THE POTENTIAL OF ALTERNATIVE FUEL TECHNOLOGIES AND OF EFFICIENCY TECHNOLOGIES FOR HEAVY GOODS VEHICLES

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Abstract

One of the main challenges of the freight transport sector is the reduction of GHG emissions. Conventional drives are already very efficient but different studies confirm that there is still a significant potential for improving fuel efficiency of ICE in trucks. On the other hand, the progress in research and development of alternative fuel technologies is visible. Trucks with CNG drive or electric drive are already on the roads in Europe for last mile delivery. The paper presents an approach to estimate the future potential of alternative fuel technologies for three different types of road freight transport. Additionally, it highlights the potential of ICE trucks for reducing GHG emissions and the cost development of the technologies by applying learning curves.

Keywords: System Dynamics, diffusion theory, learning curves, fuel efficiency, CNG, hydrogen, fuel cell

1. Introduction

Today, road transport is the major source for GHG emissions from transportation in Europe. According to the EC (2011) freight and passenger road transport were responsible for 93.5% of all transport-related domestic EU27 GHG emissions in 2008. About one third can be allocated to road freight transport. The European Parliament already set CO_2 emission performance standards for passenger cars (regulation (EC) No 443/2009) and light goods vehicles (regulation (EC) No 510/2011) in order to meet the GHG reduction targets until 2020 and the long-term targets to remain on the 2-degree pathway according to the IPCC. The probability that the European Commission is also setting a regulation for new registered heavy goods vehicles (HGV) is high. Since the first announcement of the regulation for passenger cars in 2008, the European car manufacturers managed to decrease the average CO_2 emissions per vehicle-km for new cars yearly by about 4.5 % (EEA 2010). Hence, setting emission performance standards for cars and light goods vehicle (LGV) turned out to be an effective policy for reducing CO_2 emissions. Besides setting CO_2 emission limits for new registered heavy goods vehicles various other measures and instruments exist which have the potential to reduce the energy and carbon footprint of road freight transport in Europe. Such measures are: inclusion of road freight transport into an international, non-sector specific emission trading scheme, market incentives like CO_2- based taxation, implementing intelligent traffic management systems (ITS), improving logistics management or educating drivers remains another alternative.

Technologies to improve fuel efficiency are at least to a certain degree already implemented in most recent heavy goods vehicles but several studies show that the maximum potential of fuel efficiency technologies is even higher (Akkermans et al., 2010). The remaining technical solution is the utilisation of alternative fuels and drives in heavy goods vehicles (HGV). These new technologies have to be introduced to a market which is highly dominated by the economic pressure of the carrier. Considering an already high share of fuel costs on total operation costs for carriers and increasing diesel fuel prices, there is a chance that alternative fuels and drives or fuel efficiency technologies can diffuse into the EU truck market.

The aim of this paper will be on the one hand to describe the developed approach for simulating the diffusion of alternative fuels and drives within the German truck market. The framework is given by the German truck market divided into three different truck categories: Light distribution traffic (lightDT), Heavy distribution traffic (heavyDT) and Long distance traffic (LDT) with a time horizon of 2050. On the other hand, the paper shows the potential of fuel efficiency technologies for ICE in heavy goods vehicles considering additional costs for implementing these technologies and economies of scale.

2. Methodology - diffusion of alternative technologies

The first step of the approach comprises a comprehensive literature research combined with expert interviews to get an overview of the possible technical development of alternative drives as well as of potential fuel efficiency technologies and measures. As the purchase of a new truck means 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.

Using system dynamics as a methodology for modelling allows the simulation of feedback loops which is for many systems the main driver of its dynamics. An important feedback in the diffusion model is the link between costs of trucks with alternative drive and the number of new registered trucks with this drive influencing again the manufacturing costs via economies of scale or the different types of learning (e.g. learning by researching, etc.). Another feedback consists in the life-cycle of a truck which is scrapped after some years and, if necessary, replaced by a new truck. Within this system dynamics environment, different scientific approaches are used such as discrete choice theory and the theory of learning curves. Behavioural reactions in the discrete choice functions are validated by the knowledge gained from expert interviews with carriers. Finally, a variation of scenarios proves the effectiveness of political measurements differentiated between the traffic categories. The selection of the scenarios is based on the possibility of technical and political influence on the diffusion. 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. 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 (equation 1).

