Science, Technology & Innovation Studies
Vol. 10, No. 2, December 2014

ISSN: 1861-3675

STI Studies

www.sti-studies.de

Entrepreneurial Market Shaping in the Face of Path Dependency:

The Success Story of Diesel Cars in Germany

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Abstract

This paper explores the switch from a dominant design despite its self-reinforcement effects. A mixed design study of the German car market history reveals that the dominance of Otto cars can be regarded as path dependence with self-reinforcement. The introduction of Diesel cars can be described as path creation due to multi-faceted agency. Changing for example the Diesel technology and taxation measures a momentum was created. This resulted in a decrease of the transaction costs and redirected old reinforcement effects in favour of the Diesel cars. Therefore, it is concluded, that future market introductions have to target the driving mechanisms behind the dominant design.

1 Introduction

The 'Limits to Growth' by the Club of Rome (Meadows et al. 1972) as well as the subsequent oil crises in 1973 and 1979 made the public aware of the fact that petroleum based fuel is a limited resource. Therefore a reduction in its consumption was seen as desirable through, for example, more fuel efficient automobiles. Currently, and despite several technological progresses, this aspiration has not lost its relevance. It is further intensified by the climate change debate (UNFCCC 1997) leading to the central challenge of reducing CO2 emissions per car. Possible ways to reach these goals include the advancement of existing engine technologies or the introduction of new ones like hybrid and fuel cell cars. Focusing on the introduction of new designs, the greatest challenge seems not to be their initial technological development but overcoming the current dominant design (Utterback 1994) of the Otto engine.

Although there are already comprehensive studies on the dynamics of the introduction of new passenger car technologies (Christidis et al. 2003), the outcome of the process seems hardly foreseeable. However, what can be investigated in the context of innovation processes are the driving forces behind the strength of the dominant design as well as how innovative designs are pushed into the market. This does not necessarily mean that introduced technologies automatically gain a large market share, but it is possible. Hence the central questions are: 1) Which mechanisms drive the maintenance of the status quo in the car market, possibly hindering the introduction of passenger cars with more fuel efficient engine technologies? 2) How can these mechanisms be influenced?

For the analysis of the mechanisms and agency in these diffusion processes, three theoretical approaches are combined: Firstly, the concept of path dependency explains the drive towards a stable dominant design by increasing returns (Arthur 1988, Beyer 2005). Secondly, path creation focuses on how such path dependent processes can be influenced by agency (Garud/Karnøe 2001, 2003). Finally, the S-curve-approach and its idea of technological switches from one curve to another (Sahal 1981, Christensen 1992a, b) is used as a link between these two sides of the 'path-coin'.

Using these analytical concepts the goal is to draw lessons from the history of comparable cases. For this purpose a case in the context of passenger cars is needed where an existing dominant technological design is (at least partly) substituted by a more efficient technology. It is easy to figure out that the dominant design in passenger car technologies has been the Otto engine (Otto cars) for decades now – at least in the US and central Europe in regard to sales statistics. In contrast, liquefied gas, electrical, or diesel engines challenged the Otto cars for years now. Interestingly the success story of Diesel in Germany (Jürgens/Meißner 2005), which is one of the biggest Diesel markets in Europe (Jacob et al. 2005), seems the proper case. While the Diesel engine technology for passenger cars (Diesel cars) has been successfully introduced in Germany, it does not play a major role in the US market. Accordingly, it can be analyzed which mechanisms drive the dominant design of Otto cars and how the agents in Germany were able to establish Diesel cars as a challenging design.

The outline of this paper is as follows: Firstly, the theoretical framework and research propositions are developed. Secondly, the data used and the methods applied are critically reflected. Thirdly, the propositions are tested by analyzing the market breakthrough of Diesel cars against the background of the dominant Otto cars. Finally, conclusions are drawn regarding both, implications for further research as well as the creation of new markets for fuel efficient automobiles.

2 The diffusion of innovations, path dependence, and path creation

The central conceptual assumption of this paper is that the diffusion approach of the S-curve (chapter 2.1), path dependence (chapter 2.2), and path creation (chapter 2.3) ideally complement each other. It will be explained how all paths are located in the continuum between emergence (diffusion/path dependence) and mindfulness (path-creation) (Sydow et al. 2004, Sydow et al. 2005). For a better understanding, each concept and its' assumptions are sketched briefly to pull all strings in a theoretical conclusion together (chapter 2.4). Based on that, research assumptions are provided (chapter 2.4) for the empirical case study.

2.1 S-curves and the diffusion of innovations

In the early eighties, scientist discovered that the diffusion of technology innovations follows the shape of an S-curve (Rogers/Shoemaker 1971, Sahal 1981, Rogers 1983, Sood/Tellis 2004). One of the central works in this field is the S-curve analysis provided by Sahal (1981), who used a logarithmic function to show the relationship between the stock of sold products in period t and t+1 that was influenced by explanatory variables. Interestingly Sahal maps both, the external empirical result of cumulative numbers of sold products (Sahal 1981) as well as the inner dynamics of innovations such as a rise in average service speed (Sahal 1981). Empirically, the constants of a logistic function need to be determined within the empirical data provided (Ratkowsky 1989), because the logistic function is the most common sigmoid function modelling the logistic dependence. Despite the S-curve being normally used as an ex-post instrument for technology analysis (Haupt et al. 2004), it has also been transformed into the prescriptive strategic 'McKinsey S-curve' (Krubasik 1982, Christensen 1992a, b).

Regarding the driving forces behind the diffusion, S-curve approaches list multiple causes like learning-by-doing, learning-via-diffusion, disadvantage of beginning or specialization via scale (Sahal 1981, Rogers 1983). Unfortunately, detailed explanations about the appearances and effects of those different causes are not provided.

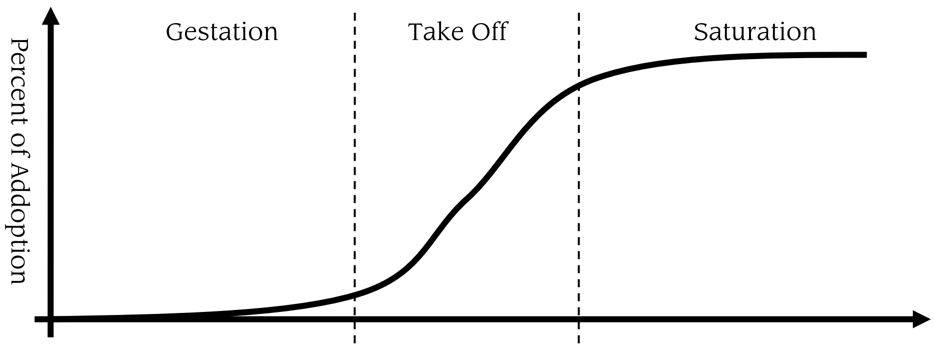


Figure 1: Typical S-Curve

This process can be separated into three phases: gestation, take off, and saturation - for a more detailed descriptions see (Sahal 1981, Fox 1973, Wasson 1974, Anderson/Zeithaml 1984, Hill/Jones 1998, Mayntz 1988).

In summary; the S-curve approach deals with the rate of adoption of different innovations in a social system (Rogers 1983). Accordingly, it can be seen as one theory describing diffusion processes, especially of technologies. Furthermore, determining whether empirical data follows a diffusion process, is easy by determining constants of a logistic function. Thus, to check whether the adoption of Otto cars and the Diesel cars followed a diffusion process can be accomplished through an S-curve analysis.

