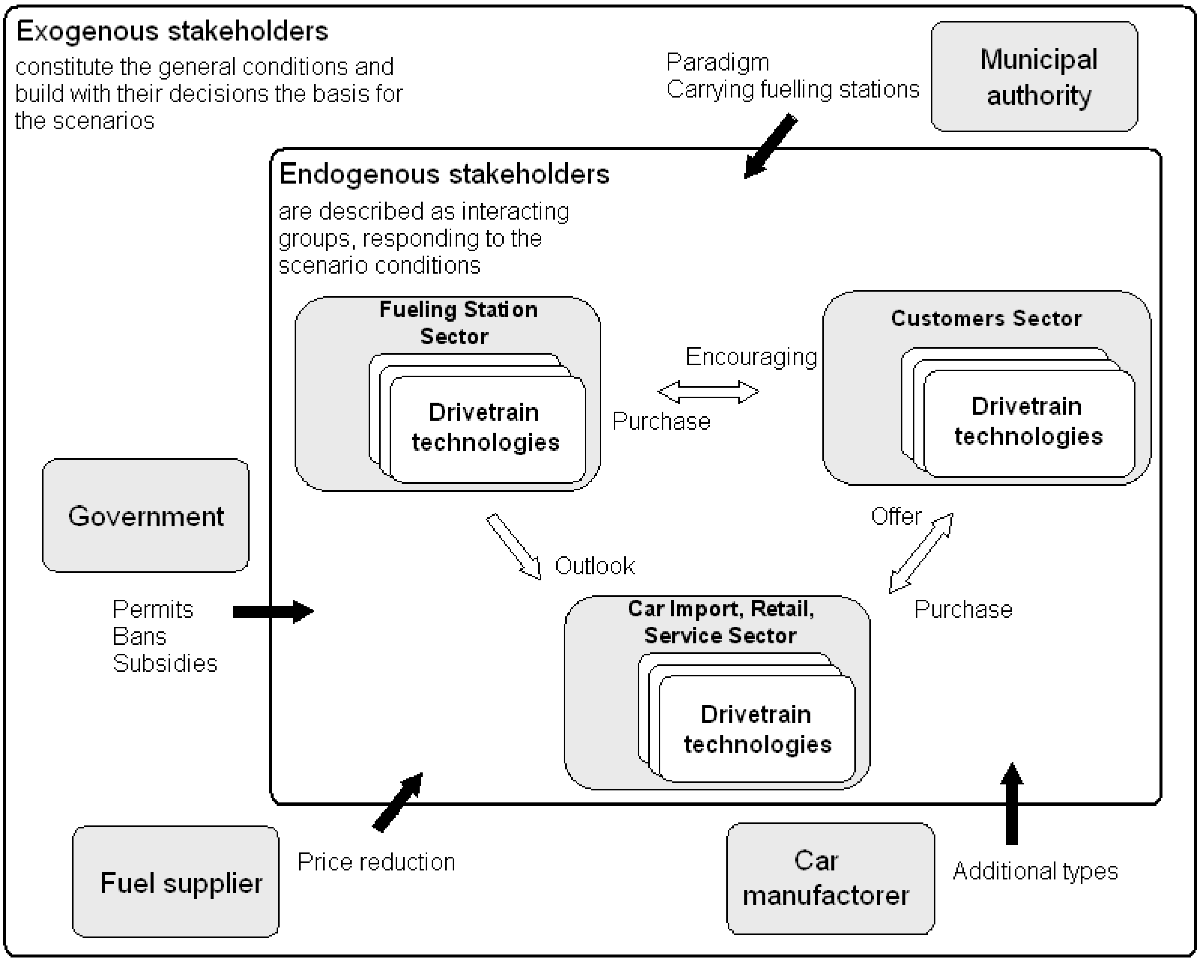

Figure 1: Box diagram showing the model boundaries with the different subsystems. White arrows indicate exemplary interactions and relationships in the inner model part. The black arrows indicate possible scenario inputs by exogenous stakeholders.

The endogenous stakeholders experience basic conditions like technology availability, performance, fuel cost, car purchase price, etc. Their options basically consist in adopting or not adopting new drivetrain technologies, taking place when a customer decides to buy a car of a certain drivetrain technology or not. Their actions have an influence on the decisions of other stakeholders within their own as well as in other sectors.

The three different sorts of exogenous policy making stakeholders in the system determine the basic conditions of the market: Car manufacturers, fuel suppliers and municipal and governmental authorities. There are generally two aspects concerning policy instruments. On the one hand they shall give an incentive – like a Pigouvian tax[1] – to change habits and guide customer behaviour. On the other hand they shall provide a basis to pay for damages, caused by emissions for example. This leads to a big variety of financial

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[1] Pigouvian tax is a generic term for taxes levied to guide customer behaviour. It is named after Arthur Cecil Pigou.

incentives that have to be considered, but likewise policies based on regulations, permits, bans and information are of the same importance. However, not all instruments can be explicitly represented in our model for two reasons: On the one hand they might involve stakeholders or decision mechanisms outside our model boundary, the effect of which on the customers‘ decision making is considered as small or simply unclear. Improvement of fuel quality for instance has certainly a big effect on consumption and emissions, but is neither depending on nor determining the vehicle fleet, at least not to an extent that would matter for the precision of our model. On the other hand, some instruments, such as urban planning or traffic management, address problems of local or regional transport externalities like pollutants or noise, rather than the fleet composition, fuel use and CO_2-emissions. The following gives a rough summary of market based and regulative instruments considered in our model to make up a high diversity of possible policies (cf. Sterner, 2003):

Area pricing, toll roads and mileage taxes are instruments of municipal or governmental authorities. With the first two, each car has to pay a fee to enter a special zone or area like the centre of a city or special sorts of roads. A technically more ambitious but still feasible instrument is the mileage tax, which is used for example in Switzerland for the "tax on heavy goods vehicles (LSVA)" on trucks.

Driving permits and bans for certain areas can be combined with area pricing. Vehicles with natural gas, hybrid, electric or fuel cell propulsion system can be excluded from the fee. Another possibility is the permit of driving on a designated fast lane for example.

Vehicle taxes can be levied by governmental authorities on new vehicles or on an annually based registration fee. Although often seen as socially more correct, the tax on new vehicles can delay the turnover of the fleet and therefore the discard of more polluting vehicles (Sterner, 2003).

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 individual investments smaller and therefore eliminates price disadvantages of new technologies. Subsidies can be granted by the government or the fuel industry, for example in the context of a Bonus-malus system[2] as discussed in Switzerland.

