SYSTEM–BASED ANALYSIS OF DIFFUSION OF ALTERNATIVE DRIVES AND FUELS FOR TRUCKS

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Abstract (143 words):

In contrast to the passenger car sector, purchasing decisions of freight forwarders are driven by economic factors by nearly 100 %. Based on a cost analysis, the factors which can clearly be dedicated to different technologies are fuel costs, maintenance costs, investment costs and taxes. The decision to buy a new truck is always accompanied by a cost comparison of each alternative. This leads to a compilation of costs for each technology in terms of negative utility within a Logit-Model. This is realized in a System Dynamics model in dependence to the ASTRA model of the European Union. The main aim is the assessment of environmental policies (tax and toll) towards the diffusion of alternative drives and hence the possibility to influence the truck stock towards sustainable drive technologies. The framework is given by the German truck market as well as the German environmental policy.

1 INTRODUCTION

Over the past decade global warming has become more and more important for environmental policy. The reason for increasing average temperatures and air pollution on planet earth is mainly found in the emission of greenhouse gases, which are dominated first and foremost by carbon dioxide. Carbon dioxide is the outcome of nearly every combustion of fossil fuel. These emissions are emitted by industries, households and traffic. As this paper is deeply related to past papers about the ASTRA project, it is focussing on the traffic sector.

The Traffic sector itself can be divided in three sections: private cars, public transportation and freight service. Due to decreasing population in most developed countries, the influence of private cars and public transport will decline in the future. The freight service on the other hand is driven by globalisation with its decentralised production sites all over the world and locations of costumers far away from manufacturing plants. The majority of freight is carried by trucks owing to higher flexibility provided by road traffic. So it seems reasonable to take a closer look at the emissions of trucks and the potential possibilities to influence their emissions by state driven environmental and traffic policies.

The only way to escape the current cycle of fossil fuel combustion is to utilise alternative fuels and drives. These new technologies have to be introduced to a market which is highly dominated by the economic pressure of the carrier. The aim of this paper will be the simulation of the diffusion of alternative fuels and drives within the truck market, mainly based on the decision theory. After a short technical introduction presenting all the possible alternatives the second part has its emphasis on the modelling of the decision process of the carrier, which is the core of the model used to describe the process in further detail.

Making the assessment of measurements easier, the truck stock should be divided in different sections. Combining the ideas of ABERLE (2000), APPEL ET AL. (2008) and BLUMENSAAT ET AL. (2007) to one categorization of the trucks used for freight transport leads to three main categories:

- Light distribution traffic (lightDT)
- Heavy distribution traffic (heavyDT) and
- Long distance traffic (LDT).

The light distribution traffic (lightDT) consists of trucks mainly used for light freight transport from 7.5 tonnes up to 12.0 tonnes gross load weight. These trucks are mostly used for inner city or urban traffic, caused by high flexibility.
Heavy distribution traffic (heavyDT) is operated in regional areas up to service distances of 200 kilometres a day and with a weight range from 12 tonnes up to 32 tonnes. Examples are construction work traffic between construction sites and concrete factories or food transportation from distribution centres to the shops, mostly food discounters.
The last category is represented by the long distance traffic (LDT) which is also the category with the highest gross load weight of up to 40 tonnes or in Sweden even up to 60 tonnes. These trucks are running mostly on highways with a yearly kilometre reading of 150.000 kilometres (HARTMANN 2009).

The model will divide the whole truck stock into these three categories. Reasons therefore are the different kilometre readings, the different costs and the different driving cycle. The following table shows the characteristics:

Table 1: comparison of the different traffic categories (ZEITZEN 2009)

Type of traffic	long distance traffic	heavy distribution traffic	light distribution traffic
Average kilometre reading [km/a]	150.000	50.000	20.000
Average fuel consumption [l/100km]	35	25	28
Average investment costs [€]	90.000	100.000	50.000

Having this categorization in mind, the next step is the evaluation of different alternative drives and their potential application in each category. This evaluation is basically the result of research in papers, magazines and books. Today's experiences with alternatives drives are barely reported, so this paper is mainly based on assumptions. The following page lists all the possible drives described in literature:

- Biodiesel

  Biodiesel is a fuel produced from organic material. In recent years, biodiesel was often regarded as the solution for all energy problems. The truth is that the space needed to grow enough plants to supply fuel in a larger amount is not available and the risk of prioritising the available space to food production is high. However, it can be used in the already existing combustion engine without major modifications.

- CNG (Compressed natural gas)

  Enlarging the low energy density of natural gas requires either compression or liquefaction. Difficulties with liquefaction tend to a single consideration of CNG. Compressed natural gas is normally transported by pipelines from countries where natural gas is located. The petrol station offers compressed gas via special infrastructure. The tanks in the vehicles have to be extremely pressure resistant which elevates the weight.

- Electric drive

  The electric drive is already partly used in cars. There are also applications in bigger vehicles like locomotives or trolley buses. The advantages of electric drives are a high efficiency especially in urban areas and a less complicated construction, as a gearbox is not required. So far the electric drive seems to be the best choice for every vehicle. However, the problems are not related to the drive but to the energy storage on board the vehicle. Only Lithium –Ion batteries appear to be the technology able to handle huge amounts of energy storage combined with relatively moderate costs. The drawbacks include low durability and high material costs (KÖHLER 2007). On the long term, prices will decrease while storage capacity will increase making full electric vehicles become widely available by 2030 (TATSUMI 2007).

- Fuel cell

  The fuel cell transfers energy by a chemical reaction from hydrogen to electricity. Fuel cells are mostly combined with an electric drive which includes the advantages of electric drives especially in urban areas. The fuel cell itself is a complicated new technology with high maintenance costs and high investment costs. The main problem besides the drive technology is the tank technology. Hydrogen has a very low energy density, which is even lower than that of gas. Hence, there are two possibilities to raise this density: high pressure or liquefaction by reducing the temperature. Both methods need strong and heavy materials making the tank weight rise.