2.2 Historical mechanisms driving and maintaining a dominant design

Path dependency focuses on the competition of at least two innovations (David 1985). Following Arthur's explanation it can be summarized as examining and tracking how one particular 'equilibrium' or 'market solution' comes to be 'selected' from a multiplicity of alternatives (Arthur 1988).

To explain the effect of the key mechanism driving a process to a particular equilibrium, Arthur and his colleagues used the Polya-urn process with some modifications. In the normal Polya-urn process there is an urn with two balls of two different colours (e.g. black and white). Then one draws a ball (e.g. one black ball) and puts back the ball with one additional ball of the same colour drawn (e.g. two black balls); and so forth. The result of the share between the balls is unpredictable in advance and varies between 99.99% and 0.01% (comparing black to white balls).

In the extended Polya-urn process from Arthur, non-linear dynamic probabilities dependent on the share (i.e. the total number of sold products) are used (Arthur et al. 1983, Arthur 1988). This means, that the probability that the drawer draws a ball of a specific colour rises in regard to the total number of balls in the urn – an observable rising market share effect. By that, the 'increasing returns' due to market shares results in an asymptotic function to either 100 vs. 0 or 0 vs. 100 percent (Arthur 1989, 1994, Leydesdorff/Van den Besselaar 1998, Roedenbeck/Nothnagel 2008).

As 'increasing returns' Arthur extended the drives already provided in the S-curve approach and groups path dependency with diffusion processes. He added learning and scale effects, fixed costs as well as coordination effects with adaptive expectations, up-front costs, network effects or customer learning (Arthur 1988, 1996). Their mode of operation is described as self-reinforcement, non-convexity or positive feedback - It means that a particular outcome has accumulated (Arthur 1988). Based on Brian Arthur's and Paul David's research numerous other effects have been identified (North 1990, Mahoney 2000, Pierson 2000, Deeg 2001, Langlois/Savage 2001, Sydow et al. 2005). Unfortunately, not every new mechanism is explained in detail – a very rich compilation of potential feedback-loops based on the Polya-urn process is provided by Sterman (2000).

A consequence of this accelerating process is an increasing inflexibility and finally a 'lock-in'. It means, that at one point in time (where the difference between the market shares of the two technologies is big enough) the product with the higher market share is selected only (Arthur 1989). Arthur called this point the 'absorbing barrier'. The degree of this lock-in is measurable by the minimum cost to effect changeover to an alternative (Arthur 1988, Utterback 1994). Roedenbeck and his colleague argued that this definition of an absorbing barrier is only arbitrarily selected. By using a weighted complexity function for simulating the network effects they could identify the lock-in during each selection process based on a return probability (Roedenbeck/Nothnagel 2008).

Interestingly, the result of the process for the winning product follows a polynomial or exponential shape as the diffusion curve. Thus it can be argued that it represents the lower half of the S-curve (Unruh 2000).

To sum up, while the S-curve approach delivers the shape of diffusion processes and names its driving forces, path dependency explains how mechanisms behind diffusion processes operate (Witt 1997). Thus, identifying a diffusion process through the S-curve analysis is a necessary condition for path dependency. As the sufficient conditions the theoretical aspects of (a) multiple alternatives in the beginning of the process, (b) at least one self-reinforcing mechanism and (c) the changeover investments need to be identified.

2.3 Entrepreneurs challenging the dominant design

While Arthur's changeover investments open up the discussion for the possibility of leaving a lock-in, a closer look reveals at least four critical aspects: Firstly, since the investments aim to overcome an inefficient equilibrium, this macro-perspective ignores that a lock-in might not necessarily be inefficient for each agent. Secondly and accordingly, this approach does not adequately consider interests, agents and agency. Thirdly, a process-perspective is missing in this idea, since it seems questionable that the changeover would be caused by one single investment or by one single agent only. Finally, measuring a lock-in (or its degree) in costs seems only to be plausible when there is an alternative – otherwise there is no point of reference (Hall 1993).

Thus, the concept of path creation necessarily departs from the shortcomings of path dependence, namely its stability-bias and macro-perspective as well as its under-conceptualization of agency and gradual change (Deeg 2001, Strobel 2004). By that, it is possible to explain how the second path of Diesel cars in Germany has been driven by different agents before its' increasing returns were able to push the path by itself.

At the core of the non-mathematical concept of path creation lies the idea of mindful deviation, i.e. entrepreneurs may intentionally deviate from existing artefacts and relevance structures - fully aware that they may be creating inefficiencies in the present, but also aware that such steps are required to create new futures (Garud/Karnøe 2001).

Starting with this disembedding from embedding structures (Garud/Karnøe 2001), the path creating process ideally contains - from the perspective of an entrepreneur - (a) the mobilization of minds by boundary spanning (i.e. the translation or modification of the new idea in order to convince other agents), leading to (b) the generation of momentum. Hughes characterizes technologies acquiring momentum as follows: They have a mass of technical and organizational components; they possess direction or goals and they display a rate of growth suggesting velocity (Hughes 1986) . A third aspect added by Garud and Karnøe is (c) that entrepreneurial agency is distributed across actors stemming from multiple domains. This implies coalition-building around new designs and their continuous re-interpretation and 'adaption' (Akrich et al. 2002b, a). Finally, the agents not only disembed themselves from the previous path, they also become (d) increasingly embedded in the new emerging path. This aspect offers two interesting connecting points: Firstly, it could be seen as the switch to a new S-curve (Sood/Tellis 2004) or to a new and stable design. Secondly, this aspect provides the opportunity to show the close relation between path creation and path dependence, since the increasing embeddedness results inter alia from the investments of the agents in their preferred alternative. Therefore it seems to be reasonable to regard increasing embeddedness as a consequence of investments as simply another mirroring perspective on Arthur's changeover investments: Looking from the perspective of path dependency, these investments serve the purpose of overcoming the current path, while looking from the perspective of path creation, the investments further the embedding of the agents into the emerging alternative.

Consequently, when investigating the overcoming of a dominant design, it is not sufficient only to focus on sponsoring investments in favour of the alternative in order to show or measure the strength of a lock-in as Arthur did. Instead, the (a) mindful deviation of (distributed) agents, their (b) boundary spanning and mobilizing activities, their (c) rising embeddedness in the new path, and finally the (d) generation of momentum have to be taken into account. Thereby, the path creation activities are investigated before path dependency takes place.

2.4 Propositions

All of the three concepts explained above, describe diffusion processes or the adoption of different innovations in a social system (Rogers 1983). But each approach describes a different facet. While the S-curve approach shows how the rate of adoption develops, the path dependency approach shows the increasing returns as the central mechanism behind that diffusion and how it might lock-in. Additionally, path creation describes how a second path dependent diffusion process can be introduced in a pre-existing market, challenging a dominant design (Witt 1997, Kemp et al. 2001). Thus, the three approaches combined allow the shift in perspective from structure to agency and back. The institutional structure of the dominant design is maintained over time by path dependency. Agency on the other hand, challenges the old design by entrepreneur-driven path creation (Windeler 2003).