$$u = v(x) + \varepsilon \qquad \textbf{(1)}$$

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

$$\begin{aligned} &where \\ &x_1 \ldots x_n = attribute \\ &\beta_1 \ldots \beta_n = utility\ coefficient \\ &\propto \quad = level\ parameter \\ &\varepsilon \quad = confounding\ factor \end{aligned}$$

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 against 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.
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:

$$P(i) = \frac{e^{v_i}}{\sum_{j=1}^{n} e^{v_j}} \qquad \textbf{(43)}$$

$$\begin{aligned} &where \\ &v_1 \ldots v_n \ : \ utility\ function\ of\ alternatives\ 1 - n \end{aligned}$$

This is known as the Logit-model mainly used for simulating modal choice based on costs and time needed for different destinations in traffic networks. For modelling the diffusion of trucks the overall costs need to be estimated in the following way:

$$C_{i,j} = aC_{i,j} + wC_{i,j} + kC_{i,j} + bC_{i,j}\ (+tollC_{i,j} + taxC_{i,j}) \quad \textbf{(4)}$$

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

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, current 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 cost factor is maintenance. As the complexity of fuel cell systems is higher than for conventional drives maintenance costs are higher. Table 1 shows the different maintenance cost of the available alternatives in the bus market.

Table 1 – 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

Today, fuel costs constitute the largest share on total annual costs. Based on different kilometer readings of every traffic category the shares of the overall costs vary accordingly. BGL (2009) analyzed the overall costs for trucks in Germany. Fuel costs have a share of 41% in long distance traffic, 32% in heavy distribution traffic and 28% in light distribution traffic. Finally, the model considers also refueling costs. Refueling costs are defined as the time required for the refueling process times the average hourly wage. Especially in the case of hydrogen, refueling takes three times longer than for conventional fuels. Further costs could be costs for taxes or road charges. At the moment, road charges and taxes are independent from the technology. In order to simulate different scenarios with political measurements, the model is able to include these costs and those for emissions. The sum of all costs is considered as a negative utility. The core of the model is the logit model handling all the different costs components, as illustrated in equation 5.

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.

$$P_{i,j} = \frac{\exp(-\beta_{i,j} \cdot (\lambda_i \cdot C_{i,j} + \varepsilon_{i,j}))}{\sum_j \exp(-\beta_{i,j} \cdot (\lambda_i \cdot C_{i,j} + \varepsilon_{i,j}))} \quad \textbf{(5)}$$

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

Besides the theory of utility based decisions, another economic theory is important for understanding the model behavior. 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. In a market which is focused on costs, cost advantages accelerate the diffusion. Decreasing economies of scale in the production processes lead to lower costs. A foundation therefore is the learning process in companies (Grupp, 1997). The original theory was applied in industrial assembly of airplanes (Wright 1936). He assumed that the production costs would increase with a constant rate. Equation 6 shows the reciprocal power function.

$$y = \frac{a}{x^b} = a \cdot x^{-b} \quad \textbf{(6)}$$

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 Wright (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 2 shows the development of the different costs:

Table 2 – 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
Refueling 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 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.

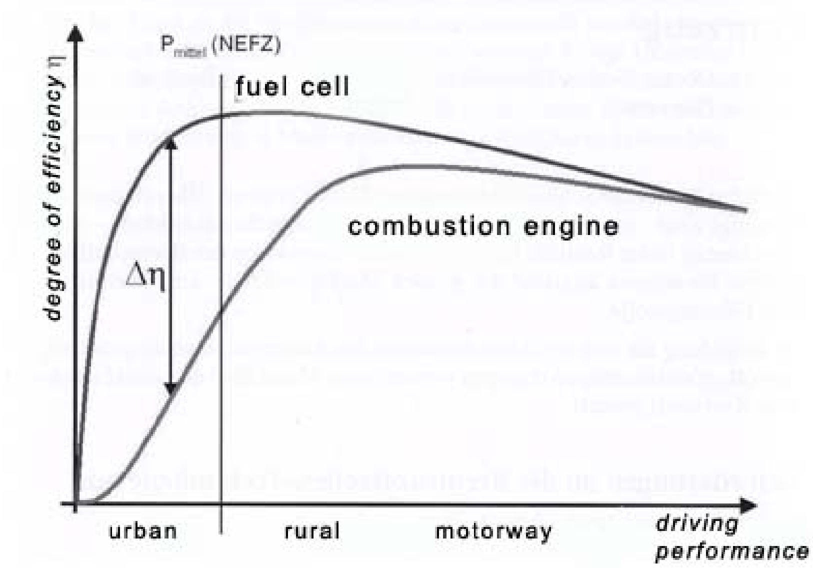


Figure 1 - Efficiency of combustion engine and fuel cell (Docter et al. 2006)

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 1 will be reached around 2030. That leads to significantly lower investment costs, maintenance costs and fuel costs of both drives.