Fuelling 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 fuelling 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 (cf. for instance Clean Energy Partnership (CEP), 2006)).

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[2] Similar to insurance, where a Bonus-malus system adjusts the premium paid by a customer according to his individual claim history, a reduced tax (bonus) could be applied to alternative drivetrain vehicles. The emerging cost could partly be compensated by an increased tax (malus) levied on less fuel-efficient conventional vehicles. Bonus-malus systems are already very common in vehicle insurance.

Fuel tax advantages can be given to fuelling station owners or 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[3]. Tax advantages are granted by the government.

Emission standards and mandatory equipment can be purely regulatory instruments if they apply to all sorts of vehicles more or less to the same extent. Nevertheless they may have a market based aspect when certain vehicles meet standards by their customary technology, while others need additional expensive changeover.

Technology improvement is a result of research and development and can be supported by regulatory instruments. Its future yields cannot be predicted and are difficult to estimate over the models time horizon of several decades. Technology improvement is based on investments made by the government, car manufacturers or the fuel industry.

Fuel marketing instruments 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 instruments comprise price reductions on cars or an increase in product diversity, improving customer satisfaction. This sort of support is granted by car manufacturers.

Information spread and advertisement has an influence on the fraction of potential adopters that effectively adopt a new technology. The estimation of the effect of information is very difficult and depends on the total amount invested in information spread. This instrument can be taken by all exogenous stakeholders.

The instruments chosen for policy analysis specify the situation for the endogenous stakeholders – customers, retailers and fuelling station owners – in terms of decision arguments such as prices for fuels or new vehicles, more or fewer vehicle types offered in the market, or fuel availability. However, there are instruments that cannot be transformed into prices or simple availabilities. Instruments like information spread or driving permits increase knowledge or utility for drivers of a given technology. People without knowledge or who had only little contact to a new drivetrain technology need to get aware and learn more about it. The first step might be getting information, either from advertisement or information campaigns. Once in touch with the new propulsion system some of these people will get inclined, and a few will finally buy it, thus increasing its market share. Driving permits or restrictions either give utility or disadvantage to drivers owning a car of some categories. This will be observed by other people, who will then incorporate this impression when it comes to their next purchase decision. The problem with this sort of impact is of course the measurability, or in our case the implementation into the model. For this reason we assign each technology an attribute called *inherent attractiveness*, summarising all those effects increasing their basic or given attractiveness to the customer. Finally, there is the concept of imitation (Bass, 1969; Rogers, 2003)

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

that may play a major role for the spread of a technology. Perception and word of mouth support the adoption of a certain behaviour. The more people act in a particular way, the more it is accepted as a social standard, a behavioural norm. This *social norm* building process is represented in our model and an important factor in the decision function of the customer.

The system is further characterised by the technologies already available or going to be introduced in the nearer future. Today‘s almost exclusively used fuels in the European passenger car sector are petrol and diesel for internal combustion engines (ICEs). According to the best selling car manufacturers in Europe, turbocharged ICEs, bifuelled natural gas vehicles (NGVs) and hybrid electric vehicles (HEVs) are the most promising short- and mid-term alternative drivetrain technologies. The hydrogen fuel cell vehicle (FCV) is commonly seen as an optimal long-term option, but its market introduction will probably still take a decade or two. Although FCVs may play some minimal role within the time frame of this work they will not be considered in this article.

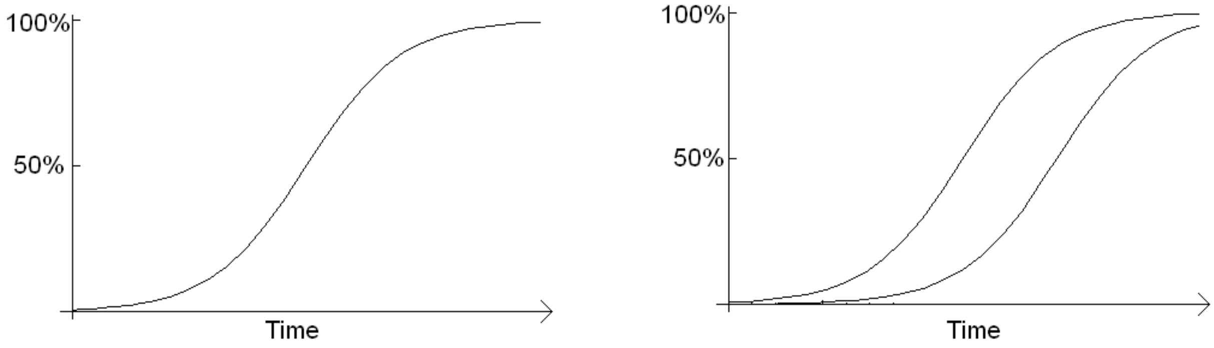
The most important issue which has to be reflected by the model is the competition between all alternatives. New propulsion systems have to break the dominance of the existing fossil fuelled ICE in order to be successful over a longer period of time, while contending with each other, too. With data of the Swiss federal statistical office the average age of scrapped passenger cars can be calculated to some 12 years in 2004 (Bundesamt für Statistik, 2004), with an upward trend, following the development in the U.S. (Davis and Diegel, 2007). The same result holds for Germany (Deutscher Verkehrs-Verlag GmbH, 2006), and generally for wider parts of Europe. Some future technologies will enter the mass market only in several years. Therefore the time horizon to perceive relevant changes in the passenger car fleet should at least be 30 to 40 years. It is clear that the reliability of the model forecasts will decrease with an increasing time frame, but if we want to analyse a complete change in dominance we even have to extend the time horizon by some more decades. This brings us directly to the question of the basic mechanisms of technology spread through society which we want to describe and analyse with our model, the technology diffusion.

3 Diffusion of drivetrain technologies

A simplified, idealised innovation diffusion in general follows – at least until a certain point in time – a sigmoid form (Rogers, 2003), as it is shown in figure 2a. The graph shows the number of units for one 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 frame specified by the goals set for the development of the system. Possible failures in this sense would be “extended diffusion time“ (diffusion takes more time than acceptable, fig. 2b), “limited growth“ (diffusion does not reach an acceptable level, fig. 2c) or “unstable development and decline“ (possibly strong fluctuations with subsequent disappearance, fig. 2d).