Analyzing creational path dependent diffusion processes thus has to identify (a) an S-curve adoption process for the dominat as well as the challenging design, (b) alternatives in the beginning of each process, (c) at least one self-reinforcing mechanism for each process, (d) the changeover investments in regard to the challenging design, (e) mindful deviation of (distributed) agents in regard to the challenging design, (f) boundary spanning and mobilizing activities in regard to the challenging design, (g) rising embeddedness in regard to the challenging design and finally the (h) generation of momentum.

According to the theoretical framework and the central research question it must be investigated whether the diffusion of Otto cars can be interpreted in a path dependent context. This path then possibly hinders the introduction of more fuel efficient engine technologies due to self reinforcement. Secondly, it must be analysed as a case whether the introduction of more efficient Diesel cars can be characterized as a path creating diffusion process. In that case it must be shown how agency influences the driving forces of the old path.

Regarding the path dependent diffusion process of passenger cars with an Otto engine (Otto cars), the first step necessary, is to show that the diffusion of Otto cars follows the shape of the S-curve. According to our theoretical background introduced above, proposition one (P1) states that the total stock of Otto cars sold has a high curve-fit according to the logistic function. Furthermore, to assure the path dependent character of this process, proposition two (P2) claims that there was an alternative to the Otto cars at the beginning of the process which has been outperformed. Proposition (P3) requires at least one mechanism of self-reinforcement favouring the Otto cars. The fourth aspect of changeover investments, to show or measure the strength of the lock-in, is included in the discussion of path creation because it aims at the introduction of an alternative (P5).

On the background of this path dependent context the case study is conducted on the diffusion of Diesel cars. Regarding the assumption that this diffusion process can be characterized as path creation, it is again necessary to show that the diffusion of Diesel cars also follows the shape of the S-curve. Accordingly, proposition four (P4) states that the total stock of Diesel cars sold has a high curve-fit according to the logistic function. The second aspect is to show the changeover investments away from the existing path plus the four aspects of path creation discussed above. Regarding Arthur's changeover investments, or the strength of the lock-in, proposition five (P5) is: The specific investments of agents in favour of the Diesel alternative increase over time. The first aspect of path creation is described by proposition six (P6): (Distributed) agents deviate from the dominant design of Otto cars. Proposition seven (P7) follows: The image of Diesel is translated to further agents leading to their mobilization. Proposition eight (P8) mirrors the changeover investments of P5, dealing with their consequences for the 'investors': Across time, the capabilities and other investments of the engaged agents increase. Finally, proposition nine (P9) states that there is a point of momentum classified by mass, direction and rate of growth for Diesel (for a summary see table 1).

	Focus of analysis		
	S-shape (1950 – 2006)	Path dependence (1950 – 2006)	Path creation (1950 – 2006)
Otto cars (context)	P1: The total stock of Otto cars sold has a high curve-fit according to the logistic function.	P2: There is an alternative to the Otto cars at the beginning of the process. P3: At least one self-reinforcement mechanism for the Otto cars exists.	Not the focus of this paper
Diesel cars (case)	P4: The total stock of Diesel cars sold has a high curve-fit according to the logistic function.	Not the focus of this paper	P5: The specific investment of agents in the diesel alternative increases over time. P6: (Distributed) Actors deviate from the dominant otto-design. P7: The image of diesel is translated to further actors leading to their mobilization. P8: the capabilities and other investments of the engaged actors increase over time. P9: There is a point of momentum classified by mass, direction and rate of growth for diesel.

Table 1: Propositions for path dependence and path creation

These propositions are analysed in the time frame between 1950 and 2006 since this is the period in which the Diesel car developed its significant share in the passenger car market. Following Arthur one might argue, that the analysis should start at that time a Diesel car has first been sold – following Garud and Karnøe it even should start at the first idea of the challenging alternative. But with the S-curve approach in mind - identifying the diffusion process - it is not necessary to have the exact length of the gestation phase. And because the focus of this article lays on the identification of the mechanisms and agency behind the take off phase, starting the analysis in 1950 is quite a good decision. However, the causal analysis stops at the point in time when the momentum for Diesel cars is reached. This is due to path creation theory which sees the momentum as its final state.

3 Research Design, methods and critical reflection on accessible data

Considering Yin's recommendation and due to the descriptive and forecasting character of this study, a longitudinal single–case study was done. The reason is, because case studies are the preferred strategy when questions about how and why are being posed to draw forecasting possibilities from the answers. This strategy is especially useful when the investigator has little control over events and when the focus is on a contemporary phenomenon within a real-life context (Yin 1994). The German market of passenger cars serves as the unit of analysis. The market success of passenger cars with a Diesel engine in Germany - one of the biggest Diesel markets in Europe (Jacob et al. 2005) – is taken as a unique case (Yin 1994). The passenger cars with an Otto engine serve as the dominant design which is challenged. Taking this unique case as a critical test for the complementarities of the three approaches, this paper claims some degree of theoretical generalisation.

Different research methods are used within a concurrent triangulation strategy (Creswell 2003, Flick 2004), analyzing the case with quantitative and qualitative techniques.

On the quantitative side (P1, P3 to P5) different data sets from different sources in the time between 1950 and 2006 were used[1]. If different values were available the mean was estimated to provide the highest coverage and eliminate failures in the sources. Unfortunately, there was a lack of separated data for the passenger car stock of Diesel and Otto cars in the time span from 1950 to 1960. Since the Diesel share reached 3% of the total car stock in 1960, a fixed rate of 2% was taken as an optimistic assumption for the time from 1950 until 1960. The data available for the German road network reached back until 1975 only, so the testimonial evidence is restricted.

In regard to P1 and P4 (the fitting of the data to the logistic function) a time series analysis was made using a non-linear regression (Ratkowsky 1989, Bates/Watts 1988). The non-linear function was the sigmoid logistic growth model used for representing the S-curve: Y = ((alpha / (1 + exp(beta - gamma * x1))) + (x2*delta). There are two independent variables x1 and x2, where x1 represents the year and x2 is a dummy variable for the German reunion. The dependent variable Y is the total stock of cars. The

[1] As quantitative empirical data sources, tables from the German Federal Ministry of Finance (BMF), the German Federal Motor Transport Authority (KBA), the German Federal Office of Statistics (Destatis), General German Automobile Association (ADAC), Association of the German Petroleum Industry (MWV), German Federal Ministry of Labour and Social Affairs (BMAS), German Association of the Automotive Industry (VDA), German Federal Ministry of Transport, Building and Urban Affairs (BMVBS) have been used.

parameters in the logistic function represent the following: alpha is the asymptotic limit of the S-curve, (beta / gamma) is the x-coordinate of the inflection point and (alpha / 2) is its y-coordinate. Delta is a parameter for the dummy variable. For estimating the parameters of the S-curve the statistical software R was used. The starting values for alpha to delta where estimated by a graphical analysis of the data. The strength of the model is expressed by the t-values and their significance for each parameter under the condition of normal distributed residuals.

For P3, at first, the possible increasing return loops need to be explained theoretically. Then, between each two aspects of the increasing return loop either a positive correlation - following the direction of the influence - or qualitative evidence is needed. Analysing the correlation, the standard Pearson correlations were calculated between two time dependent variables using the coefficient of correlation.

Last but not least, P5 was analysed with a calculation: The difference of the pure Diesel taxation and the total Diesel taxation weighted with the quotient of the annual rate of taxation for gasoline and the annual rate of taxation for Diesel was estimated.