- Hydrogen combustion

  Another possibility of using hydrogen as a fuel is hydrogen combustion. The system is nearly the same as diesel combustion, which makes maintenance easier. The investment costs and maintenance costs are lower than those of the fuel cell. The problem with the tank technology is the same.

As there is limited experience with most of these technologies in the truck sector, a consideration of urban busses seemed to be reasonable to assess the technologies in terms of performance, costs and practicability. The Reason is that most buses are owned by communities, which are more open to green technologies not having economic pressure like freight carries.

In addition to the technologies described above, hybrid technology is often mentioned in terms of alternative drives. Generally, every drive technology can be combined with a hybrid. The hybrid technology gets energy back from every breaking process. Hence the more breaking processes there are the more energy can be recaptured. This energy is put back into a battery to use it for the electric drive. In general, hybrid means the combination of two or more different drives. A very common variant is the combination of electric drive and a combustion engine. The mayor question is if it makes sense to consider the hybrid technology for every category of traffic. Coming back to the important number of braking processes, figure 1 shows a typical driving cycle of each traffic category.

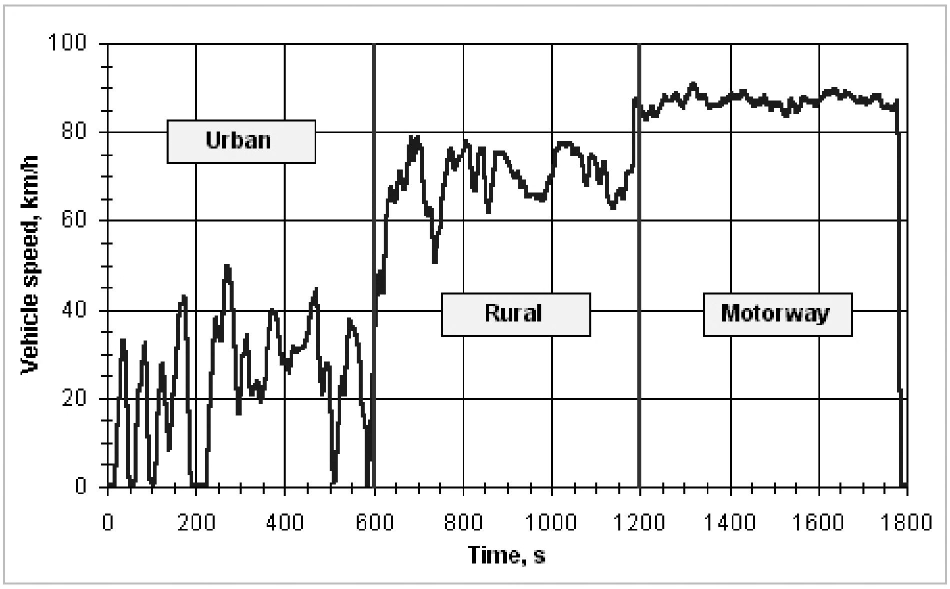

Figure 1 - European Transient Cycle (FALTENBACHER 2006)

As a matter of fact this figure shows that only rural and urban traffic have a certain number of breaking and acceleration processes to make a hybrid efficient. All these facts taken together lead to results shown in table 2 demonstrating the possible combinations of traffic categories.

Table 2: possible drives for every traffic category

Traffic category	Biodiesel	CNG	H2 Combustion	Fuel Cell	Electric	Hybrid
LDT	X		X	X		
heavyDT	X	X	X	X	X	X
lightDT	x	X	X	X	X	X

Hence, electric and hybrid as well as CNG will not be examined for long distance traffic. The decision for drives useable for heavy distribution traffic will be hard. Even though electric and hybrid drive will not play a dominant role, the combination will be assessed.

It is very important to transfer these aspects not into a single stand-alone model but in connection with existing system dynamics models. To assess policies concerning traffic and environment a system dynamics model was installed during a European research project (SCHADE 2004). ASTRA (=Assessment of Transport Strategies) allows to include different effects in different modules. Besides the macro-economic module (MAC) and the environmental module (ENV), the vehicle fleet (VFT) will have a dominating role on the next pages. The model allows forecasting the vehicle stock for passenger cars and trucks. KRAIL 2009 extended the model making considerations for the vehicle fleet per alternative car technology possible. Combined with the environmental module (ENV) influences on emissions can be assessed easily. To complete the model this article will describe a possible extension towards simulating the development of alternative drives and fuels in the truck sector by dividing the truck vehicle fleet into different technologies.

2 METHODOLOGY

This part will show how the diffusion process was realized in a system dynamics model and which further scientific methods where used within this model. The advantages as well as the disadvantages of each method will be mentioned.
Using system dynamics as a modelling framework allows the simulation of feedback loops to create a model as realistic as possible. Furthermore the system dynamic modelling is not based on the equilibrium theory of classic economic approach. Hence, there are nearly no limits in the modelling process, which can also be seen as one of the disadvantages. One of the main reasons why the system dynamics approach was used in this model is on the one hand the easy creatable connection to already existing modules of the ASTRA model and on the other hand the possible enlargement to create a more realistic model. This can be realized as soon as there is more information about the diffusion process and the different technologies. Then the extension towards feedback loops will be necessary. Feedback loops are not installed so far due to the lack of information. Installing feedback loops without enough information will lead to outcomes in a potential wrong direction.

Within the system dynamics environment, different other scientific approaches are used. The following part describes the realization of intra-model modules with the utility based Logit-theory and the learning-curve-theory.
Dividing the model into two main parts, the one is modelling the decision process of the freight carrier and the other part tries to forecast the right time of market entrance for the different technologies.

