Dynamics of the transition towards alternative fuel vehicles in advanced and emerging markets

Edmundo Molina* (emolina@rand.org)
*** RAND Corporation, 1776 Main Street, Santa Monica, CA 90407, USA**
***PARDEE RAND GRADUATE SCHOOL OF POLICY STUDIES, 1776 Main Street, Santa Monica, CA 90407, USA**

Abstract

The global diffusion of alternative fuel vehicles is strongly associated with deep social and technological uncertainties, which result from considering the market differences of advanced and emerging markets, and the technology maturity and potential of alternative fuel vehicles. We analyzed the effect of the interplay of these uncertainties using a system dynamics model characterized by the socio-technical feedback processes inherent to this transition context, and the interdependencies of automakers, consumers and fuel suppliers. We explore a large set of scenarios varying the social and technological factors in our model, and use the scenario discovery method to identify sets of policy relevant cases. We find five policy relevant behavioral clusters associated with the diffusion of hybrid vehicles and the diffusion of electric vehicles. Our analysis shows that the initial transition inertia towards alternative fuel vehicles in advanced economies can be exhausted, and thus threaten the global transition towards alternative fuel vehicles. Emerging markets can offer a complementary market niche that can be used to support this transition. We conclude that the process of diffusion of alternative fuel vehicles can be enriched and strengthened if it is seen as a complementary process between advanced and emerging markets.

Keywords: Alternative fuel vehicles, emerging markets, system dynamics, scenario discovery, social uncertainties, technological uncertainties, technological change.

1. Introduction

The diffusion of environmentally sound technologies is a fundamental measure needed to mitigate the negative consequences of climate change, and to advance our society's sustainability goals. Given the global scale and the shared responsibility of our contemporary environmental problems, the diffusion of these technologies needs to occur not only at a local level, but also at a global level (Gallagher 2006). This increases the complexity of analyzing this type of technological transitions because, in addition to the inherent uncertainty associated with innovation process (Dawid 2006), it is also necessary to consider the social uncertainties associated with the interaction of developed and emerging markets (Hu, Hung, and Gao 2011). Considering the interplay of these social and technological uncertainties in technological forecasting studies opens a new field of study that has not been fully explored (Hu, Hung, and Gao 2011; Pillania 2011), and that is also relevant for broadening our understanding of technological change, and for designing policy interventions that can effectively incentivize the adoption of environmentally sound technologies at a global scale. This paper aims at expanding our knowledge in this field by analyzing how the interplay of these uncertainties influences the transition towards alternative fuel vehicles, and the effectiveness of proposed policy interventions to incentivize their global adoption.

The transition towards alternative fuel vehicles has two main features that make it a relevant transition case to be studied: 1) alternative fuel vehicles are key environmentally sound technologies, for which global diffusion is highly desired, and 2) this transition case is strongly associated with both social and technological uncertainties.

On the one hand, global diffusion of alternative fuel vehicles is important because these technologies can significantly diminish the demand for fossil fuels and the environmental pollution of the transportation sector. Also, if the electricity needed for alternative fuel vehicles is supplied using on a more diversified energy mix, including renewable energies, the widespread usage of these technologies can substantially reduce the overall greenhouse gas emissions of the transportation sector (Demirdoven and Deutch 2004). Nevertheless, given the future growth in car ownership in emerging countries (Achtnicht, Buhler, and Hermeling 2012), if alternative fuel vehicles are only successfully adopted in advanced nations, and emerging countries remain lock-in with conventional internal combustion engines, then the global contribution of these technologies to mitigating our global environmental problems will be marginal (Dechezlepretre et al. 2011). As a result, it is highly important that in the coming decades these technologies can be successfully adopted in both advanced and emerging markets.

On the other hand, this transition case is associated with several social and technological uncertainties. First, vehicle markets of advanced countries are sizeable markets that have reached a mature stable stage (Pavlinek 2012); in contrast, vehicle markets of emerging markets are smaller markets that are growing much more rapidly (Pillania 2011). These market differences between advanced and emerging countries make it very difficult to estimate how these markets will co-evolve at a global scale (Amatucci and Mariotto 2012), which is quite relevant for an global automotive industry that serves both markets. Second, there is also ample technological uncertainty associated with this transition case because we cannot forecast accurately the technological potential of the different alternative fuel vehicles, or the time needed for these technologies to be brought into the market, and the technical co-dependencies and spillovers across vehicle platforms (Struben 2006).