On the qualitative side (P2 and P6 to P9), causations have been identified by a tentative reconstruction of the process using two daily business newspapers: 'Handelsblatt' (HB) as well as 'Finanncial Times Deutschland' (FTD). By using the search engine of the HB, approximately 5.000 results regarding Diesel were analysed. Furthermore, secondary literature was used.

4 The German 'Dieselization' against the dominant 'Otto path'

As outlined above, the propositions will be tested in this empirical section by focussing first on the context – the dominant design of Otto cars – and next, by investigating the process of the Dieselization (Hård/Knie 2000).

4.1 Analysing the 'Otto path' in Germany

The Otto-engine was invented in 1876 by Nicolaus August Otto and implemented into passenger cars by Gottlieb Daimler and Karl Benz in 1886. In its early days, Otto cars competed with other designs such as steam engines as well as electric vehicles. However, due to production and marketing decisions as well as technical solutions, these alternatives were outperformed at the beginning of the 20th century. The Otto-engine became the dominant design for automobiles (Cowan/Hulten 1996, Rao/Singh 2001, Diekmann 1979). Considering the total stock of Otto cars, the market success in Germany took place relatively late: In 1938 the total car stock in Germany numbered 1.27 million, shrinking to 0.19 million by 1946 (Diekmann 1979, Edelmann 1989). From then on, the total number of registered cars in Germany increased significantly to about 0.54 million in 1950 (Diekmann 1979) due to the immediately revived automobile production – e.g. 10 000 VW 'Käfer' in 1946 (Edelmann 1989). A stimulating condition in this process were institutional changes in the German taxation system – e.g. by making kilometres driven deductible from income taxation in 1953 (Klenke 1993) as well as by lowering the motor vehicle taxation (KFZ-Steuer) by 20% in 1955 (Edelmann 1989).

According to P1, the analysis starts with the non-linear regression analysis identifying whether the development of Otto cars between 1950 and 2006 in Germany has a high curve fit with the logistic function provided above. The starting values for the parameters in the case of Otto cars can be determined in the following manner: "alpha" as the asymptotic limit of the S-curve is set to 4e+7, "beta / gamma" as the x-coordinate of the inflection point is thus set to 4000 divided by 2, and "alpha / 2" as its' y-coordinate is set to 2e+7. Using the dummy variable "x2" for the German reunion once with a delta of 6e+6 and once with a delta of 0 lead to the following results:

The strength of the model can be evaluated using the t-values and their significance as well as the residual plot.

	Regression with dummy variable		Regression without dummy variable	
Parameters	Parameter Estimation	t-Value	Parameter Estimation	t-Value
Alpha	2.955e+07	49.89***	4.063e+07	32.23***
Beta	2.440e+02	16.41***	1.879e+02	17.76***
Gamma	1.237e-01	16.37***	9.494e-02	17.65
Delta	FIX: 6e+6	* / *	FIX: 0	* / *

*** 0.0001 Significance

Table 2: Results of the non linear regression for Otto cars

In both models, all t-values are highly significant, while the model with the dummy for the German reunion has a slightly better fit:

Additionally, the residual plots and their histograms (on the left for the model with the dummy and on the right without), are in both cases normally distributed.

The results lead to the conclusion that both models have a high fit to the S-curve where the one with the dummy is preferred. The diffusion process of Otto cars in the German passenger car market can therefore be seen as a standard innovation process. Interestingly, interruptions in the data can be linked to historical data: These points are the two oil crises in 1973 and 1979/80, and the German reunification in 1990. Obviously, these events delayed the diffusion process (oil crisis) or supported it (reunification).

Consequently, proposition P1 is supported. The introduction of Otto-car's can be seen as a standard diffusion process which is possibly path dependent. In order to find out whether this standard diffusion process represents a path dependent process, P2 and P3 have to be confirmed. As already mentioned above, passenger cars with an Otto engine outperformed steam engine cars (Hölzinger 2002) as the first alternative. In Germany, the Diesel cars represented a second alternative from 1936 on (HB). Therefore proposition P2 can also be accepted.

On the subject of proposition P3, the operationalization of increasing return loops is more difficult. In the case of the diffusion of the Otto engine, it is embedded into a social setting (Hughes 1986) where a broad variety of qualitatively different aspects could have influenced the engine's market success. Correspondingly, Hård and Knie consider the cultural ambience of the automobile to consist of four dimensions: organization and network, routine and daily practice, meaning and discourse, as well as law and politics (Hård/Knie 2000). More concretely, Unruh suggests positive feedback between the size of the road network, the volume of traffic, and the collected taxes (Unruh 2000). Combining these ideas with the suggestions of Sterman, at least the two self-reinforcing loops of the 'network effect' and the 'hot-product effect' are to be investigated, while others also may be present.

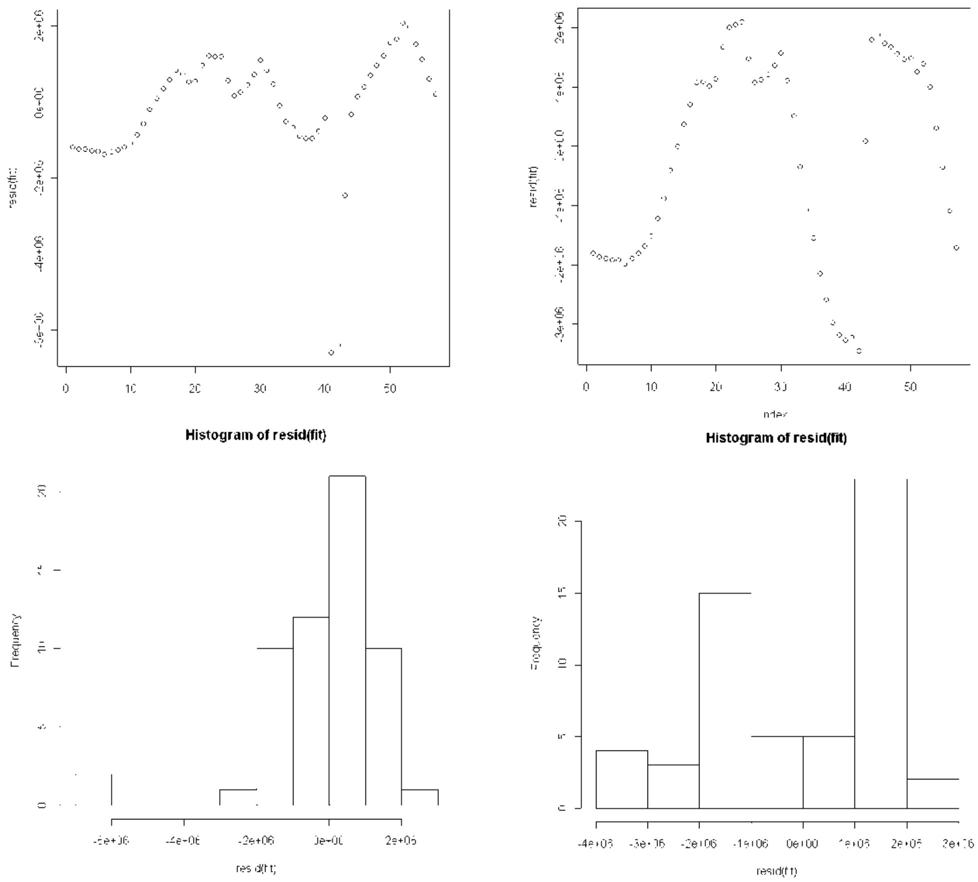
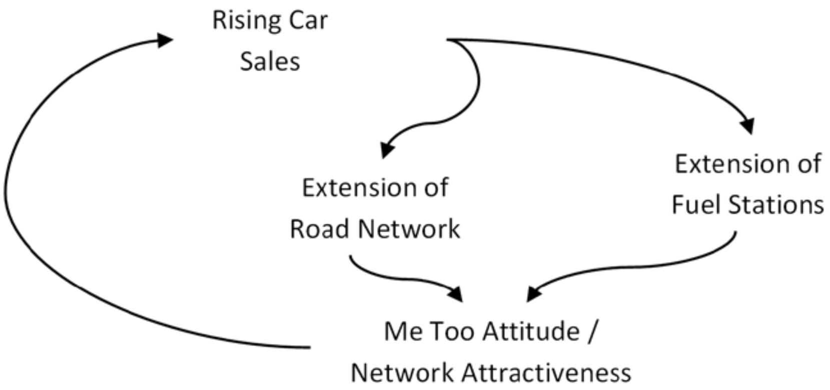