Taking a closer look at the decision process of the freight carriers, it is useful to go into some economic theory. The decision of investing in a new technology is driven by economic forces. So the freight carrier compares the costs of all alternatives before the decision takes place. The aim of this process is a utility based decision, where costs mean nothing but negative utility. Utility of an alternative can be expressed as the sum of a constant function plus a confounding factor simulating uncertainty (equ. 1).

$$u = v(x) + \varepsilon \qquad \text{(equ. 1)}$$

$$u = \alpha + \beta_1 x_1 + \beta_2 x_2 + \ldots + \beta_k x_k + \varepsilon \qquad \text{(equ. 2)}$$

$where$
$x_1 \ldots x_n = attribute$
$\beta_1 \ldots \beta_n = utility\ coefficient$
$\propto = level\ parameter$
$\varepsilon = confounding\ factor$

This constant function can be split into a level parameter, different attributes and the appropriate utility coefficients. So each alternative can have different attributes weighted by utility coefficients. Hence, the utility of each alternative can be calculated as the attributes are given. In practice, the utility coefficients are estimated on the basis of values from the past.

A person is now preferring alternative i to another alternative j, as long as the utility of i is higher. The likelihood of an alternative to be chosen is equal to the likelihood of having a higher utility. (equ. 3)

$$P(i) = P(v_i > v_j) \qquad \text{(equ. 3)}$$

As already mentioned above, there is a confounding factor. A Gumble distribution of this factor leads directly to the following equation, calculating the likelihood of the choice of an alternative:

$$P(i) = \frac{e^{v_i}}{\sum_{j=1}^{n} e^{v_j}} \qquad \text{(equ. 4)}$$

$where$
$v_1 \ldots v_n \ : utility\ function\ of\ alternatives\ 1 - n$

This model is also known as the Logit-model used for traffic choice models based on costs and time needed for different destinations in traffic networks. The output is normally the so called modal split which shows for instance which percentage uses public transport.

For the modelling of the diffusion of trucks you have to calculate the overall costs in the following way:

$$C_{i,j} = aC_{i,j} + wC_{i,j} + kC_{i,j} + bC_{i,j}\ (+tollC_{i,j} + taxC_{i,j}) \qquad \text{(equ. 5)}$$

$where$
$C\ = overal\ costs\ per\ vkm,$
$aC = investment\ costs\ per\ vkm$
$wC = maintanance\ costs\ per\ vkm$
$kC = fuel\ costs\ per\ vkm$
$tollC = toll\ per\ vkm$
$taxC = tax\ per\ vkm$
$bC = refueling\ costs\ per\ vkm$
$i = index\ for\ three\ different\ kinds\ of\ traffic$
$j = index\ for\ ten\ different\ technologies$

In the first step of the simulation, the focus is on the costs which are influenced by the type of drive and fuel. First of all, investment costs differ significantly between hydrogen technologies, electric drives and conventional technologies. Today in the urban bus market, a fuel cell bus is twice as expensive as a diesel bus. (EBERWEIN ET AL. 2009) Another important factor is the maintenance costs. As the complexity of the fuel cell system is much higher than the complexity of conventional drives, the maintenance costs are higher. This table shows the different maintenance cost of the available alternatives in the bus market.

Table 2 – maintenance costs of the different alternatives (FALTENBACHER ET AL. 2007)

Maintenance costs [€/km]	Diesel	Diesel-hybrid	CNG	CNG hybrid	Fuel cell hybrid
Expenses for staff and material	0,49	0,59	0,55	0,66	0,73

Apart from these costs, the fuel expenditures have the biggest shares of the annual overall costs. Based on different kilometre readings of every traffic category the shares of the overall costs vary accordingly. BGL (2009) analyzed the overall costs of trucks in Germany. The results show that the fuel costs have a share of 41% in long distance traffic and 32% in heavy distribution traffic as well as 28% in the light distribution traffic.

The last costs component followed in the model are the refuelling costs. Refuelling costs are defined as the time needed for the refuelling process times the hourly wage. Especially in cases of hydrogen technologies the refuelling process takes three times longer than for conventional fuels.

There are also costs based on tax or toll. At the moment, these costs are not dependent on the used technology. In order to simulate different scenarios with political measurements, the model is able to include these costs and those for emissions.

All these costs taken together are considered as negative utility. The core of the model is the logit model handling all the different costs components, as illustrated in equation 6:

$$P_{i,j} = \frac{\exp(-\beta_{i,j} \cdot (\lambda_i \cdot C_{i,j} + \varepsilon_{i,j}))}{\sum_j \exp(-\beta_{i,j} \cdot (\lambda_i \cdot C_{i,j} + \varepsilon_{i,j}))} \qquad \text{(equ. 6)}$$

$where$
$P = share\ of\ new\ registrated\ trucks\ per\ technology$
$C = overal\ costs\ per\ vkm,$
$\lambda = factor\ Lambda$
$\beta = Logit\ factor\ Beta$
$\varepsilon = neagtive\ utility\ at\ launch$
$i = index\ for\ three\ different\ kinds\ of\ traffic$
$j = index\ for\ ten\ different\ technologies$

Finally, the results are the shares to which percentage a buyer of a new truck will choose which technology. Having for each technology the likelihood of choice leads to the composition of the truck stock used as a road traffic. The future aim is to forecast the emission of the truck sector based on the composition of the truck stock.

Besides the theory of utility based decisions, another economic theory is very important for understanding the model behaviour. As the most alternative technologies are not used on the market yet, it is very important to forecast the key data for each technology.

The diffusion of new products is going along with changes in the production process, which leads to lower prices. Only low prices are accelerating the diffusion. Lower prices are generally achieved by decreasing economies of scale. That means that a higher number of produced goods lowers the costs per unit. A foundation therefore is the learning process in companies. (GRUPP 1997) The original theory was applied in industrial assembly of airplanes (WRIGHT 1936). The main point of this theory is nothing else than an increasing production expenditure with higher numbers of produced units. WRIGHT (1936) assumed that the production costs would increase with a constant rate. Equation 7 shows the reciprocal power function.

$$y = \frac{a}{x^b} = a \cdot x^{-b} \qquad \text{(equ. 7)}$$

$where$
$y \ = average\ costs\ for\ producing\ the\ xth\ unit$
$a \ = costs\ for\ producing\ the\ first\ component$
$x \ = number\ of\ components\ produced$
$b \ = degression\ factor$

The idealistic analysis of WIRIGHT (1936) does not consider in detail the real progress during production of new products. The realistic development of the learning curve is related specifically to each production process.