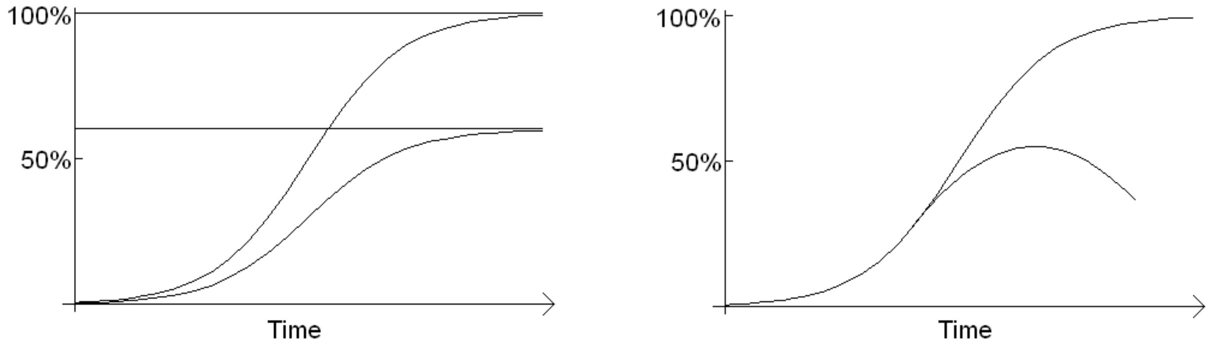
Curves with a completely different outcome show a similar behaviour at the beginning. Success or failure can generally not be distinguished in the starting phase of the diffusion process, and the difference in early observable numbers may lie below precision of measurements. Once collapsed, a diffusion process can hardly be re-initiated (Janssen, 2004). 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 (2003) the introduction of alternative drivetrains



a) Successful development

b) Extended diffusion time



c) Limited growth

d) Unstable development-path

Figure 2: Comparison of four different fundamental behaviours of the diffusion curve. These curves should be considered as qualitative. In theses graphs adoption goes from 0% to 100%, and the time axis has arbitrary units.

and their corresponding fuelling infrastructure in a car fleet is a process of technology spread through society, called technology diffusion. The way for the diffusion of the innovation‘s hardware is paved by communication. For a successful introduction of alternative technologies for example 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 the 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 (Arthur, 1989) for certain technologies have always the consequence of locking out competing technologies, which is particularly not preferable in the case of alternative drivetrains and fuels.

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 a substantial 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‘ drivetrain technology as a lock-in of the internal combustion engine (ICE) and all its corresponding systems, such as fuelling infrastructure. In this sense the challenge with introducing new drivetrain 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 perspective. 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.

Likewise 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, 2003, 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. According to Rogers (2003), the critical mass is a fundamental concept that expresses the social nature of the diffusion process. Assuming the critical mass exists – from our point of view not yet answered in literature – two questions 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. Ulli-Beer et al. show a criterion to determine whether a critical mass exists for a given model, and they show that for instance the widely used Bass model does not map this important concept (Ulli-Beer et al., 2008b). The critical mass resulting from our model strongly depends on the norm building process, more precisely on its nonlinearity.

4 System Dynamics Model

The purpose of the developed model on competing alternative drivetrain technologies is to explain the chronological behaviour of the diffusion rates of alternative drivetrain technologies in the passenger car market. Its main function is therefore to link the single technologies in the market and describe the competition between them. This is done using different layers and describing their interaction by means of consumer choice. The entirety of quantities or variables associated with the same technology layer are designated as a technology platform. The idea of such platforms was first developed and implemented into a model of competing propulsion systems by Struben (2004). In the following we concentrate on the subsystem shown in figure 3. The dynamics underlying the system and the treatment of several quantities like e.g. customers, number of fuelling stations or vehicles as aggregated clusters, indicate the System Dynamics modelling approach.

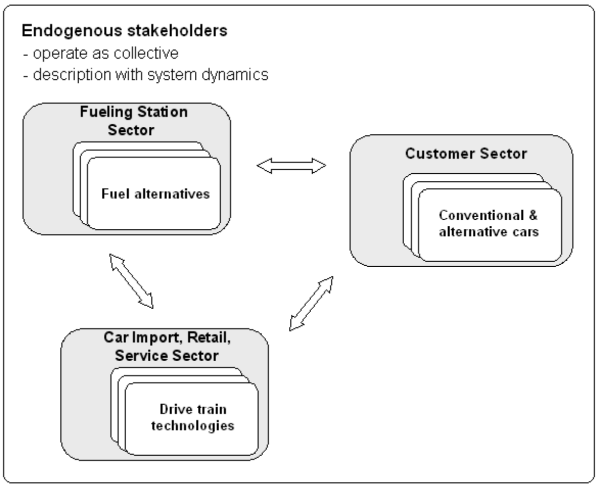


Figure 3: Box diagram showing the general structure: The simultaneous handling of more than one alternative fuel technology with the resulting competition can be realised by the introduction of different coupled platforms, analogously structured within individual sectors.

4.1 Model structure

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 drivetrain technology, and flows, which are the rates defining the transfers between the stocks. The flows, precisely the flow rates, are determined by a number of other variables discussed below, which may depend on time as well. Table 1 gives an overview of the variables so far considered in the model.

Table 1: Model variables

Endogenous	**Exogenous**	**Excluded**
Vehicle stocks	Median lifetime	Fleet aging
Vehicle sales	Fleet growth	Vehicle classes
Vehicle discards	Availability	
Customer satisfaction	Inherent attractiveness	
Comparative attractiveness	Mileage	
Perceived attractiveness	Fuel price	
Social norm	Purchase price	
Adopter potential	Fuel consumption	
Filling facility cost		
Market forecasting		
Filling stations		
Type spectrum		

While using the work of Janssen (2004) on the relationships between car stocks, vehicle spectrum and infrastructure within a technology platform, our model is primarily focussing on the interactions between different platforms. The consumer choice mentioned above is represented by purchase probabilities for each platform based on different aspects, comprising the vehicle and fuel prices, the type spectrum in the market, the fuel supply, the effect of a technology specific attractiveness (inherent attractiveness) and the social norm building (Gassmann and Ulli-Beer, 2006; Ulli-Beer, 2004). The single attributes are normalised when necessary and are considered as independent. Therefore the corresponding probabilities are multiplied to calculate the market share.

The dynamic hypothesis of the model is illustrated in figures 4 and 5. The causal loop diagram (figure 4) shows the whole decision-making structure, which applies to all technology platforms equally, but with different parameter values. The basic structure is generic and can be applied to multiple countries and different drivetrain technologies after few modifications.