Figure 3: Residual plots and histograms of the non linear regression for Otto cars

Sterman's 'network effect' resembles Unruh's outline stating that rising sales have a positive impact on the installed base – i.e. the number of participating customers -, thus raising the attractiveness of the network and of the product, spurring the whole industry demand and thereby the sales.

Translated into the diffusion story of Otto cars, this means that rising sales



of Otto cars caused the extension of petrol stations (NW1a) and the road network (NW1b). This caused a 'me too' attitude spurring the attractiveness of the network, leading again to an increasing motorization (NW2). Regarding NW1a a high correlation between the rising numbers of cars and the expansion of the petrol station infrastructure can be found in the early years from 1950 to 1970. After that point, the number of petrol stations steadily decreased due to low margins and market pressure to rationalise (HB, FTD). Accordingly, the results need to be handled carefully and the development after 1970 does not further support the increasing return loop.

Analysing NW1b, the correlation between the rising numbers of sales and the road network does not provide any useful evidence either. Although there is a high correlation in the time span from 1950 until 2006 the development of the road network starts on a high level with little increase in regard to its length. Thus we draw the conclusion, that the impact on the decision to buy passenger cars in Germany has been low. Therefore, part NW1b has to be neglected, too.

Regarding NW2 the attractiveness of the network can be illustrated by the decreasing number of alternative transportation systems, such as railways, as well as the increasing number of kilometres driven per year. For example, between 1950 and 1966, the use of personal vehicles increased

	Stock of Otto-Cars (1950-2006)	Petrol Stations (1950-1970)	Petrol Stations (1970-2006)
Stock of Otto-Cars (1950-2006)	1	0.967	-0.879
Fuel Station (1950-1970)	0.967	1	-
Petrol Stations (1970-2006)	-0.879	-	1

Table 3: Correlations between the total number of Otto cars and the petrol station infrastructure

from 10% to nearly 50%, while the use of the public transportation system decreased to the same degree (Schlette 1999). Edelmann 1989) and of modernity per se (Buhr et al. 1999). Meanwhile the media discussed the 'last pedestrian' (Bretz 1960, Klenke 1993).

	Stock of Otto-Cars (1950-2006)	Road Network (1950-2006)
Stock of Otto-Cars (1950-2006)	1	0.965
Road Network (1950-2006)	0.965	1

Table 4: Correlation between the total number of Otto cars and the length of the road network (without city streets)

The second mechanism, the 'hot-product-loop', is operationalised in the following way: Rising motorization spurs the growth rate of firms, which stimulates a hot-product perception, beside possible marketing investments, giving rise to positive media reports. These influence the attractiveness of the Otto car, further pushing the sales.

Interestingly, there seems to be a time lag between the two mechanisms: While the 'material' network effect takes place in the early phase of the diffusion, the hot-product loop passes over into the cultural and cognitive framework of modernity.

Data provided for the analysis of P3 supports the existence of reinforcement loops in the form of a network effect and a hot-product loop. In combination with the proof of P2, the development of the Otto cars can be seen as a path dependent process. Therefore the introduction of Diesel cars faced a dominant design of Otto cars which was driven by path dependent mechanisms. How the 'path creation' of the Diesel cars took place despite this previously existing path is subject of the next section.

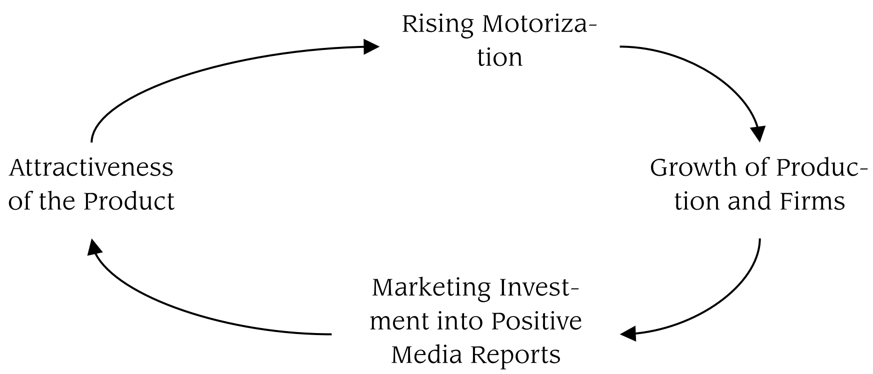


Figure 5: Self Reinforcement Loop of Hot Product Effect

The sales rates above and their exponential growth leading to an increase in the growth rate have already been discussed. The third step in this loop, the hot-product perception, becomes obvious in the fact that the automobile developed into a status symbol (RAC 1999). A special case in that regard is the VW 'Käfer' as a 'car for everyone' (Edelmann 1989). Moreover, passenger cars with an Otto engine became the expression of new freedom, individualism and social success (Klenke 1993,

4.2 The long and winding 'road' of Diesel

Compared to Otto, Diesel is very much a late bloomer regarding its acceptance as an engine design for automobiles. Invented in 1892 by Rudolf Diesel, it was mainly used in stationary power systems and vessels. In the 1910s and 1920s, MAN and Peugeot started to modify the Diesel for use in buses and trucks (Hård/Knie 2000). The first passenger car with a Diesel engine, launched in 1936, was the 'Mercedes Benz 260 D' (Oldtimer-Klassiker.de 2006). The Diesel got the image of being a 'heating-oil Ferrari', and it remained in a 'niche'-car for 'Vielfahrer' accompanied by buses, trucks, and tractors (HB).

Due to these starting conditions, the network effect in favour of the Otto cars can be excluded immediately as a hindering factor for the success of the Diesel cars: The one reason is that Diesel cars – contrary to other alternative such as railways – use the same road network. Second, due to the previous existing Diesel-markets of busses and trucks, the fuel supply infrastructure was already in place.