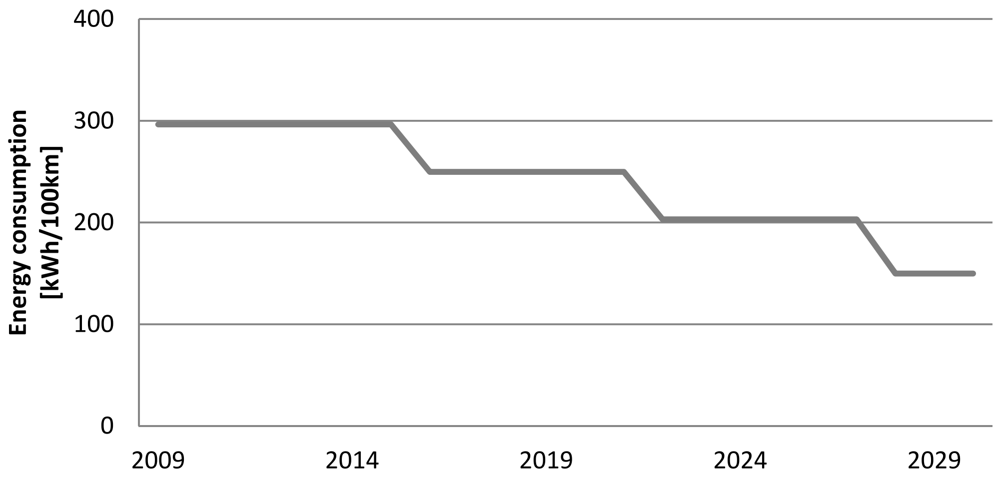


Figure 2 – Developmemt of energy consumption of fuel cells (lightDT)

Figure 2 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 1 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 is supposed to develop as well in the coming years. Lighter tank systems with higher capacity will make alternative technologies competitive. The market entrance of the new technologies in the truck market 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.

3. The potential of efficiency technologies for ICE trucks

In the context of the FP7 research project GHG-TransPoRD (Akkermans et al., 2010) a comprehensive literature research has been conducted to evaluate the potential for reducing GHG emissions respectively improving fuel efficiency of ICE trucks. About 20 different technical solutions could be identified. The main references were TIAX (2009), Ricardo (2009) and Roland Berger (2010). The fuel efficiency potential cited in these studies was adapted for two different types of trucks: semitrailer trucks representing the traffic on long distance relations and last mile delivery trucks representing urban road freight transport. Reduction potentials are based on average trucks registered in 2010. Additionally, additional costs for implementing trucks with the technologies and a realistic point of time for the first market entry of the technology were collected. Based on this long list, the single technologies were assigned to eight technology clusters (see table 3).
In order to estimate the fuel efficiency potential of a set of measures belonging to a cluster, the reduction potentials were multiplied and not added. Furthermore, cannibalism effects between technologies or even incompatibilities needed to be considered. Interviews with experts and stakeholder workshops were used to close gaps in the literature in this context. An example for cannibalism effects is the implementation of measures to improve aerodynamics in combination with vehicle platooning (assigned to intelligent vehicle technologies).

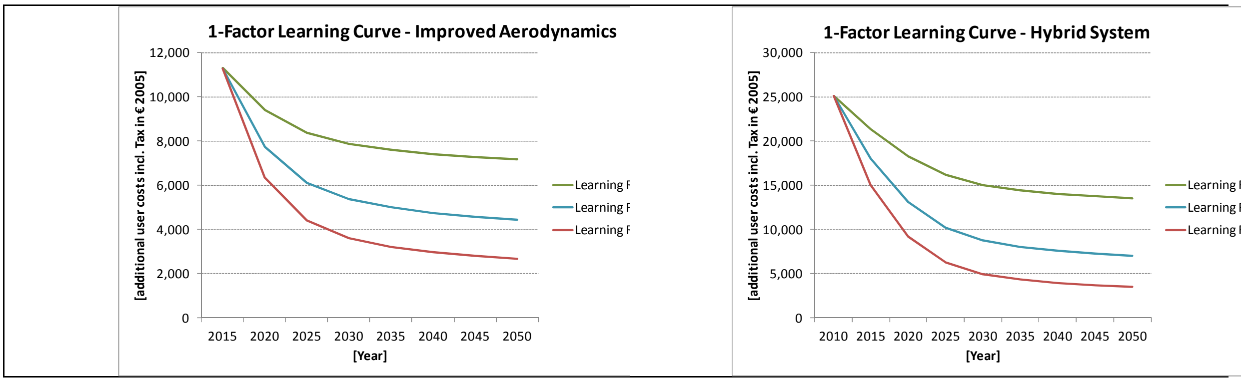
Table 3 – Potentials of GHG reduction technologies and their costs for trucks