The interplay of these social and technological uncertainties in a global context sketches a complex system that is rich in feedback interactions and dynamic behavior. Given this richness and resulting dynamic complexity, we consider feasible that: 1) hybridization and technology transfer policies to support the diffusion of alternative fuel vehicles can fail, and 2) advanced and emerging countries can follow different diffusion patterns of these technologies. By constructing and analyzing a simulation model of this transition case, we aim at increasing our understanding of the long-term dynamics of this transition, and to discover plausible policy relevant scenarios that result from the interaction of different social and technological uncertainties.

This paper studies the effect of the interaction of social uncertainties (i.e. consumers' vehicle preferences and consumer's income level), and technological uncertainties (i.e. technologies' performance, development potential and technological spillovers) in the transition towards alternative fuel vehicles. Our model focuses specifically in the role of these uncertainties is a socio-technical system in which consumers, automakers and vehicle technologies interact through mechanisms of social learning, research and development, learning-by-doing and economies of scale. We expect that this approach will shed light into the challenges and opportunities that can be encounter in technology transfer and hybridization policies to support the global diffusion of alternative fuel vehicles

2. Background

Technological change in carbon intensive sectors has proved very challenging because the firms, the infrastructure and the institutions supporting these sectors have coevolved around incumbent technologies. This creates strong positive feedbacks that support the dominant position of carbon intensive technologies, precluding the entrance of cost and performance inferior environmentally sound technologies (Unruh 2000; Struben and Sterman 2008)

There are two main approaches to induce technological change in mature carbon intensive sectors, these are: niche accumulation and hybridization (Raven 2007; Kemp, Schot, and Hoogma 1998). In the medium term, the introduction of hybrid vehicles is seen as the most viable way to improve fuel efficiency and reduce overall life-cycle greenhouse gas emissions in a cost-effective way (Avadikyan and Llerena 2010; Demirdoven and Deutch 2004). In addition, the introduction of hybrid vehicles can accelerate the transition towards electrical and fuel-cell vehicles because this can create economic and knowledge spillovers that can become useful for developers of these radical platforms. More importantly, the introduction of hybrid vehicles will also induce the development of the fuelling infrastructure needed for the radical platforms, as in the case of plug-in hybrid vehicles (Raven 2007; Struben and Sterman 2008). In the long term, we can conservatively expect that the transition towards alternative fuel vehicles will occur in two phases: first, from conventional vehicles to hybrid vehicles, and, second, from hybrid vehicles to a radical new platform (e.g. electric vehicles, fuel cell vehicles) (Hekkert 2006; Geels and Schot 2007; Raven 2007).

The possibilities of success of hybridization and niche management strategies have been widely studied in the literature. Previous research shows that none of the actors involved in this transition (i.e. consumers, automakers, fuel suppliers, policy makers) has sufficient power to induce unilaterally the diffusion of alternative fuel vehicles in the transportation sector (Farrell, Keith, and Corbett 2003). As a result, there is a set of barriers associated with each actor that can deter the entrance of these technologies. On the consumers' side, it is argued that income levels, technology familiarity, social norms, fuel availability and vehicles' emission levels are key factors influencing consumer's adoption decisions (Gallagher and Muehlegger 2011; Ozaki and Sevastyanova 2011; Struben and Sterman 2008; Bunch et al. 1993). On the suppliers' side, it is argued that regulatory uncertainty, the industrial competitive environment, and technological uncertainties play an important role in automakers, policy makers and fuel supplier's decisions to invest in the development of alternative fuel vehicles (Avadikyan and Llerena 2010; Struben 2006; Jacobsson and Lauber 2006).

These conclusions have been drawn mainly by analyzing this transition case in advanced economies; for example in California (Ozaki and Sevastyanova 2011; Walther et al. 2010; Bunch et al. 1993; Struben 2006), Canada (Potoglou and Kanaroglou 2007) and the UK (Kohler et al. 2009). Recent research has started focusing in emerging markets (Pillania 2011), mainly in China (Hu and Phillips 2011; Leung 2011; Zhao and Melaina 2006), and to a lesser extend in Brazil and India (Hall et al. 2011; Yeh 2007). By comparing the results of these studies we assert that consumers in both regions use a similar decision making framework in their adoption decision, however the market conditions they face, and the weight they give to the different vehicle attributes can differ significantly.