Regarding the diffusion of the challenging design of Diesel cars again a non-linear regression with the logistic function was made. The starting values for the parameters in the case of Diesel cars were set to the same values as in the case of Otto. Using the dummy variable "x2" for the German reunion once with a delta of 1.8e+6 and once with a delta of 0 lead to the following results:

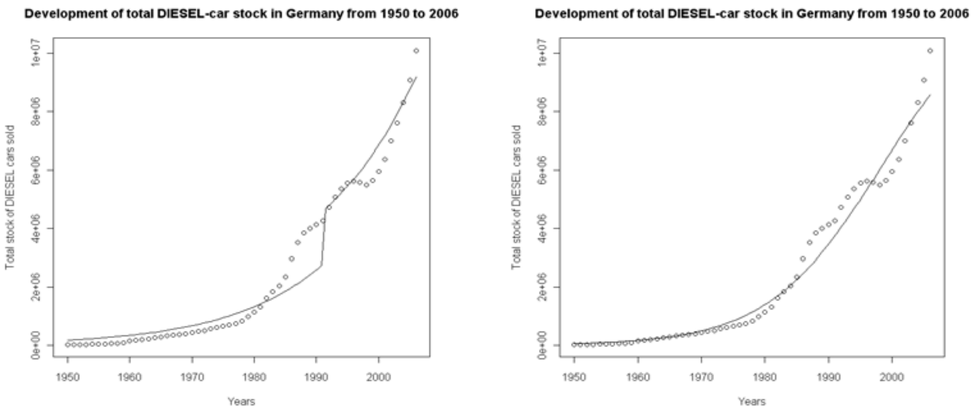


Figure 6: Total number of registered Diesel cars in Germany (1950-2006)

The strength of the model can be valued using the t-values and their significance as well as the residual plot. This time, only the model without the dummy for reunification has t-values which are highly significant. Thus, the reunification plays a minor role in the case of Diesel cars.

The residual plots and their histograms (on the left for the model with the dummy and on the right without), are in both cases normally distributed.

Interestingly, other interruptions in the data can again be linked to historical events, but these differ from those in the case of Otto cars. The oil-crisis did not have a significant effect on the diffusion of this less consumptive engine design. Contrary, technical innovations such as the 'turbo Diesel' (1984) and the 'direct injection' (1998) seemed to be more influential. As a result of this analysis, P4 can be accepted.

Considering the advantage of the dominant Otto cars this rocky diffusion of the Diesel can only be explained by investigating the role of agency (for example innovation, political action and so on) according to propositions P5 to P9. In other words: How can agency explain that the Diesel engine is the only prime mover that has challenged the gasoline hegemony on a substantial scale (Hård/Knie 2000)?

Although the first Diesel car, the 'Mercedes 260 D', did not lead to an immediate market success for Diesel passenger cars, Daimler Benz stayed tuned to this technology due to its success in commercial vehicles (HB). A similar commitment can be recognized for the automobile supplier Bosch, which invented the first high-pressure injection for Diesel in 1927 (HB), and

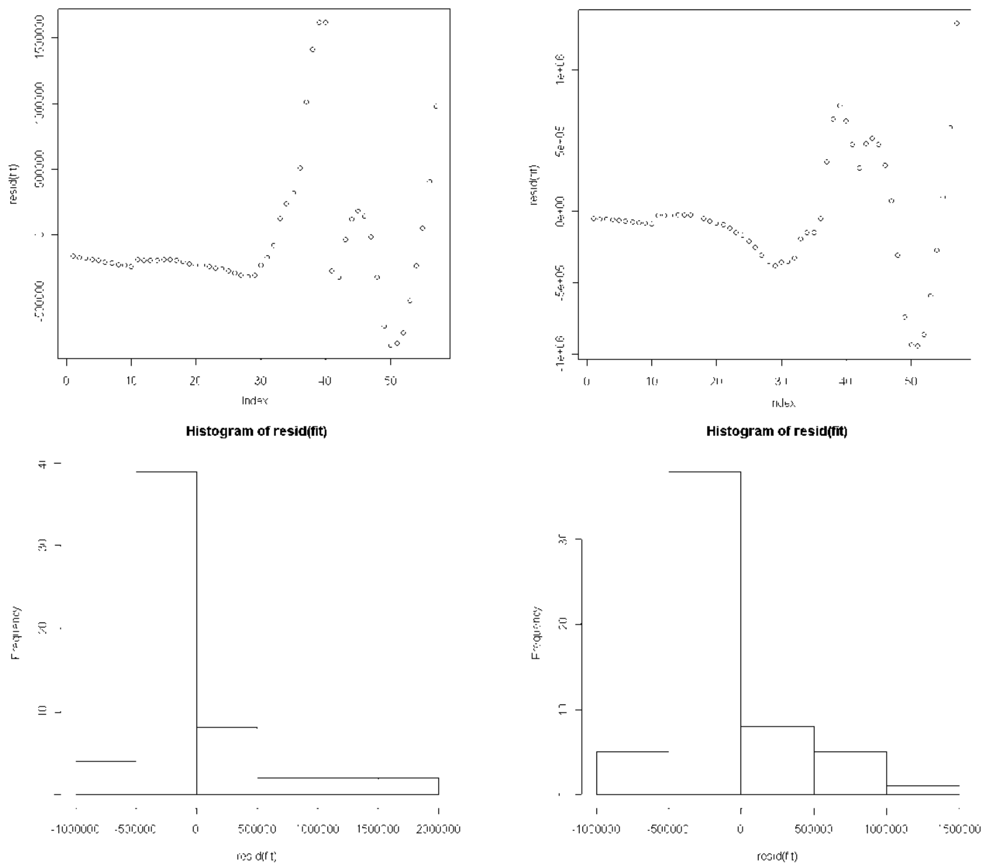


Figure 7: Residual plots and histograms of the non linear regression for Diesel cars

the common rail-injection together with Fiat later on in the 1970s (Jürgens/Meißner 2005). Peugeot (later on PSA) as the developer of the first Diesel lorry also increased its experience in this sector (Hård/Knie 2000). Another central enterprise was, for example, VW enhancing the Diesel technology through the introduction of the pump nozzle in 1998. Interestingly, input by the German federal state and the European Union was important but also contradictory, such as the much criticised "zigzag" (HB) in the German environmental and transport policy. The European Community stimulated the development through the support of research projects and regulation of emissions (EURO I to IV) (Knie 1991, Böttger 1996). This picture of distributed agency is rounded off by the latecomers BMW and Opel (HB). Taken together, this clearly supports proposition P6.

The engagement of Daimler Benz also supports proposition P8: It can be assumed that, since the share of Diesel cars had already reached 50% of Daimlers sales by 1987 (HB), Daimler Benz allocated an increasing amount of capabilities and investments towards this technology. The same conclusion is close at hand for BMW, considering its involvement in the Austrian 'Diesel cluster' in Steyr (HB). Certainly this development was fostered by the fact that the Diesel branch was a critical internal factor of success for Daimler Benz in 1985 as well as in 1994 (HB).

Contrary to the continuous and increasing technological progress of Diesel illustrated above, the history of its image (P7) is marked by a large number of changes: From being a fuel efficient but somewhat noisy, uninspired and sooty alternative in the late 1970s, it changed into an environmentally friendly one in the mid- 1980s (HB). In the time following, the development of the Diesel was marked by repeated interaction between negative discussions regarding its NOx- and soot-emissions on the one hand and technological solutions to this on the other (HB). Combined with the increasing debate on climate change and CO2 emissions, the Diesel turned into an environmental 'Janus-head' (HB). More important than this ecologically motivated discussion was the increasing adjustment to the characteristics of the Otto car (quiet, spirited and 'clean') in combination with better efficiency. Finally, the 'joy to drive' (a typical German cultural aspect) met a new lifestyle, namely, the 'joy to save money' (HB). To sum up, the technological efforts of the car manufacturers gained acceptance due to the changing image of Diesel coinciding with the appearance of a new lifestyle – this supports P7.