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 drivetrain type, while the total size of the fleet may be growing. All stocks are linked to each other by flows in a symmetrical way (cf. fig. 5). This allows a customer to replace his car after scrapping by anyone of the drivetrain technologies considered. The options for the policy making stakeholders – such as subsidies or special driving permits – are implicitly manifest in variables like purchase prices or inherent attractiveness etc. Those are influencing the purchase decision of the customers and determine the flow rates between the stocks and

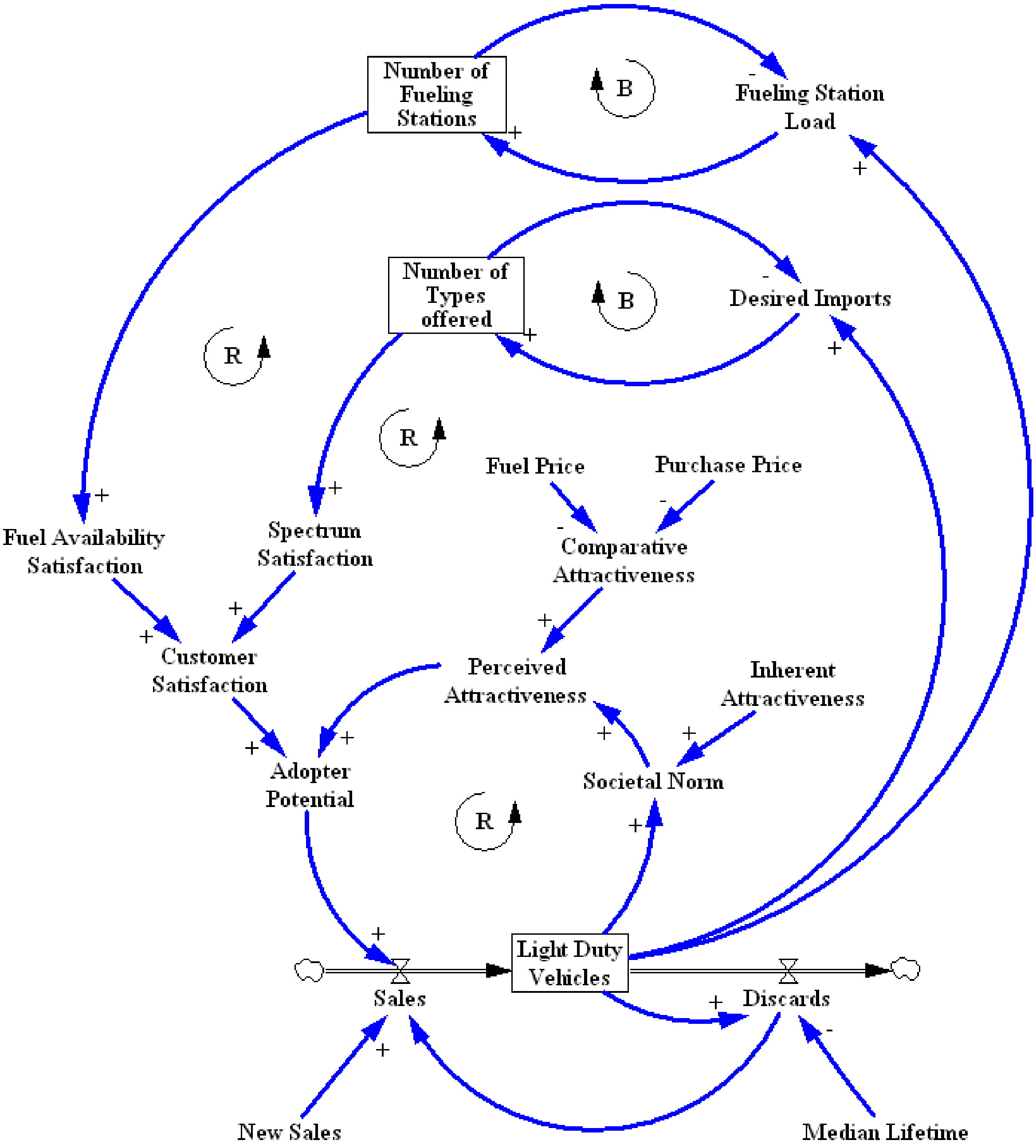


Figure 4: Causal loop diagram showing the decision-making process.

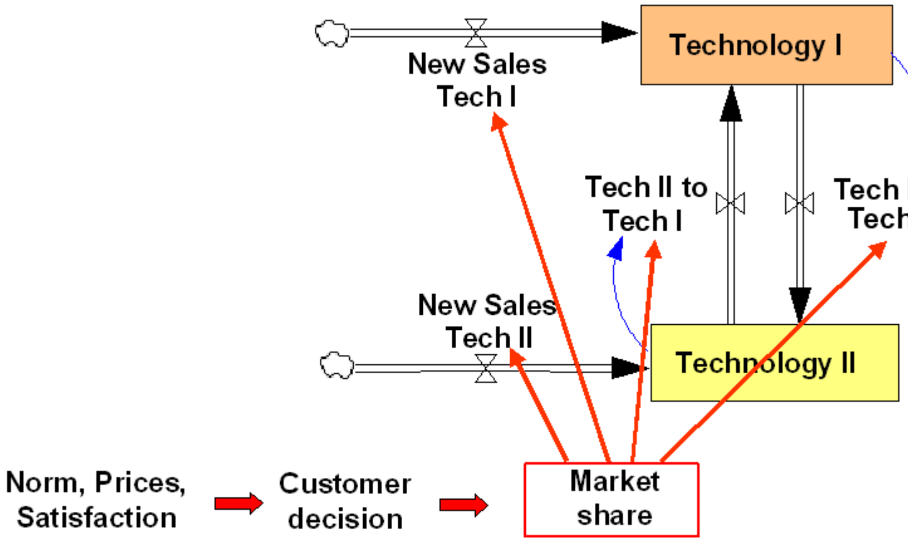


Figure 5: Illustration using stocks and flows of the basic model structure for two different drivetrain technologies. This structure can analogously be extended to several technology layers.

therefore the technology substitution. For a more detailed description of the flow rates see Bosshardt et al. (2007).

An alternative way to look at the model is exemplified in figure 5, taking two different drivetrain technologies into account. This illustration shows the competition and the way the different drivetrain 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.