While the majority of the studies related to the adoption of alternative fuel vehicles have focused primarily in understanding the decision frame of consumers, there is also another body of literature that focuses specifically in patterns of technological change in the automotive industry, and in the global life-cycle of vehicle technologies, which we consider to be important for this transition case.

First, technological change in the automotive industry is strongly associated with cost-cutting pressures and incentives to exploit scale economies (Pavitt 1984). This key driver of technological change is pushing global car manufacturers to increasingly diversify the geographic location of their manufacturing and R&D activities (Colovic and Mayrhofer 2011; Heneric, Licht, and Sofka 2005). As a result, the automotive industry can be depicted today as an oligopolistic global industry serving heterogeneous markets, using a highly geographically diversified supply chain (Sturgeon et al. 2009; Sturgeon, Van Biesebroeck, and Gereffi 2008). Second, the global life-cycle of vehicle technologies has followed a pattern of international trade in which, initially, advanced economies were the early users and producers of this technology, to subsequently, allow for a greater market intake and production capabilities of developing countries (Vernon 1966; Amatucci and Mariotto 2012). We consider that, given the current saturation state of the automotive industry, it is unclear whether or not this same pattern will be followed in the case of alternative fuel vehicles.

All the aspects of this transition case presented in this section form the backbone of our simulation study. Our analysis takes into account the decision making framework of consumers, the global structure of the automotive industry and the patterns of international trade of vehicle technologies. Our model analyzes specifically how all these concepts come to play in the success or failure of hybridization and technology transfer processes of alternative fuel vehicles.

3. Model Description

Our simulation model considers three different vehicle platforms: incumbent vehicle platform, hybrid platform and a radical platform. We also consider two different vehicle markets: advanced and emerging markets. Finally, we consider the interaction of three different decision makers: consumers, automakers and fuel suppliers. In the following sections we discuss in more detail these features of our model.

We used the system dynamics modeling approach to build our simulation model. We consider this is a suitable approach to analyze this transition because system dynamics is a mature modeling framework specifically designed to analyze systems characterized by long-term dynamics, interdependencies, nonlinearity and feedback processes (Sterman 2000),which are all features of the transition towards alternative fuel vehicles. In addition, system dynamics is a modeling approach that allows explaining system behavior using endogenous mechanisms.

Finally, we have decided not to frame our analysis to any particular country context, rather we have focused on building a model that can allows to explore different facets of this transition using generic features of this case.

3.1 Overview of the model

In this section, the fundamental issues, factors and interactions included in our system dynamics model will be described in accordance to the actor-option framework (Yücel 2010), this facilitates the explanation of the different model components. The detail documentation of the model, including the full list of variables, parameter values, and mathematical equations can be found in the attached model.

Figure 1 presents a highly aggregated diagram of our model, it depicts the main feedback processes, as the well as the bordering factors of the system. We can see that our model consists of three main subsystems. There are two subsystems associated with each vehicle market: advanced market and emerging market. These subsystems describe the processes by which consumers become familiar which vehicle platforms, and their adoption decision making processes. These subsystems also deal with the mechanisms associated with the formation of the fueling infrastructure. The third subsystem deals with the processes by which automakers invest in the development and commercialization of the three vehicle platforms. The bordering factors in our system represent the social and technological factors that we use to study the effect of social and technological uncertainties in this transition context.

The time scope of our analysis is set to the next five decades. This time period of analysis is appropriate to analyze these types of technological transitions studies (Yucel and Barlas 2010; Struben and Sterman 2008; Kohler et al. 2009), and this time period also allows us to tide back our results to policy targets set for the year 2050.