As a consequence of these developments the hot-product loop supporting the Otto cars was neutralized. This was achieved by the mimicking of the technological properties of the Otto cars. Later on, the hot-product status was even attributed to Diesel cars due to the combination of technological mimicking and the changing 'Zeitgeist' in favour of energy- and cost-saving technologies

The coincidence of the new positive Diesel image with the 'Zeitgeist' plays an important role for the newly generated momentum (P9): While in the 1980s negative debates were sufficient to reduce the sales (HB), this pattern can not be found in the late 1990s. Instead, sales steadily increased despite a negative debate on its soot emissions and the potential prescription of particle filters (HB). A second pattern that does not hold anymore is the negative correlation between 'discriminatory' higher motor vehicle taxes for Diesels and their sales rate (Kunert 1997). Another convincing aspect is that traditionally sceptical Japanese car manufacturers started to enhance their Diesel capacities in order to participate in this development (HB). Finally, it can be argued that the still increasing total number of Diesel cars, in combination with a decreasing number of

Otto cars, indicate an ongoing switch from the current S-curve to the next one. These findings support the notion that Diesel has acquired a direction leading clearly towards a higher penetration of the market, which is reflected in the current percentage of newly registered Diesel cars being nearly 45% of the total (KBA 2005). Since the rate of growth increased strongly after 1999 (rhomb, cumulated to 83 billion € up to now). Two 'waves' can be recognized over time in the analysis of the annual taxation investment.

Of course, it has to be taken into account that the lower taxation rate for Diesel is historically rooted in the special interests of the German transportation business (Kunert 1997, Jürgens/Meißner 2005). This differentiated

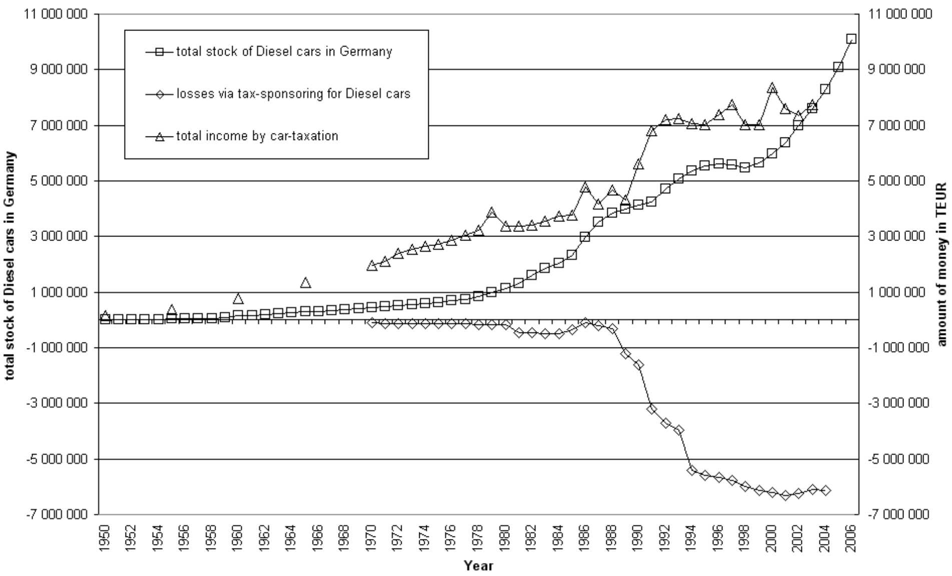


Figure 8: Total number of Diesel cars in comparison to the losses via taxation

(Jacob et al. 2005), proposition P9 can be accepted.

Last but not least, the so far neglected proposition P5 (changeover investments) represents an attempt to transfer agency, breaking the lock-in into countable costs. In regard to the effects of path braking activities of distributed agents (see P6), the decisive taxation by the German federal state seems an additional central driver in the process. It shows the immense costs nearly no other agent was able to invest for a successful technological change. Empirically, the lack of mineral oil taxes due to the lower rate of taxation for Diesel compared to gasoline has been estimated. It can be seen that the changeover investment from the perspective of the federal state lasts over a long period of time taxation was countered, however, by inversely differentiated motor vehicle taxation (Kunert 1997). Other changeover investments can be found in the build-up of capabilities by the automobile producers, such as BMW's involvement in the 'Diesel cluster' in Austria. Although only the costs of one agent are estimated here, they support proposition P5 as well as the evidence presented for P8. However, considering the statement that the Diesel has already acquired its point of momentum, a continuation in sponsoring this alternative by the federal agent does not seem to be necessary.

Because of the evidence collected above for all research propositions, the aspect of path creation in the case of Diesel can be accepted. In their interlay, the propositions investigated

	Technology	Regulation	Exogenous shock	Image
1892	Invention of the Diesel			“Heating-oil-Ferrari”, i.e. fuel efficient but noisy, uninspired and sooty
1923	First Diesel truck by MAN and Peugeot			
1927	Invention of the high-pressure injection by Bosch			
1936	1st Diesel car (Mercedes Benz 260 D) by Daimler Benz			
1973			1st oil crisis	
1978	1st Golf Diesel by Volkswagen			
1979/ 1980			2nd oil crisis	Environmentally friendly
1985/ 1986		Tax relief for ‘low emissions vehicles’ by the FRG	Discussion on forest dieback	
1987			Three-way-catalytic converter	Negative discussion of the emissions of Diesel
1988	First Turbo-Diesel (Fiat Croma TD)	Introduction of European emission standards (EURO 0); first regulation of Diesel-soot-emissions		
1988/ 1989		Fading of the tax relief by the FRG	Start of the greenhouse gas-debate	Environmental Janus-head, i.e. low CO_2- but high soot-
1989	Audi TDI			
1989/ 1990		Rising motor vehicle tax on Diesel cars	German reunion	
1991/ 1992		New tax relief		

1992/ 1993		EURO I		emissions
1993	Invention of the Common-Rail-Injection (CRI) by Fiat and Bosch			
1994		Rising motor vehicle tax on Diesel cars		
1995/ 1996		Rising tax on gasoline		Merger with new lifestyle, i.e. „the joy to drive“ meets “the joy to save money” (two typical German cultural aspects)
1996/ 1997		EURO II		
1998	Application of the CRI by Daimler Benz; Introduction of pump-nozzle by VW			
2000	Introduction of the Diesel particulate filter by Peugeot			
2000/ 2001		EURO III		
2004		EURO IV		

Table 6: Timeline of the path creation process

above explain the rocky S-curve of the Diesel by providing ‘multiple layers of causation’.