Technology Cluster	Urban Potential	Long-Haul Potential	Add.Cost (€$_{2005}$)
Improved Aerodynamics	8.1%	19.4%	11,292 €
Resistance	19.6%	19.6%	11,447 €
Hybrid Vehicles	20.0%	7.0%	25,107 €
Intelligent Vehicle Technologies	5.9%	31.6%	2,389 €
Transmission and Driveline	9.4%	9.4%	1,790 €
Lightweight construction	11.0%	11.0%	23,668 €
Diesel Engine	12.3%	12.3%	16,328 €
Heat and Cooling Management	6.0%	6.0%	21,664 €

Source: GHG-TransPoRD (Fraunhofer-ISI)

Table 3 shows the results for all eight technology clusters. Cannibalism impacts between technologies in different clusters are not included in this calculation. They are considered in a second step. *Improved Aerodynamics* consists of three technologies: teardrop trailers, aerodynamic fairings and spray reduction mud flaps. The first of these three is under current

legislation in Europe not allowed but the European Commission is currently discussing about solutions to overcome this problem.
The cluster *Resistance* covers five technologies: low rolling resistance tires, automatic tire pressure adjustment, tire/wheel alignment, single wide tires and rear axle types. Predictive cruise control, vehicle platooning and route optimization are included in the cluster *Intelligent Vehicle Technologies*. Dual-stage turbocharging with intercooling, electric turbocompound, variable valve actuation and engine friction reduction are the components in the cluster *Diesel Engine*. Automated manual transmission and low friction lubricants were considered in the cluster *Transmission and Driveline*. Akkermans et al. (2010) describes in detail the composition of each technology cluster.
As table 3 highlights the implementation of the whole set of technologies can be considered as a costly investment. The displayed costs reflect costs at first market entry. Hence, declining costs due to economies of scale and learning can be expected. The application of a one-factor learning curve with low learning rates (5%) seems to be a moderate estimation. In the light of high and still increasing raw material prices e.g. for steal, copper or aluminum a cautious estimation of learning rates for those technologies is supposed to be realistic. In this case in a scenario in which all new registered trucks will be equipped with the available set of technologies a reduction of additional costs from 113 k€ per truck to 74 k€ until 2030 is expected. Figure 3 presents possible cost developments for the cluster *Improved Aerodynamics* and *Hybrid System* based on learning curves and an assumed s-shaped diffusion curve considering worldwide sales of the technologies.



Source: GHG-TransPoRD (Fraunhofer-ISI)

Figure 3 – Declining costs for fuel efficiency technologies based on learning curves

Accounting all information about incompatibilities or cannibalism between single technologies, this leads to an overall potential of 60% to 65% until 2025 compared with a reference truck of the year 2010. This represents a fictive mixture between a long-haul and a heavy distribution traffic truck. Under these conditions the investment costs amortize during the average lifetime of a truck due to significant fuel cost savings.

4. The potential of alternative fuel drives

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 simulation results a baseline scenario. This scenario assumes that there are no political or technical changes besides the development already known in the current state of the art technology. The baseline scenario results distinguish between each traffic category (long distance, heavy distribution and light distribution traffic).

Long distance traffic is characterized by long motorway cycles with constant speed. Hybrid drives will therefore not be offered. Long daily distances require a high tank capacity. Thus, a long term dominance of the ICE is expected. Decisions are mainly influenced by fuel costs.

Not every alternative will be offered for this category. The CNG-drive fails because of high tank weight, which reduces the payload too much. The same holds for 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 hydrogen combustion engine in 2024. Figure 4 shows the development of the share of new registrations in the basic scenario.