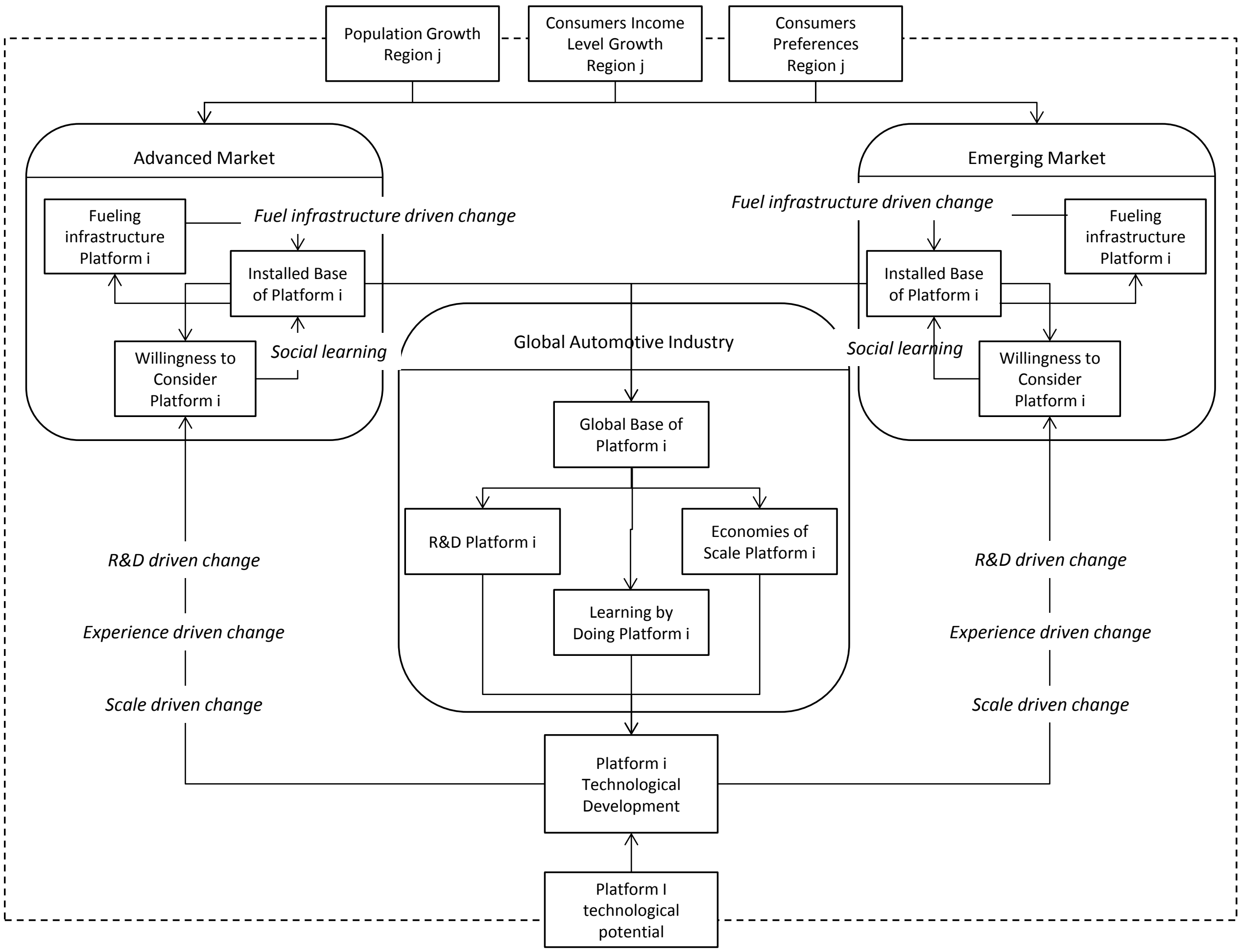


Figure 1. Schematics of the model architecture, italics indicate interaction mechanisms across subsystems, bordering factors represent social and technological uncertainties.

3.2 Decision Makers in the System

We consider three different decision makers in our system: consumers, automakers and fuel suppliers. Consumers (vehicle users) are the most heterogeneous element in our system; their characteristics vary in terms of their geographic region, vehicle's preferences, driving habits and income levels. Automakers are the developers and sellers of vehicles; through sales of vehicle platforms they accumulate resources that they assign to the development of the three vehicle platforms. Finally, fuel suppliers install and decommission fuelling stations for each vehicle platform. They do this by responding to the profitability of the fuel market.

3.3 Considered Decision Making Processes

Consumers decide which vehicle platform to adopt. They make this decision when they purchase a vehicle platform for the first time, or when they replace their current vehicle once its operational life has elapsed. In deciding upon which vehicle platform to purchase, consumers are assumed to make a multi-criteria decision, which is based on four aspects: the vehicle's selling price, its operational costs, its driving range and its carbon footprint.