It is important for the model that the key data of each technology investment and maintenance costs will change in the future. The costs will decrease due to the previously mentioned learning curve. As the costs change, so will the decision towards new technologies. Table 3 shows the development of the different costs:

Table 3 – different costs and their future development

Type of cost	development
Maintenance costs	Decreasing due to learning effects in maintenance
Fuel costs	Decreasing fuel consumption due to more efficiency of the drives, Increasing prices due to shortage of resources
Refuelling costs	Decreasing due to learning effects
Investment costs	Decreasing due to learning effects in the production process

The two main types of drive (electric drive/fuel cell and combustion engine) have very different curves of efficiency facing different levels of driving performance. Figure 2 shows that the efficiency of the fuel cell has a potential of being twice as high as the efficiency of the combustion engine in the case of driving inner city routes. Interestingly, the efficiency on long routes with constant speed is nearly the same.

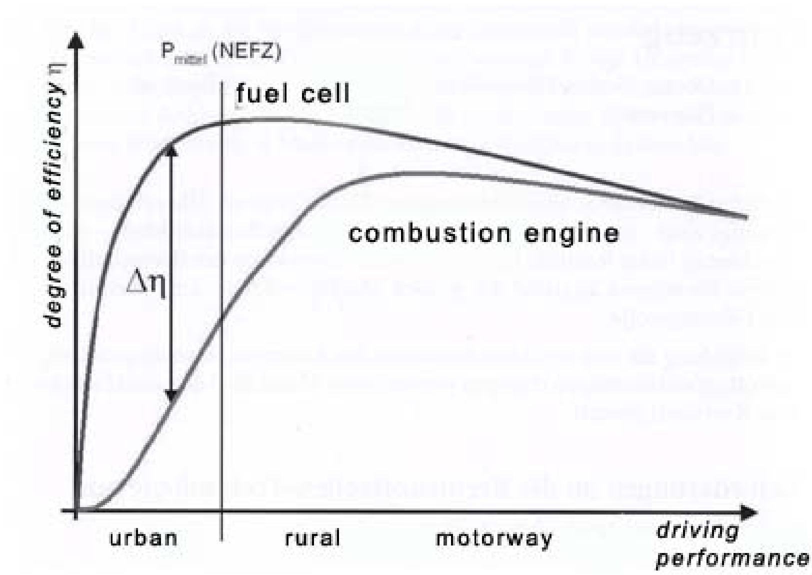

Figure 2 - Efficiency of combustion engine and fuel cell (DOCTER ET AL 2006)

Today's energy consumption of fuel cells and electric drives are significantly higher. This paper assumes that, based on the learning curve, the optimal efficiency shown in figure 2 will be reached around 2030. That leads to significantly lower investment costs, maintenance costs and fuel costs of both drives.

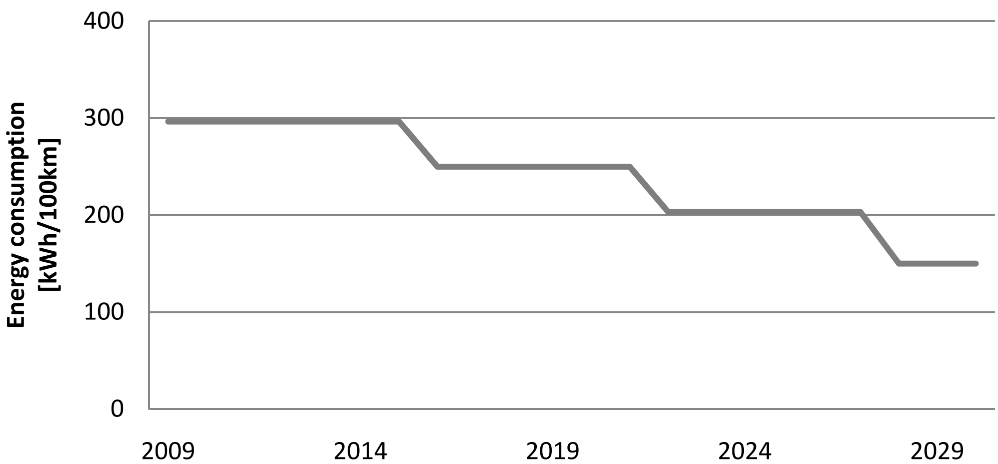

Figure 3 - Development of the energy consumption of fuel cells (lightDT)

Figure 3 shows the development of a fuel cell's energy consumption. The development is based on both, JERMER (2008) (today's values) and the learning curve theory (future forecast). The efficiency illustrated in figure 2 will be reached in 2030. The stepwise function is a result of the typical development cycles in the car industry which last around seven years.

Besides the costs, tank technology will also develop in the coming years. The learning curve will lead to lighter tank systems, which will make alternative technologies competitive. The market entrance of the new technologies is closely linked to the weight of the tank system. Hence, the model simulates a progression in tank technologies. Furthermore it provides new possible alternatives to the existing ones as soon as the percentage of the total weight falls below a certain value.

Taking all this together, the model consists of two main parts: the decision process of the freight forwarders driven by utility comparison, and simulation of the market introduction based on development in tank technologies. Consequently, you get for each time period a share for every available technology. The time horizon for the simulation is 2050. The next chapter shows the results of the simulation and comments on them.

The model calibration is based on the data found in literature. As the quality of this data is partly scarce, the calibration would be much better if more experiences with alternative drives in the truck sector were gained. Within the first introduction of alternative drives to the market in the coming years the forecast will improve.

3 ANALYSIS AND RESULTS

The common steps after creating a model are to check validity and expressiveness. The given model combines content from scientific approaches – like the *diffusion theory*, the *learning curve theory* and *utility based decision theory* – and self accomplished technological assessment. Due to a lack of market exposure of most alternatives, the parameters of the model have to be estimated.