4.2 Resulting behavioural characteristics

The behaviour resulting from the structure described in the previous section reveals the existence of different stable states, i.e. fleet shares of different drivetrain technologies that do not change over time without modifying the parameters. These equilibria can be interpreted as lock-in situations when there is a particular technology dominating the market. Changing the parameters means to alter the technology shares of the equilibria, thus forcing the system to “move“ to a new equilibrium. This behaviour reminds of a ball moving downhill seeking a stable equilibrium as a mechanical metaphor developed by Gassmann and Ulli-Beer (2006). Figure 6 shows a possible “landscape“, a potential function in arbitrary units, derived from the model equations (Bosshardt et al., 2007) in a situation with three competing alternative drivetrain technologies, say A, B and C. The state of the system (red ball) is thereby characterised by its two coordinates on the x- and y-axis, representing the fleet shares of technologies A and B. The share of C is determined by subtracting the other shares from 100%. At time 0 of the simulation the system could for example be in the position with the red dashed circle. As in the mechanical analogon, the system moves towards one of the minima, according to the local gradient. Following the path indicated it ends up in the stable position with the red ball.

However, policy based consumer incentives may influence the purchase decision and move the system away from its equilibrium state. Subsequently, there are two sorts of outcomes possible: Firstly, the incentive is ceased again and the system moves back to the minimum, meaning that the lock-in situation could not be broken, and the incentive

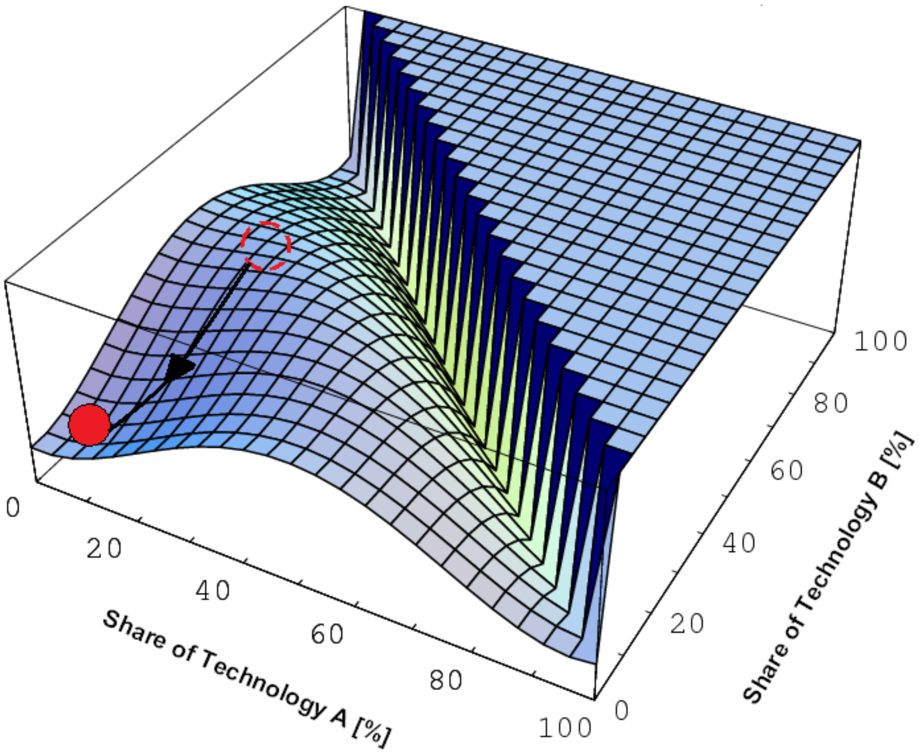


Figure 6: Plot of the "landscape" (potential function in arbitrary units on z-axis) resulting from a situation with three competing drivetrain technologies A, B and C. The fleet shares of technologies A and B are represented by the ball's coordinates on the x- and y-axis respectively. The share of technology C cannot be depicted but is determined by "100 % - (share of A + share of B)". Local minima in the landscape correspond to stable equilibria, as seen in the left corner of the coordinate system. The area where fleet shares would sum up to more than 100 % is restricted for the system (ball) by an insurmountable potential wall.

had no long-term effect. Secondly, the incentive is ceased after the system has crossed the "watershed", where the gradient changes its direction towards another stable equilibrium. In that case, the system ends up in another stable state with a different dominating drivetrain technology. The "watershed" is characterised in our model with the critical market share, which has to be exceeded to get a self-sustaining diffusion process.

4.3 Social norm

The social norm is a very important quantity in the model, nonlinearly depending on the fleet share of each drivetrain technology. By tuning the assigned weighting factor, the "coupling constant" so to speak, the influence of the normative behaviour on customers' purchase decision can be adjusted. If we double the strength of the norm by increasing the coupling constant, a delay in the change of dominance occurs. The share of an upcoming technology needs to be higher to attack the dominant role of the prevalent propulsion system. The social norm has a stabilising effect on the current state. Referring to figure 6 it is responsible for the depth of the local minima in the potential function, or the "landscape". The deeper the minimum, the more it takes to break out of the technology lock-in. The norm building process must be carefully adjusted when calibrating the model. For a more profound discussion on the social norm and its effects on consumers' choice see Ulli-Beer et al. (2008a) and Bosshardt et al. (2007).

5 Model based policy testing

It would go far beyond the scope of this paper to present the complete results of the overall-study. Therefore we concentrate on some example cases more in detail. The effect of certain policy measures and strategies analysed with the model in different scenarios is exemplified by means of four simulation runs for France. Different policies are tested to reach market penetration or emissions reduction goals. The simulations compare the influence of single or combined incentives, also showing that the needed financial support can be significantly reduced when the platform dependent inherent attractiveness is increased, for example by granting city access for vehicles using low-emission drivetrain technology etc.

The technology platforms considered comprise pure internal combustion engines (ICEs), in our case petrol and turbocharged petrol vehicles, diesel vehicles and natural gas vehicles (NGVs), as well as petrol and diesel hybrid electric vehicles (HEVs). Fuel prices, mileage, consumption, median age when scrapped and types offered are represented by average numbers. Vehicle specific parameters for each drivetrain category are taken from the Volkswagen Golf in its different variations or equivalent. The time horizon for all simulations is set to 2045. This is needed in order to observe long time behaviour that shows a real change of technological dominance.

France is an interesting case because this country represents about 13.6% and 14.3% of all EU25 population and car fleet respectivley[4]. A further reason is its unique diesel sales share of 69%. This is an increasingly important issue because growing diesel shares are an observed trend throughout Europe. The basic developments we want to investigate are a 50% overall emissions reduction and reaching a 10% fleet share for natural gas vehicles (NGVs) by 2020. The latter is a rough objective approximating one part of the 20% oil replacement target in motor fuels stated in the 6th European Framework Program. After looking at the baseline scenario, which is equivalent to a business as usual scenario, we will analyse three different policies.