The technological enhancement of the Diesel engine was a necessary factor for the success of Diesel cars, but not asufficient one. This factor interacted with exogenous and endogenous changes; the first two breaking points in the S-curve can be correlated with the exogenous shocks of the oil crises in 1973 and 1979/80, making Diesels especially attractive for those who drive a lot of km per year (HB). The next increase in momentum in 1985 is explained by the motor vehicles tax relief for ‘low emission vehicles’. At that time, the limit value for exhaust gases was easier to keep for Diesels than for Ottos, so this relief had the effect of a sales discount, fostering the first ‘Diesel wave’ (HB). This development was broken in 1987 by the broad introduction of three-way catalytic converters for Otto cars and their increasing thriftiness (HB). Additionally, the tax relief was not only phased out in 1988 and 1989, the motor vehicle tax for Diesels was even increased in 1989. Furthermore, the Diesel made negative headlines due to its sooty particle emissions and potential driving bans in the event of smog were discussed (HB). Against this, the position of the Diesel cars was furthered by the use of new technologies reducing the harmful emissions as well as the 1989 / 1990 debate on CO2 and climate change. Together with new tax relief from 1991 to mid 1992, these factors spurred a new Diesel boom (HB). This boom lasted until 1995 when a strong decrease in Diesel sales occurred. The reason seems to lie in the taxation system: Despite the fact that in 1994 the fiscal advantage of Diesel against gasoline regarding mineral oil taxes was enhanced, this effect was overcompensated by a parallel increase in the motor vehicle tax on Diesels (Kunert 1997). The final drivers towards the momentum of Diesel cars were the introduction of the TDI by Volkswagen and the CRI by Daimler, making the Diesel and Otto equivalent and meeting the new lifestyle.

5 Discussion – results and future research

This paper has shown that S-curve, path dependence, and path creation can be fruitfully combined: While the S-curve serves as an indicator for 'diffusion-paths', path dependence enables the researcher to identify driving forces behind it. Path creation, on the other hand, provides close and intriguing insights into the role of agency influencing and creating these forces.

This theoretical background was used in order to gain insight into potential future market introductions of more fuel-efficient automobiles. On the one hand, the paper provides evidence for the path dependent development of the dominant design of Otto cars. This was done by highlighting that the diffusion of Otto cars in the German car market followed a typical diffusion curve (proposition 1; P1). Additionally, Otto cars outperformed the steam engine in its early days (P2), while its diffusion was driven – at least to a certain degree - by a network- as well as a hot-product effect (P3). High and long-lasting changeover investments by different agents in favour of a more fuel-efficient alternative showed that the dominant design was locked in (P5).

On the other hand, this paper provides evidence for the path-creating attempts in favour of the Diesel car by identifying distributed deviation from the dominant design by agents such as Daimler Benz, Bosch, and the German federal state (P6). All these agents invested in the challenging design (P5). Only partly supported by political regulations and taxation, these agents managed to change the image of Diesel and to fit in with a new 'Zeitgeist' (P7). At this point, Diesel acquired momentum (P9), leading to an exponential growth rate in comparison to a decline in the Otto car stock. Thus this could be seen as a change from the S-curve of one technology to another.

Because evidence could be provided for each individual proposition, the main proposition (MP) can be accepted as well. Hence, the case of the 'Dieselization' can serve as a critical case for a process of path creation on the background of path dependence. Accordingly, the case provides some insights for the questions (a) which mechanisms are behind the status quo in the car market and (b) how these mechanisms could be influenced. Regarding the first question, network effects and a hot-product loop clearly played a role in the diffusion of Otto cars. Interestingly, these two effects took place in partially different phases of the diffusion process: While the network effect is closer connected to the beginning of the diffusion, the hot-product loop changed its character over time and ended with the recognition of the Otto-driven passenger car as the core concept of modernity. These two effects also played an interesting role in the diffusion of the Diesel car: Firstly, the network effect played no negative role for the diffusion of Diesel, simply because Diesel cars use the same road network and due to the existing Diesel-fuel infrastructure so far dedicated to busses and trucks. Secondly, the disadvantageous hot-product loop was neutralized by mimicking the technological characteristics of the dominant design of Otto cars. Later on, the hot-product image was even transferred to the Diesel car as a consequence of the changing 'Zeitgeist'. Last but not least, the transaction costs from one design to the other were shared between different, more or less co-operating agents. A significant part of the sponsorship was carried by the German federal state with its tax subsidies. However, other kinds of agency might be successful too, as, for example, the 'hybridization' of the dominant design as has been done by Toyota's Prius or bivalent gasoline-natural gas passenger cars.

Concerning future investigations six theoretical-methodological aspects and three empirical ones can be pointed out. The first theoretical suggestion is that the concept of path dependence needs to be developed further by using the plateau of the S-curve. This seems to fit with the assumption of decreasing returns as discussed in literature (Unruh 2000, Deeg 2001). Secondly, it would be useful to put the relationship between path creation and path dependency into one mathematical model (possibly as tried by Witt (Witt 1997) or Katz and Shapiro (Katz/Shapiro 1985, 1986). This could be done by using the inspiration of the switch from one S-curve to the other. Thirdly, it is questionable how important the lock-in is for the concept of path dependency, when a changeover is possible as shown in this paper. Fourthly, the concept of self-reinforcing mechanisms clearly needs to be investigated further because they (a) seem not to operate constantly. Moreover, (b) in the literature, only 'arbitrary' suggestions are made regarding how these mechanisms could look. Also (c) the necessary excessive use of longitudinal data - including a high variety of variables - resulting from their highly complex nature is currently underestimated. Fifthly, the 'neutrality' of the network effect in the case of the Diesel cars reveals that the degree of deviation of the new design from the old one – respectively the radical nature of the innovation – plays an important role regarding the question which mechanisms of the old path have to be surmounted. Finally, the question how mechanisms can be addressed by the agents opens up the question of an active management of these mechanisms and thereby of paths.

Regarding the empirical case, the first aspect to mention is that it would be worth to investigate the still neglected agency in the case of the establishment and maintenance of Otto cars. Likewise, it is necessary to look for mechanisms that drive the diffusion of Diesel cars before and after the momentum was reached. This would provide a broader picture of the complex development of path phenomena. Findings may then be contrasted with those of this paper. Secondly, as the changing image of Diesel revealed, it would be worthwhile to carry out a discourse analysis in order to closer monitor these developments strongly influencing the behaviour on the demand side. Thirdly, it would be important to consider the consequences of the newly established Diesel-path for an eventual stabilization of the fossil fuel-consuming engine technologies in general, as well as for the introduction of other, even more efficient engine technologies into the car market.

6 A forecasting conclusion – a plea for taking mechanisms into account

A path-perspective focusing on mechanisms as drivers for dominant designs adds three new features to the study of innovations and for future attempts to introduce more fuel efficient engine designs: Firstly, the driving forces behind existing design encompass nested causalities between very different spheres such as petrol stations and consumer's images. These aspects can be very closely related, wherefore the different spheres can not be addressed separately. Instead, the linking mechanisms between the spheres need to be identified. This is the necessary first step. The second step is to identify how the driving mechanisms affect the attempted alternative – i.e. if they affect them negatively (e.g. the hot-product loop, the transaction costs) or positively (e.g. the existing fuel infrastructure) or not at all (e.g. the road network). The third step then is to develop strategies, as to how these mechanisms have to be addressed in order to introduce the new alternative. E.g. the hot-product loop can be affected by mimicking the dominant design, by influencing the consumer's image regarding the desirable characteristics, by adding new characteristics and / or by hybridizing the dominant design. Furthermore, initial inertia both on the side of the consumers as well as the product developers can be targeted by lowering the transaction costs via sponsoring. Thus, the lesson to be learned is that it is not the image of the dominant design or the economies of scale per se but their interrelatedness.

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