This chapter presents selected deliverables which appear to be interesting. Different scenarios prove the effectiveness of political measurements differentiated between the traffic categories. The selection of the scenarios was based on the possibility of technical and political influence on the diffusion. Hence, the following scenarios have been considered:

- basic scenario (scenario 0):

  This scenario assumes that there are no political or technical changes besides the development already known in the current state of the art technology.

- CO_2-based tax (scenario 1):

  Scenario 1 simulates a political measurement to support the diffusion of alternative drives and fuels. In order to reduce the emission of carbon dioxide a CO_2-based tax is introduced on the basis of the already existing one in the car sector. As the tax is, in general, a small part of the overall costs of a truck, in this scenario a value based on the amount of emitted grams is added to the tax already paid today.

- CO_2based tax with high CO_2 price (scenario 2):

  To provoke extreme results the price of CO_2 from scenario 1 is doubled. The reason therefore is the variation between CO_2 prices estimated by different institutes.

- CO_2-based toll (scenario 3):

  The second possibility to influence the diffusion of alternative drives and fuels is the installation of a CO_2-based toll. The base for the research was the German toll system. The idea of this toll is not to punish high emission vehicles as in scenario 1 and 2, but to reward low emission vehicles by a lowered toll. For non-emitting technologies like fuel cell and electric drive a maximal reduction to 10 cents/km is possible.

- Progress in tank technology (scenario 4)

  As the progress of the tank technology is the limiting factor for the diffusion, this scenario assumes high technical progress and hence an earlier point in time of the market entry for each alternative.

All the announced scenarios are now simulated for every traffic category (long distance traffic, heavy distribution traffic and light distribution traffic).

3.1 The simulating results for long distance traffic

The long distance traffic is pressed by long motorway cycles with constant speed. Hybrid drives will therefore not be offered. The high kilometre reading requires a high capacity of the tank system. Based on this knowledge, a long term dominance of the combustion engine is expected. The strongest influence on the decision are fuel costs.

Not every alternative will be offered for this traffic category. The CNG-drive fails because of the high tank weight, which reduces the payload too much. The same is true of the electric drive. Besides diesel and biodiesel, only hydrogen technology (fuel cell and combustion) will be offered. With the part of the model simulating the time of the market entrance, the fuel cell will be introduced in 2019 and the combustion engine in 2024. Figure 3 shows the development of the share of new registrations in the basic scenario.

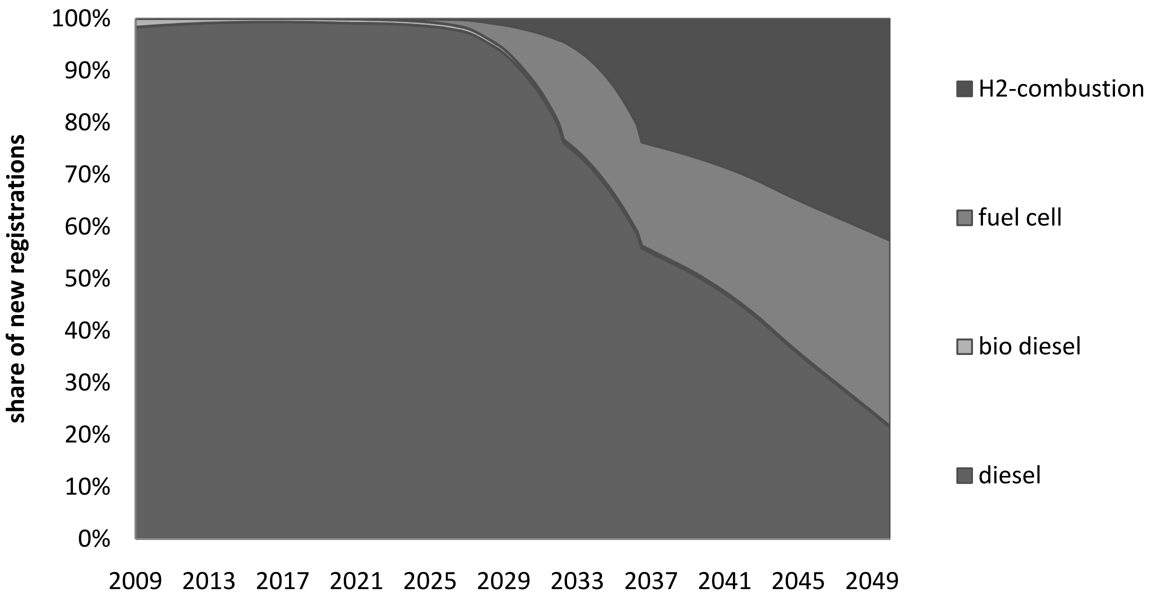

Figure 3 - share of new registrations LDT (scenario 0)

The low share of biodiesel is remarkable. Biodiesel will not play an important role. Although the H_2 combustion engine enters the market later than the fuel cell, its share tops the one of the fuel cell within ten years. After the year 2044 the alternative drives are dominating the market of new registrations. The higher share of the H_2 combustion engine can be explained by the same fuel consumption as with the fuel cell combined with lower maintenance and investment costs.

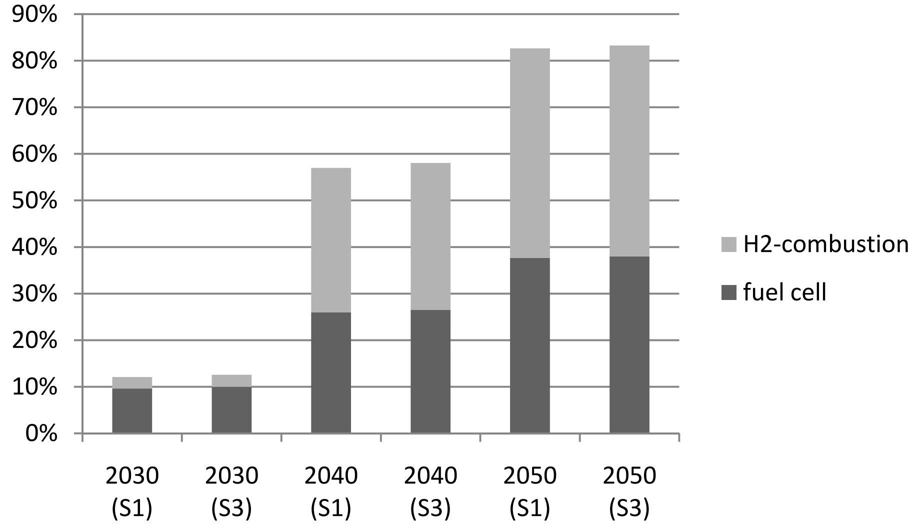

Figure 4 - share of new registrations LDT (scenario 1+3)