However, the information that consumers receive to evaluate each vehicle platform is distorted by social exposure. This phenomenon is conceptualized by using the concept of "familiarity", which captures the social and cognitive learning process by which consumers gain information, understanding and attachment for a vehicle platform (Struben and Sterman 2008). Familiarity can increase or decrease through time and it is dependent on three factors i) marketing of a platform, ii) word-of- mouth of drivers of a platform to non-drivers of the platform and iii) word-of-mouth solely from non-drivers of a platform to other non-drivers of that platform,

Automakers are faced with the decision of how to allocate resources to the R&D of the three platforms. Similarly to the case of consumers, we have considered different behavior profiles for automakers. On the one hand, there are those automakers who decide how to allocate resources for R&D only taking into account the market share of each vehicle platform in the global market. This behavior is defined as a market driven investor. On the other hand, there are those automakers that allocate equal resources to the development of each platform. This behavior is defined as a balanced investor.

Fuel suppliers decide whether to enter or leave the fuel market. In doing this, fuel suppliers will take on account the profitability of the fuel industry for each platform and the demand for fuel for each platform

3.4 Technology Options

In this study we consider three different vehicle platforms: 1) incumbent vehicle platform, 2) hybrid vehicle platform and 3) radical vehicle platform. These three vehicle platforms are characterized through several attributes. There are four attributes that are taken into account by consumers to make their purchasing decisions, these are: purchasing price, operational cost, driving range and carbon footprint. In addition, the technology potential of each vehicle platform is described by their maturity level and their development potential. The technology maturity of the different vehicle platforms indicates the position of each platform in the learning curve. As shown in **Figure 2**, in the reference case, we consider that the incumbent vehicle platform is quite ahead of its technology learning curve. As a result, further accumulation of knowledge will not improve significantly the proficiency of the incumbent vehicle platform. On the contrary, the hybrid and the radical vehicle platforms could be considered to be at early stages of development, progressing more noticeably as new knowledge is acquired. This intuitive conceptualization is not certain, and several scenarios are feasible. As shown in the dotted lines in Figure 2, it could be that the incumbent vehicle platform is in an early stage of development with still ample room for development. In contrast, the radical vehicle platform could have a much greater development potential than expected, represented by a higher learning coefficient. A sample of the set of parameters used to model these technologies is presented in **Table 1.**

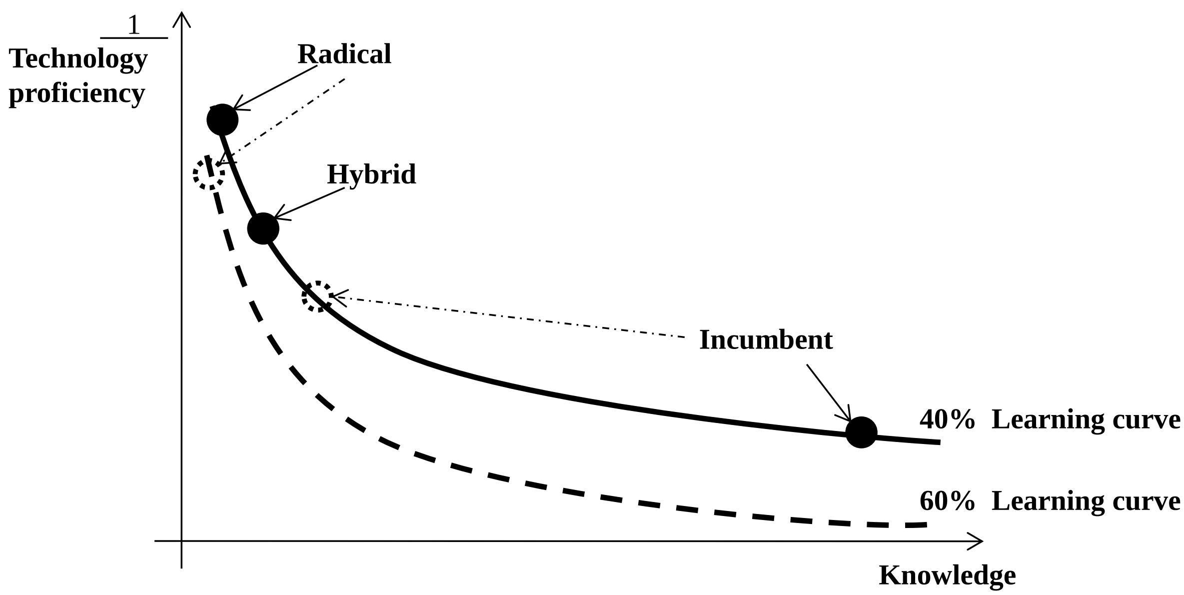


Figure 2. Learning curve scenarios for vehicle platforms; technology proficiency is represented as an inverse function of accumulated knowledge. In the reference case alternative technologies are represented as immature technologies of similar technology potential.