5.1 Baseline scenario

The key assumptions for the baseline scenario comprise a purchase price increase until 2045 of 6% for petrol (also turbocharged) and diesel cars and a decrease of 1.5% for hybrids, because of expected exhaust aftertreatment measures and technological improvements respectively. We further assume a general technological improvement in combustion engine technology that reduces consumption by some 25-30% depending on the vehicle category. We account for increasing fuel prices of about 50% due to the expected oil price development (International Energy Agency (IEA), 2006), as well as for an increasing median age of vehicles when they are scrapped, reaching 14 years in 2045 (following the trend in the U.S., cf. Davis and Diegel (2007)). Figure 7 shows the comparison of the stock data resulting from the model with the historical data available.

In this scenario natural gas vehicles account for some 10% market share and a 5% fleet share in 2020, far from the aspired 10%. Although alternative drivetrain technologies experience a rise in the coming decades, petrol and diesel ICEs remain the dominant propulsion systems. In all of the subsequent scenarios we investigate changes to the baseline scenario in the context of policies aiming at the targets mentioned above. Only changed assumptions are referred to.

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[4] Directly following Germany with 18% and 21% respectively.

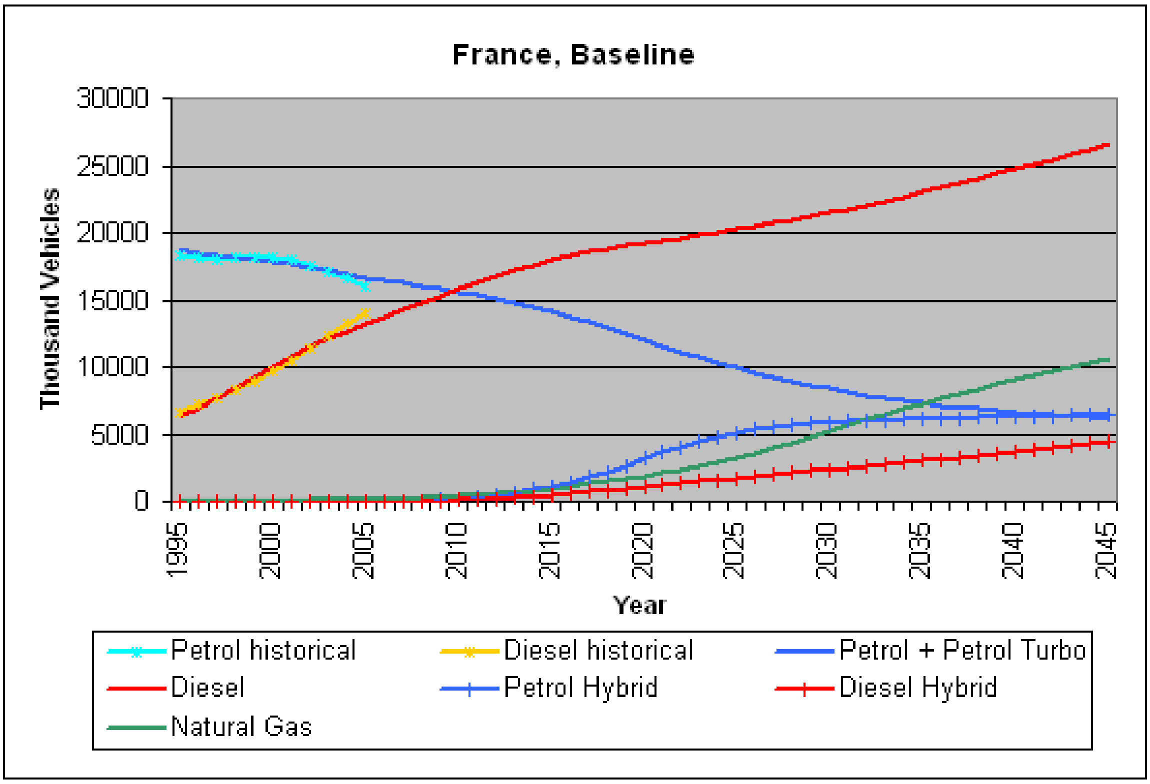

Figure 7: Comparison of historical data with the baseline model run after calibration. Conventional and turbocharged petrol cars are unified to one vehicle category for comparison with the historical data series.

5.2 Fuel price increase scenario

We now compare our model output with the results of a rather simple elasticity model for the relationship of income, fuel price and consumption. Sterner‘s example of a “crude policy experiment“ (Sterner, 2003, p.245) may provide the basis for the following increased fuel price scenario. In this case he assumes that fuel demand G is determined by $G = YP^{-0.8}$, with income Y and price P. It is also assumed that income will increase by 50%, while a long-term goal suggested by the International Panel on Climate Change is a 50% decrease in carbon emissions for the transportation sector. In this case, what would a suitable market price look like? If the carbon emission goal is to be achieved only by reducing the fuel demand, then the comparison of the original and the adjusted price – using the formula above – leads to

$$\frac{P'}{P} = \left(\frac{0.5}{1.5}\right)^{-\frac{5}{4}} = 4$$

This is, an adequate fuel price should have to be 4 times higher than today, given the elasticities are valid over a large interval. In the absence of alternative vehicles the emissions decrease will have to be achieved by changing the customers‘ driving behaviour, i.e. particularly the average mileage, which is arguable, even with high fuel price as assumed[5] According to the European Commission (2001) personal mobility has doubled from 17 km a day in 1970 to 35 km in 1998, and it is nowadays seen as an “acquired right“. Either way the change would take time, which cannot be considered by this simple sort of model.

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[5] For instance, high prices for cigarettes did not reduce smoking significantly in Great Britain.