Figure 4 shows the results of the simulation of scenario 1 (S1) and scenario 3 (S3). The interesting output is that the effects of a CO_2 based tax and of a CO_2 based toll have nearly the same influence on the diffusion of the alternatives. Therefore, the state can decide which measurement is easier to implement with less transaction costs.

3.2 The simulating results for heavy distribution traffic

The fact that the purposes of driving as well as the structure of the costs are very different to those of the long distance traffic, makes an assessment even harder. Since the range of the trucks is lower, the alternatives are entering the market earlier. The high weight of the battery leads to big disadvantages for the electric drive. The model shows that hybrid and CNG technologies will be available by 2011, the hydrogen technologies by 2014. A difference between H_2 combustion and fuel cell is not certifiable.

Figure 5 shows how the shares of the new technologies develop. It is remarkable that the hybrid technologies are not able to reach the same level as the technologies without hybrid. The lower fuel consumption is not able to equalise the higher costs in maintenance and investment.

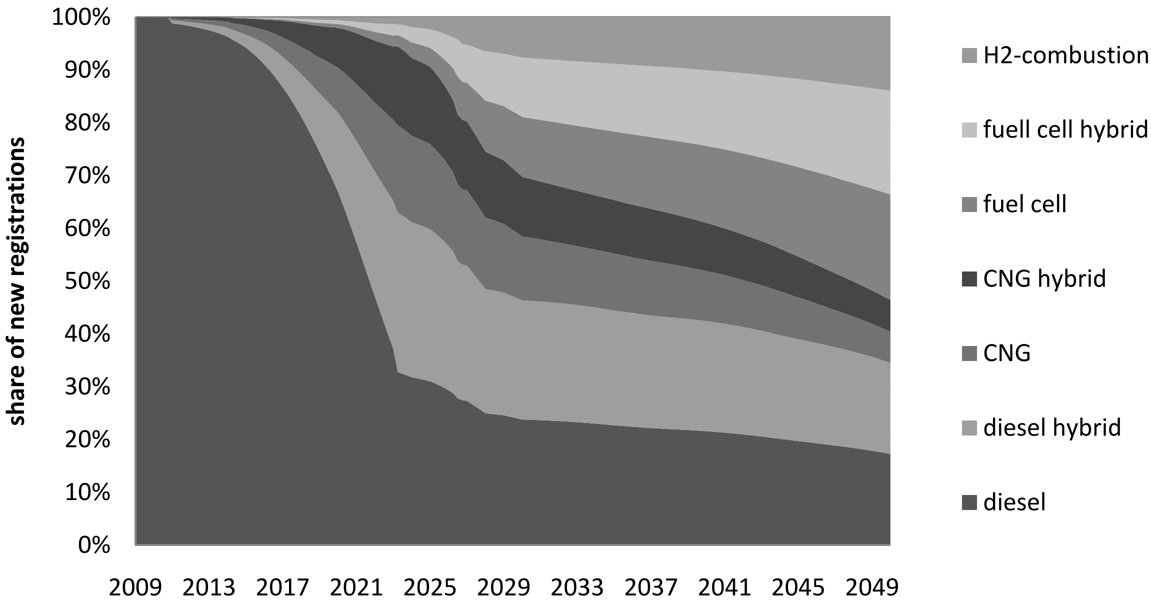

Figure 5 - share of new registrations heavyDT (scenario 0)

Biodiesel, as already seen in the long distance traffic, is playing a secondary role. CNG technology will be filling the gap between the high costs of the hydrogen technologies very soon. As the efficiency of the fuel cell is higher, the share is becoming increasingly steep compared to that of the hydrogen combustion engine. The dominating technology until 2048 will be diesel technology (diesel + diesel hybrid) due to low investment and maintenance costs.

Comparing the impact of CO_2 based tax on a high level (scenario 2) with the basic scenario shows that the influence is high, especially for the non-emitting technologies (hydrogen) which become increasingly strong. With a high CO_2 price the fuel cell is reaching a share of 25% percent of all new registration in 2037. Together with the combustion engine the hydrogen technologies have a share of more than 40%. This fact shows how an increasing CO_2 price could influence the diffusion in the case of an emission based tax policy.

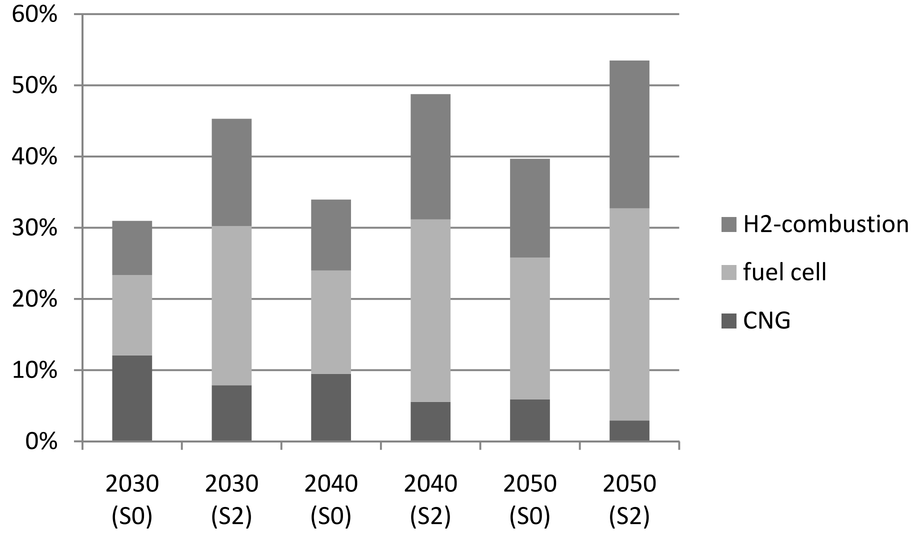

Figure 6: share of new registrations heavyDT (scenario 0+2)

The results of simulating scenario 3 are little lower shares of alternative technologies. This can be explained by less kilometre aging which means higher share of taxes in the overall costs and less toll costs a year.