Table 1. Technology Parameters

Attributes	Units	Incumbent Platform	Hybrid Platform	Radical Platform
Average lifetime of vehicle platform	Yr	8.00	8.00	8.00
Initial purchasing price	$/vehicle	8,000.00	25,000.00	45,000.00
Initial fuel efficiency	lt/km;kwh/km	0.08	0.05	0.25
Initial fuel carbon emissions	kgCO2/lt	2.32	2.00	0.25
Technology maturity level	Dmnl	0.80	0.20	0.00
Learning coefficient technology development	Dmnl	-0.40	-0.40	-0.40
Initial recharching time radical platform	hr/kwh/station			0.80
Initial battery storage capacity radical platform	Kwh			5.00
Development Spillovers				
Strength of knowledge spillovers pi-pk	Dmnl	0.05		
Strength of knowledge spillovers pj-pi	Dmnl	0.30		
Strength of knowledge spillovers pj-pk	Dmnl	0.30		

Source: Modified from International Energy Agency (2008), chart 15.6, p436, and from the US the Environmental Protection Agency at epa.gov/oms/climate

3.5 Interaction Feedback Mechanisms

There are two types of feedback mechanisms which are active in this study: 1) mechanisms related to the properties of the vehicle platforms and 2) mechanisms related to actors' perceptions.

3.5.1 Feedback Mechanisms Related to the Properties of Vehicle Platforms

There are three main feedback mechanisms that change vehicles' attributes. These are: resource driven changes, experience driven changes and scale driven changes. Figure 3 shows the first resource driven mechanism, which refers to changes in the attributes of the vehicle platforms through R&D, which increases the body of knowledge of the vehicle platforms, which in turn improves the proficiency of each platform.

The formation of fuelling infrastructure is an essential element to increase the attractiveness of vehicle platforms. Figure 4 describes this mechanism of change. Sales of the three vehicle platforms in both regions promote the growth of fuel demand for the specific fuel market of each platform, which is an incentive for fuel suppliers to enter the fuel market of the different platforms. As the number of fuel stations increase, the driving range of the different platforms expands.

Another source of change in the attributes of the vehicle platforms is the experience driven change. Figure 5 shows how this process of change occurs in the context of the automobile industry. The experience of automakers in manufacturing the different vehicle platforms increases and accumulates in time through the sales of the vehicle platforms. This implies that automakers learn in time to produce more efficiently the vehicle platforms, which ultimately reduces the production costs of the vehicle platforms.

As shown in Figure 5, scale driven changes are also taken into account. Contrary, to the case of accumulation of experience, the sales of each platform in both regions help the automakers achieve scale economies in each platform.

3.5.2 Feedback Mechanisms related to Actor's perceptions

In this transition context only one mechanism that affects the perception of consumers is considered. As shown in Figure 3, when the fleet of vehicles of a particular platform increases in one of the regions, it also increases its social exposure. This occurs through word-of-mouth of current drivers of a vehicle platform to other non-drivers of that platform, through word-of-mouth of non-drivers of a vehicle platform to other non-drivers, and through marketing of each vehicle platform. This mechanism of interaction is very important for this transition context. Without social learning consumers have no way of finding out the real proficiency of each platform, only through this process, consumers can gain enough information to assess more accurately the performance of each vehicle platform, this in turn increases or decreases sales for a particular platform depending on the preference structure of consumers (Struben and Sterman 2008).

4.1 Simulation analysis

4.1 Reference behavior of the model

In our reference case, automakers behave as market driven investors, which means that they allocate resources to the development of each vehicle platform based on their individual market share. In addition, the base case considers conservative technology development potentials for the three platforms (learning coefficients=40%). Moreover, the incumbent platform is considered to be way ahead of its learning curve, and the hybrid and radical platform are considered to be at the beginning of their respective learning curves (initial position: 20%, and 0% respectively). Finally, consumers' preference structure in both regions is considered to be price oriented, which means that they only consider vehicle platforms' selling price in their adoption decisions.