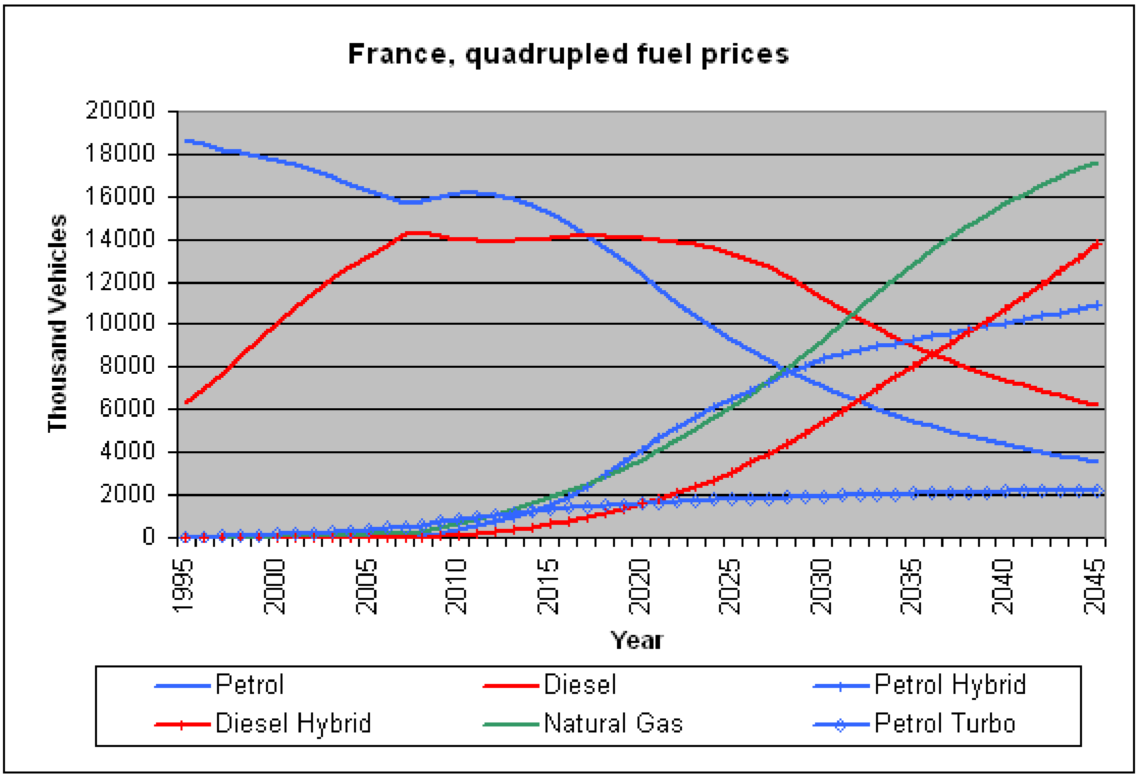

Figure 8: Vehicle stocks in France when applying a quadruplication of all fossil fuel prices. In the long run we observe a strong rise in alternative drivetrain vehicles.

However, with alternative drivetrains on the market, people could buy less fuel consuming vehicles such as natural gas vehicles or petrol hybrids to overcome the conflict between high expenses and an increasing mobility demand. This can be seen in our simulation, using the same parameter settings as for the baseline scenario, except for the increased fossil fuel prices. If we increase the prices by a factor of 4, the fleet share of alternative cars increases as people tend to buy an economical car when they purchase a new one. Figure 8 shows the stock curves for the increased price scenario with a quadruplication of fossil fuel prices after 2007.

In our model parameters we assume a constant mileage on today‘s levels. The sudden rise in fuel prices by a factor of four causes the increasing diesel trend to cease[6]. With the rise of alternative propulsion systems internal combustion engines loose their dominance on the car market. The increased use of cleaner vehicles leads to a reduced fuel consumption, though the fleet is assumed to be growing and there is no net effect. Freezing the size in 2008 at 30 million vehicles would lead to an effective emissions reduction of some 30% in 2040. Though the process starts early, it would take some decades to reach the level necessary to halve the carbon emissions. However, limiting the fleet growth to 37 million vehicles would result in the desired emissions reduction by 50%. Note that the reduction is achieved by changing the customers‘ purchase preferences without any further constraint on their mobility.

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[6] The short-term increase in petrol vehicles is due to the new level of prices which reduces the relative advantage of diesel compared to petrol vehicles.

5.3 Double financial incentive scenario

In this scenario we apply two simple financial incentives on compressed natural gas and natural gas vehicles: a fuel tax reduction of 30 Eurocent per litre petrol equivalent as well as a purchase price subsidy of 1500 Euro, both granted from 2008 until 2030. Figure 9 shows that these are important measures, accelerating the diffusion of NGVs, but the effect of financial instruments is limited. After the incentives are stopped, a drop in sales occurs, revealing an overshoot at that point.

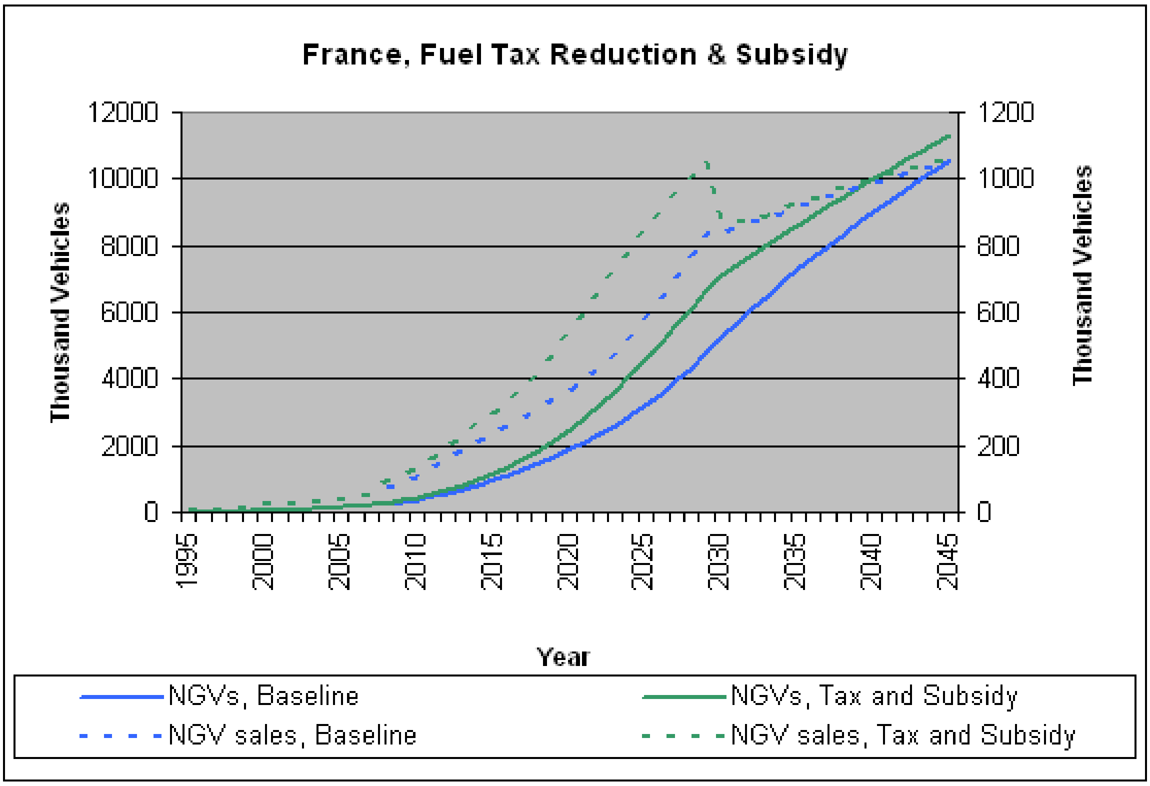

Figure 9: Stock and sales for Natural Gas Vehicles (NGVs) in the baseline and the fuel tax reduction and subsidy scenario. The right scale applies to the sales numbers.