Interestingly in scenario 4 (strong progress in tank technology), the electric drive is entering the market around 2045. As the market launch is late, it is hard to assume the potential of an electric drive for the heavy distribution traffic. The interesting question is if the electric drive will enforce change against the so far dominating hydrogen technology.

3.3 The simulating results for light distribution traffic

The light distribution traffic is affected by a high share of inner city drives with continuous starts and stops. Hybrid technologies can realize the most fuel savings of all traffic categories. The reduced kilometre reading lowers the influence of the fuel costs on the overall costs. Hence, the fixed expenses (investment costs and taxes) have a higher influence. The model assumes that no toll is paid. The reason therefore is that most vehicles are operated on toll free streets and in Germany trucks with an overall weight of less than 10 tonnes are not forced to pay the toll.

Figure 7 shows the results simulating the basic scenario. Caused by a lower range and hence lower dimensioned tanks, new technologies are entering the market earlier. The main findings of this simulation are the early market entrance of the electric drive and the following leadership in new registrations. Likewise, the hybrid technologies are able to produce higher savings caused by less fuel consumption than the extra costs in maintenance and investment.

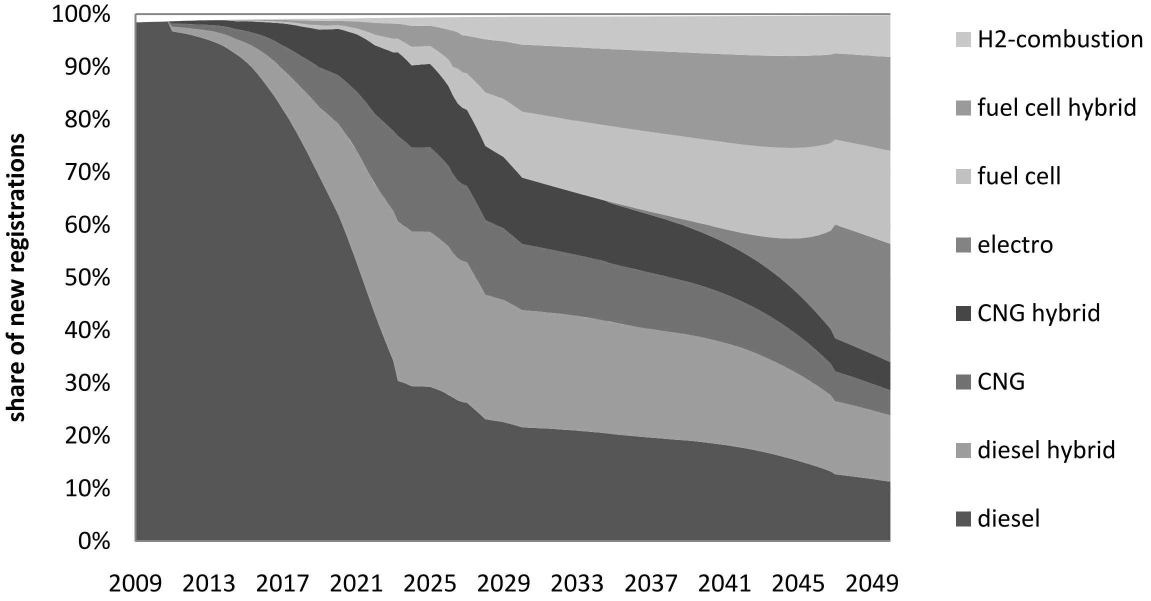

Figure 7 - share of new registrations lightDT (scenario 0)

Even in the basic scenario, the electric drive is able to realize a share of over 20% of all new registrations in 2045, thus it appears that it is the most popular technology. Together with the fuel cell the alternative drives are reaching nearly 50% in 2050. As in heavy distribution traffic CNG is only playing a temporary role until the market entrance of electric drive and hydrogen technologies have competitive costs. Caused by less efficiency in urban areas the distance between the hydrogen combustion engine and the fuel cell is the biggest one of the three traffic categories.

The results of scenario 1 and 2 are that, due to the high share of the fixed expenses of the overall costs, a policy towards emission based tax has a high influence on the diffusion. The alternative technologies are dominating the market earlier. For instance, in the case of a high CO_2 price, fuel cell and hydrogen combustion engine have a share of about 50% until 2030. The interesting fact is that hydrogen technology seems to be only a temporary solution for the light distribution traffic. The reasons therefore are the advantages in maintenance and investment costs of the electric drive. Scenario 3 was not considered as no toll paying is assumed.

Scenario 4 shows very interesting results. As soon as a fast progression in tank technology is assumed the electric drive dominates earlier. The market launch will be around 2029. The consequence is that the hydrogen technologies are not gaining much share in the new registrations due to their temporary success. Figure 8 illustrates the development of each technology. It is remarkable that there is a rise of the fuel cell from 2045 on after its decline during the second half of the 2030s.

As a matter of fact the light distribution traffic seems to be the traffic category with the most opportunities for alternative technologies whose development is highly influenced by tax policy.