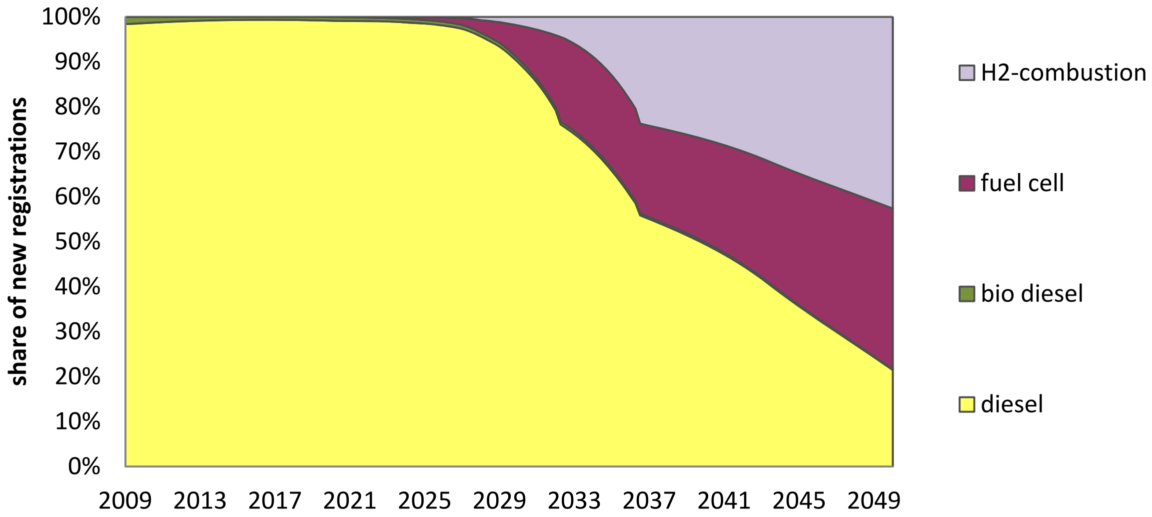


Figure 4 - Share of new registrations LDT

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 2045 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.

The purposes of driving as well as the structure of the costs are very different in the heavy distribution market compared to those of the long distance market. This makes an assessment even more difficult. Since the range of alternatives for trucks is smaller, 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.

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.

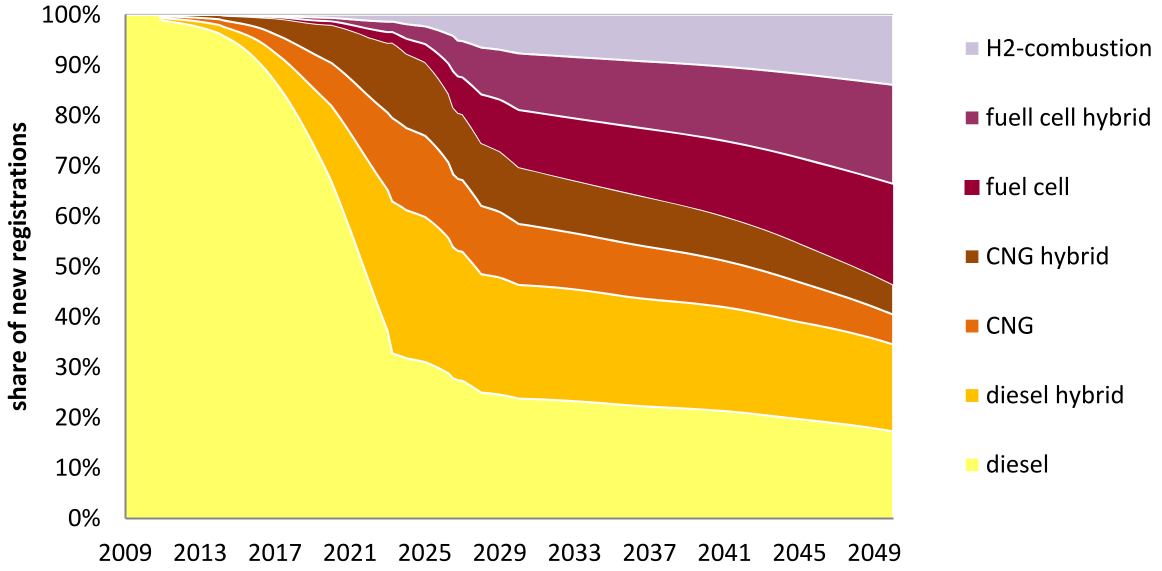


Figure 5 - Share of new registrations heavyDT

Light distribution traffic is affected by a high share of inner city drives with continuous starts and stops. Hybrid technologies can achieve most fuel savings of all traffic categories. The lower daily kilometers decrease the influence of fuel costs on overall costs. Hence, 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 roads and in Germany trucks with an overall weight of less than 10 tonnes are not forced to pay tolls.