The market and fleet share of NGVs in 2020 reach 15% and 7% respectively. The incentive is not granted long enough, showing that only financial policy instruments do probably not lead to the desired result, even if they are not stopped early.

5.4 Multi-incentive scenario

Several instruments applied simultaneously lead to a much more successful development. Especially when there are not only financial incentives, but also an increased inherent attractiveness. In this case we add a regulated driving permit to the incentives in our last scenario, raising the inherent attractiveness over the same time period from 5% to 20%, referring to 20% for diesel vehicles for example. The increased attractiveness remains after the tax reduction and subsidy are ceased. Therefore, and because the norm is already stronger with more NGVs on the road, the overshoot is partly compensated.

From figure 10 we can see, that a multi-incentive scenario still shows an overshoot after stopping the financial incentives, but a steeper trend afterwards. The level of market penetration is now reaching 30% in 2020, the fleet share is about 12%. In this

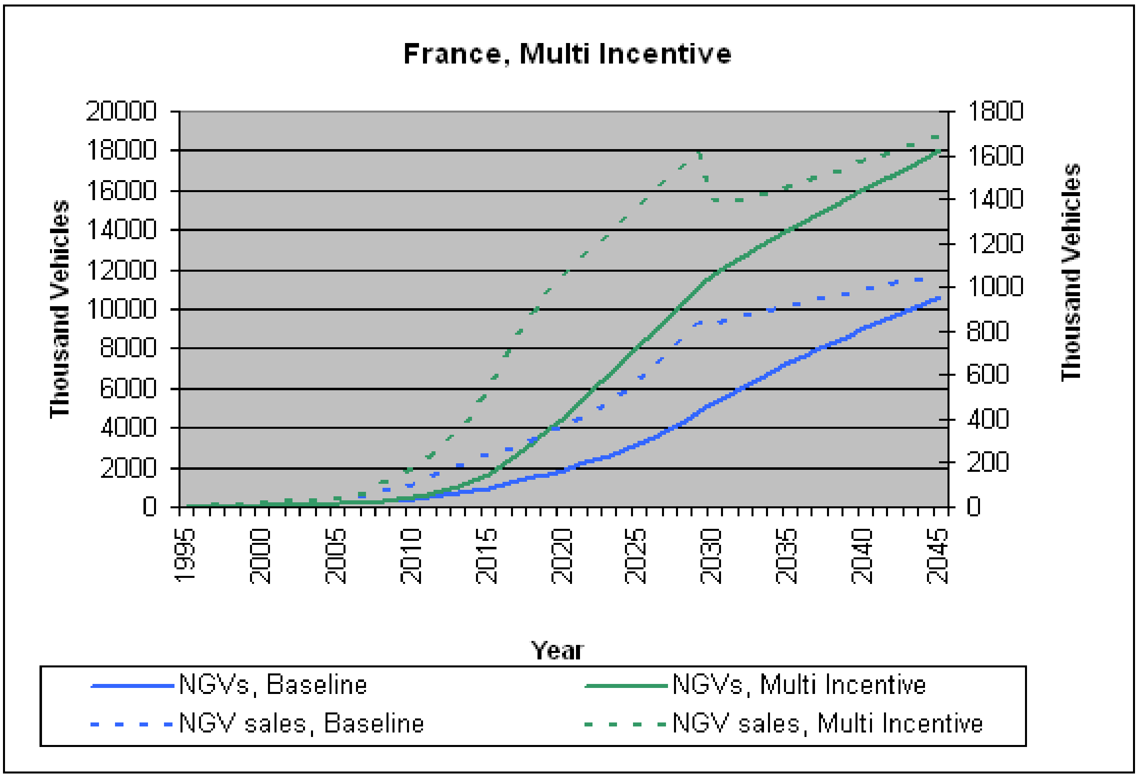

Figure 10: Stock and sales for natural gas vehicles (NGVs) with financial incentives and additionally increased inherent attractiveness, compared to the baseline scenario. The right scale applies to the sales numbers.

case, the package of the three policy instruments applied can be successful. Using only a financial incentive would necessitate a higher subsidy over a longer time period to achieve comparable results. A subsidy increase of 500 Euro would bring significant additional costs that can be avoided or at least partly compensated.

6 Conclusions

The System Dynamics model for the diffusion of competing alternative drivetrain technologies described in the previous sections is able to test policy instruments for their effectiveness and to estimate their cost-effectiveness. The simulations support the argument that policies should always comprise a package of different instruments to get the highest added value (European Commission, 1995; Sterner, 2003)). A single financial or other incentive is often not enough to reach the critical mass for a break out of a lock-in situation and a subsequent self-sustaining development. If the “watershed“ could not be crossed, the system goes back to its original stable state as soon as the incentives are stopped. This is the case if either the incentive was too weak, leading to a stagnation in the development, or if it was stopped early. The social norm building process is not strong enough to compensate for the incentive abolished. However, once the system moved beyond the tipping point – i.e. the norm building process has become strong enough – the diffusion becomes self-sustaining. Afterwards all incentives can be stopped, and the system moves into another stable state.

Coming back to the three questions raised to the beginning of this paper, we conclude that stable states and self-sustaining diffusion processes emerge by the social norm, but still depend on its interaction with the effects of other attributes, such as prices or fuel availability. The competition in the system leads to different platform specific equilibria. This means that coexistence over a long time period can still be a slow transition process towards a new platform specific equilibrium. Dominance of one technology seems to be unavoidable without incentives in the long run. In order to initialise a transition we can summarise that financial incentives remain an important category of instruments, but that their impact is higher when they are combined with incentives raising the inherent attractiveness of a technology platform.

We finally note that the time needed for the system to move from one stable equilibrium to another is strongly dependent on the path that is chosen and the measures taken to promote one or more technology platforms. Sometimes the support of more than one platform is required to break the dominance of the leading technology and to reduce the critical mass, but may take longer to get to a new equilibrium state. This may influence the cost and effectiveness of a policy and should be considered when designing the package of instruments. After all, breaking the current lock-in situation does not guarantee that the most desirable solution will become the dominant one by all means. However, the variety of technology platforms help to select the most promising and competitive solution. An early restriction in technology should therefore be avoided.

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