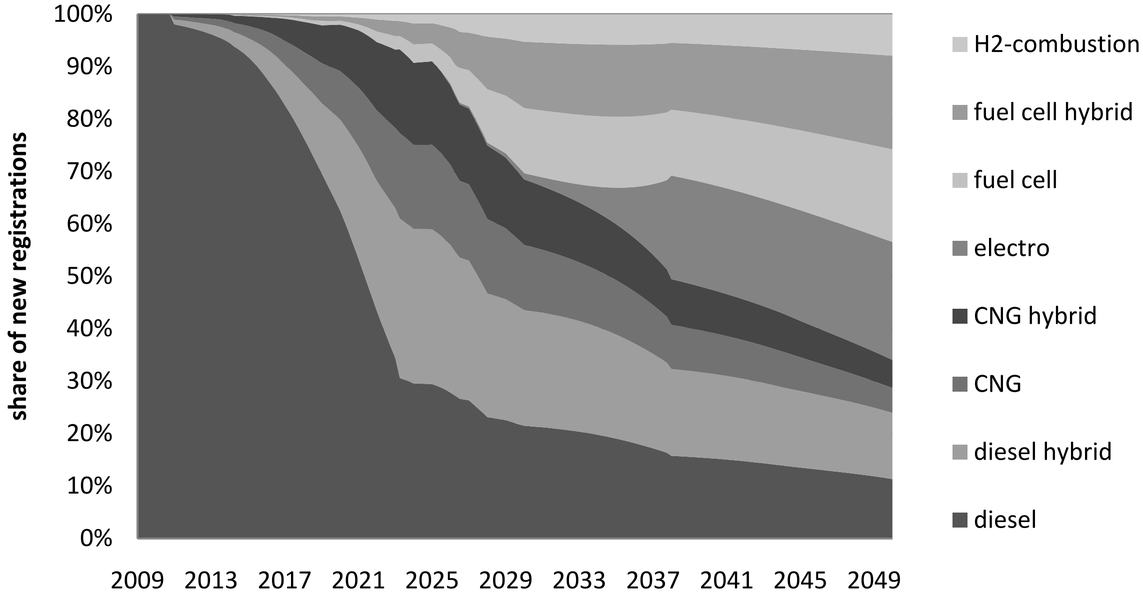

Figure 8 - share of new registrations lightDT (scenario 4)

4 CONCLUSION

The main objective of this paper was the system based analysis of the diffusion of alternative drives and fuels on the truck market. The theoretical basis therefore was the *diffusion theory* on a macro level as well as *utility based decision theory* on the micro level. To assess the development within the production of the trucks, the theory of the learning curves gave the main input.

The simulation and analysis were based on a model using the system dynamics software VENSIM as a foundation. The future aim is the integration of that model in the ASTRA model and the extension towards feedback loops. The main advantages in using system dynamics are the dynamic and mostly unlimited possibilities to model coherencies not relying on equilibrium processes like the most economic models.

As the truck is an investment for the carrier used for service production, the decision to buy a new truck is driven by economic aspects. In order to forecast the diffusion of each alternative technology, it is very important to assess the costs and efficiency of each alternative. Fuel, maintenance and investment costs are the main incentives. A single consideration of each traffic category is compulsory because of differences between light and heavy distribution traffic as well as long distance traffic.

The choice of new alternative drives or fuels at every single registration is based on cost comparison. The higher the difference, the more distinctive will be the decision towards one alternative. This utility based decision process with likelihood of deviation is realized in the best way by using the logit model, already known from traffic decision models.

With lots of alternative drives being in development at the moment, the market entry has to be estimated. Based on the technique foundation the development of the tank system seemed to be an adequate indicator for marketability. Falling short of a certain percentage of the gross load weight of a truck, a technology is competitive and hence will therefore enter the market.

In order to assess the outcome of political measurements and technical progress besides the basic scenario, four others scenarios were considered. All of them have been simulated for each traffic category.

Within long distance traffic, the combustion engine will play a dominant role caused by identical degrees of efficiency of fuel cell, electric drive and the classic combustion engine. The high share of fuel costs in the overall costs and the high demanded range of vehicles lead to the fact that only hydrogen technologies can face this challenge. This share can be positively influenced by emission based toll and taxes. The result of each measurement is nearly the same.

It is hard to assess the development in the sector of the heavy distribution traffic. The conventional drives will dominate over a long period of time. The hybrid version is not able to beat economically the conventional drives. CNG can be considered as a bridge technology. Provided that the electric drive will not enter the market, fuel cells will dominate the market on the long term. Supporting alternative drives, the CO_2 -based tax seems to be more effective than the differentiated toll calculation.

Affected by many trips in urban areas, the light distribution traffic is highly rewarding for electric drives. In turn, the CNG drive will capture the place of a bridge technology until the electric drive is introduced. In this traffic category, the hybrid technology reaches a fuel saving high enough to beat the conventional drives. The hydrogen technology presented by fuel cells seems to be at first view also a bridge technology. In the long term (after 2050), the achievement of similar high shares as the electric drive appears to be possible. The impact of tax policy is significantly higher than those for the other traffic categories.

Taken all together, hydrogen is a future technology for long distance traffic on highways and in regional traffic. The role of CNG, as well as other drives based on limited resources, is likely to be replaced by alternative drives. The light distribution traffic is predestined for electric drives. Hybrid technologies will only be found in urban traffic where they make economical sense.

The results of the simulation show that it is compulsory to differentiate between long distance traffic and distribution traffic. The highest potential for alternative drives can be found in the light distribution traffic highly influenced by tax policies. Hence, emissions can be reduced by the right policy. In the long distance traffic and heavy distribution traffic, tax policy as well as emission based toll are only able to induce small changes. The limited factor is the technological progress, only able to produce competitive solutions on the long term prospective.

Electric and hydrogen solutions benefit from all the political measurements caused by zero emission at the vehicle. Always keeping the production process in mind, a sustainable environmental policy should include every kind of emission. The relation between energy policy and traffic policy is going to be more important in the future.

Finally, the question should be how far the prognosis will change due to developments in technical basic conditions. Even in the last century extensive break-throughs have taken place in several technical fields. Reference is given to the fact that the state is able to influence and support alternative solutions in a certain frame. After all, the success depends strongly on technological progress.

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