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The emergence of hybrid-electric cars: Innovation path creation through co-evolution of supply and demand

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ABSTRACT

Hybrid-electric vehicles have experienced a significant rate of growth in the last 10 years. This is remarkable, since the automotive sector is typically averse to the more radical technological change of engines. The internal combustion engine has been around for more than 100 years after all.

In this paper we describe and explain the emergence of electric engines in the automobile market after 1990. We explicate the role of techno-economic mechanisms alongside social and regulatory mechanisms (including the social meaning of an engine). The co-evolutionary analysis is novel in the integrated conception of actor perspectives, feedback effects and competition between products. We find three sources of lock-in through path dependency: from demand, supply as well as the regulatory side. We conclude that automotive engines were significantly locked into a trajectory of internal combustion technology due to techno-economic mechanisms, which produced inertia despite social pressures. The creation of an alternative path, on the other hand, initially stalled. Various stakeholders were unsuccessful in marketing their electric or hybrid-electric vehicles in the 1990s, such as Peugeot/Citroen with various electric models, or Audi with their Duo in 1997. However, after 2000 we find that sustaining efforts of California's Air Resources Board and Toyota were triggering creation of a new innovation path of hybrid-electric engines.

1. Emergence of new technology

In the last few years the automobile market has demonstrated a surprising rise in sales of a new type of engine: hybrid-electric engines. Consumers increasingly drive them and car firms more and more explore them. Critics argue that similar short-lived hypes appeared in the mid-1990s with electric vehicles and around 2000 on fuel cell vehicles, and they are right. Still, today's momentum is distinctive in one important way: hybrid-electric engines have been sold 1.5 million times worldwide now. How could this happen in a sector that is typically aversive to risky radical technological changes and a classic example of 'locked' into a dominant technology [1,2]?

Studies in various scientific fields have addressed the emergence of new technology and innovation. Broadly there are three stands of literature. Although most economists treat innovation as just another investment opportunity, one strand originates from the Austrian economist Joseph Schumpeter (1883–1950), who bequeathed us with a scheme of technological change consisting of *invention* — the first practical demonstration of an idea; to *innovation* — the first commercial application of an invention to the market; to *diffusion* — the spread of the innovation into the market [3]. In this tradition a new wave of economists revitalized evolutionary theorizing of innovation [cf. 4–6] from the early 1980s onwards. Studies in this strand have explained the domination of internal combustion (IC) technology in the automotive sector for more than a century now as lock-in through path

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dependency [1]. The models are, however, as yet less applied to consumer products in a changing social context. For consumer products symbolic meaning or social connotation of products may play a significant role, for instance for hybrid-electric cars of which many owners see their vehicle as 'socially responsible', as 'the right vehicle for society' [7]. Progression of such connotation will affect the further development (supply side) and diffusion process (demand side) of the technology. There are currently few theories in this economic field that incorporate this interaction of such social and technological aspects [e.g. 8,9] and as Saviotti [10] notices, these dynamics are still poorly understood.

A second strand of innovation studies, *innovation diffusion studies*, is conceptually broader and originates from social geography, later adopted in marketing studies. The focus in most diffusion studies is on aggregate patterns, which are often found to be S-shaped. The seminal work of Rogers [11] offers a typology of adopters based on *when* they adopt but does not offer a dynamic model of innovation diffusion in terms of endogenous and exogenous mechanisms. In the field of marketing the symbolic meaning or value that goods and innovations hold is well established [e.g. 12,13], where it is typically distinguished from the functional value. Symbolic value is as a social connotation or meaning attributed to the product, and individual consumers will have a certain degree of inclusion in such a social construct. It may be positive or negative (even at the same time, for different groups of consumers), thus adding value in the eyes of a consumer, or reducing it.

A third strand of innovation literature originating from the sociology and history of technology, where authors have emphasized the social context in which technology is created and used. A key concept is the *social construction of technology* (SCOT), where 'technology' is viewed not as an objective entity (as in economic and technical studies), but rather described 'through the eyes of social groups' [14]. These authors demonstrated how various social interpretations of technology drive various directions of technological development.

Authors in the latter two strands have addressed the interaction of technology and social factors [for example 8,15–20]. Most recently Rip and Kemp [21] elaborated on co-evolution of 'the social' and 'the technical', analysing the emergence, transformation and decay of socio-technical systems. Their 'multi-level' model of innovation distinguishes between the macro level of the socio-technical landscape, the mesolevel regime, and the microlevel niche. Geels [22,23] added the key idea that radical innovations come about through interactions between processes at these three levels. That is: the breakthrough from niche to regime level occurs gradually, as a new technology 'branches' or 'penetrates' different application domains, before entering mainstream markets. These studies have highlighted more than previous studies the patterns in which established technologies are sometimes abandoned and overthrown by emerging niches. Dijk and Kemp [24] have argued that these studies have been less clear on *why* some niches are 'successful' in growing and even overtaking a regime, while other niches die. Interactions between niche and regime are claimed to be important, yet the interactions are not specified in terms of processes; feedback effects, such as scale and learning, and taste formation mechanisms are neglected. Dijk and Kemp have suggested a conceptual framework that highlights actor perspectives and feedback effects.

In this paper we elaborate on the latter framework by explicating the role of techno-economic mechanisms alongside social and regulatory mechanisms for the case of automotive engines. We present the emergence of (hybrid-) electric engines on the automobile market in the context of evolution of demand and supply of car engines, which results in a co-evolutionary analysis. We perform an explanatory case study, applying our co-evolutionary framework to this case. Explanatory case studies are suitable for applying pre-defined frameworks to a new case, testing causalities and explanatory value [25].

After amplification on our methodology (Section 2), we describe our framework and hypothesize that six feedback mechanisms are key in the emergence of hybrid-electric engine technology (Section 3). Subsequently, we provide rich descriptions of how and why propulsion technologies were developed and adopted after 1990, tagging two levels. In Section 4 we focus on aggregate patterns (sales levels and technological progress), while in Section 5 we address the micro level perspectives of individual stakeholders (firms, consumers, and regulators). Section 6 integrates the previous sections into a co-evolutionary framework. Section 7 draws conclusions.

We find that automotive engines were locked into an established trajectory of internal combustion technology sector due to techno-economic mechanisms, which produced inertia despite some sustainability pressures. In the 1990s the creation of a new innovation path of electric engines initially stalled, since the vehicles were broadly regarded as expensive and unpractical due to little autonomy. However, after 2000 it recurred through hybrid-electric engines, mostly triggered by efforts of Toyota to find a new market, and stimulated by the gradual social formation of a positive connotation.

2. Methodology

In the following sections we perform an explanatory case study, applying our co-evolutionary framework to the case of automotive engines. Explanatory case studies are suitable for applying pre-defined frameworks to a new case, testing causalities and explanatory value.

In our explanatory case study we fit in evidence from a range of other methods, most notably discourse analysis, patent analysis and a questionnaire survey. Such a combination of methods has a few advantages. The simultaneous use of various methods can improve the quality and adequacy of a study considerably, and conclusions are usually more convincing if they are based on several different sources of information [25]. Combining methods can compensate for one-sidedness. In complex issues, one method easily results in only partial explanation of a phenomenon, as in the blind men and the elephant tale (as observed in [26]).

Combining methods has difficulties too. Integration of outcomes and knowledge elements is difficult to validate scientifically, and methods may have a similar bias. Roe argues the various methods need to be orthogonal (i.e. very different)