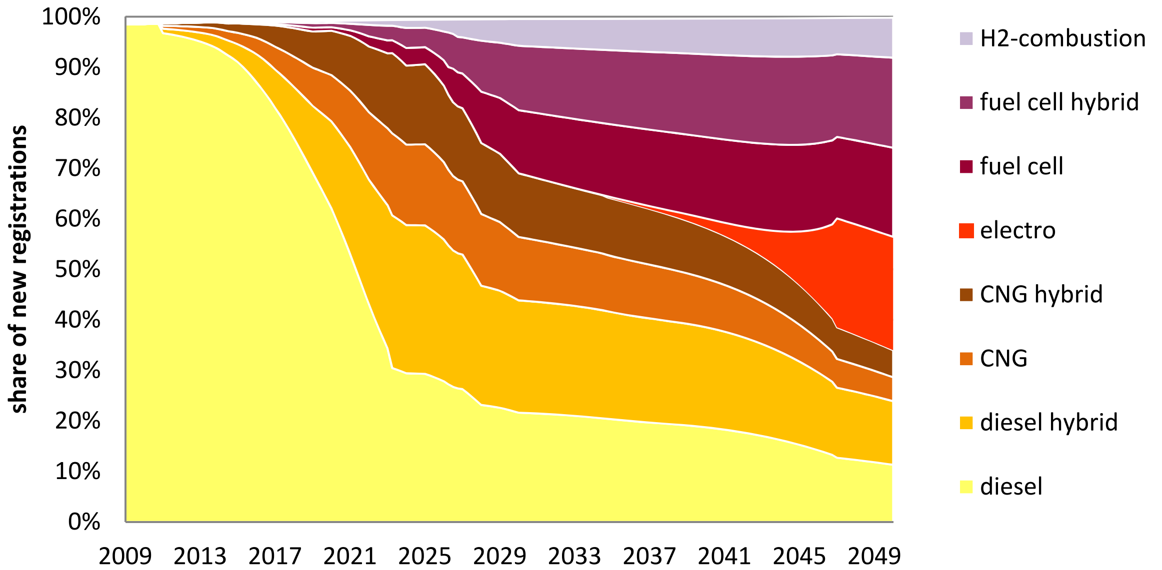


Figure 6 - Share of new registrations lightDT

Figure 6 presents results for light distribution traffic. 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.

The electric drive is able to achieve 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. As a matter of fact the light distribution traffic seems to be the category with the most opportunities for alternative technologies.

5. Conclusion

The main objective of this paper is a system based analysis of the diffusion of alternative drives and fuels on the truck market in parallel to a techno-economic analysis of fuel efficiency potentials of conventional ICE trucks. The theoretical basis therefore is 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 gives the main input. Within long distance traffic, the combustion engine will remain the dominant role caused by identical degrees of efficiency of fuel cell, electric drive and the classic combustion engine. A comprehensive literature research proved that the fuel efficiency potential of ICE trucks is by 60% up to 65% still very high. High additional costs arise which could decline over time assuming an accelerated diffusion of these technologies. The alternative for long haul transport is hydrogen technology. The high share of fuel costs in the overall costs and the high demanded range of vehicles make hydrogen technology competitive. This share can be positively influenced by emission based toll and taxes. The result of each measurement is nearly the same.

An assessment of the development in the sector of heavy distribution traffic is difficult. The conventional drives are assumed to dominate at least until 2030. The hybrid technology is not able to compete with 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 an effective incentive. 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 sight also a bridge technology. In the long term (after 2050), the achievement of similar high shares as the electric drive appears to be possible. In summary, hydrogen can be considered as a promising future technology for long distance traffic on highways as well as for 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.

Finally, the question remains how far the projections will change due to developments in technology. The development of storage technologies will play a key role. Even in the last century extensive breakthroughs have taken place in several technical fields. Reference is given to the fact that governments are able to influence and support alternative solutions to a certain degree.

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