The diffusion patterns of this reference case are shown in Figure 6. Here, it is possible to see that in both regions diffusion of the alternative vehicle platforms is quite limited. In both regions, the market share of the hybrid platform only starts growing in the last years of the simulation. In the case of the radical platform, it is possible to see that it does not penetrate these markets at any significant level in both regions.

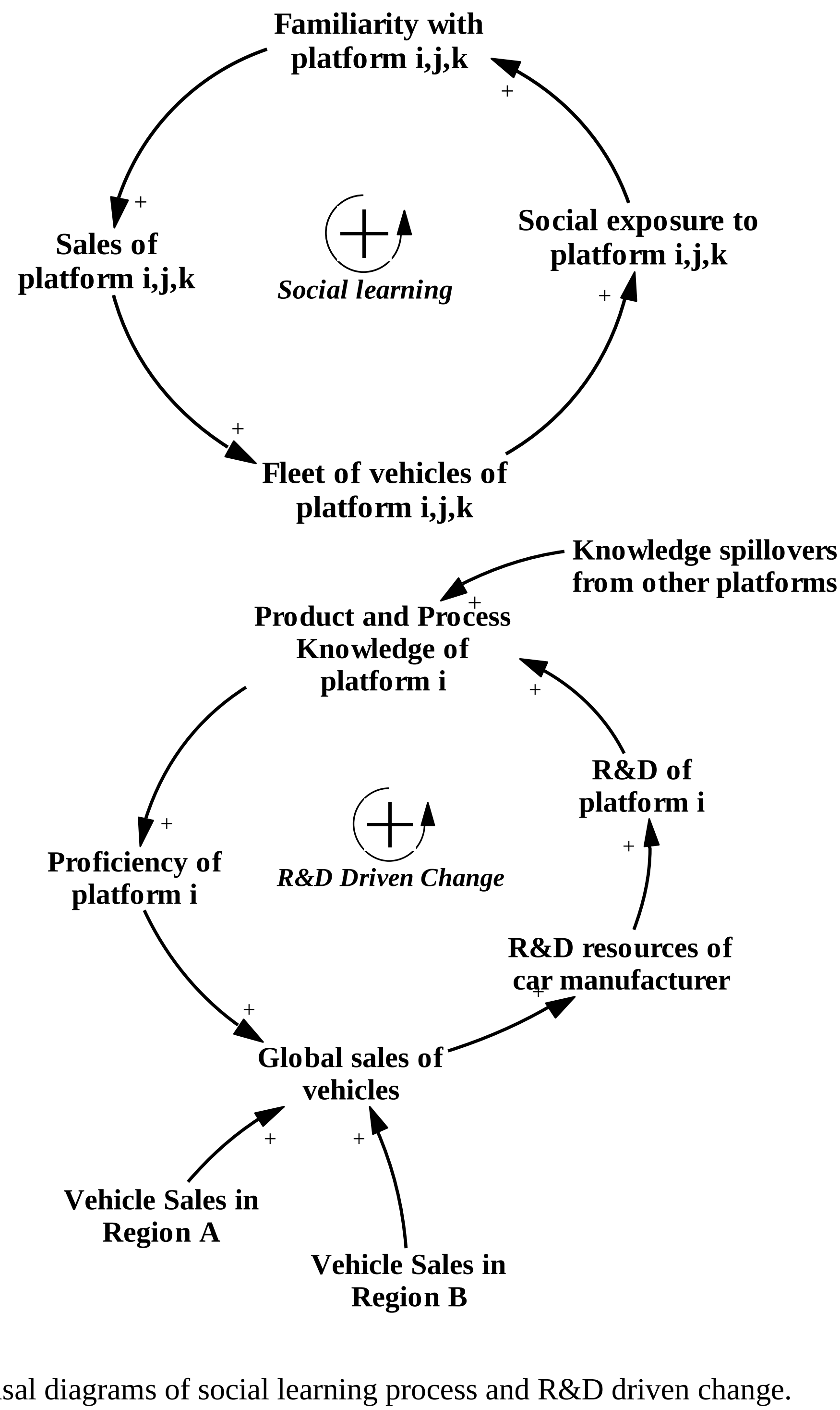


Figure 3. Causal diagrams of social learning process and R&D driven change.

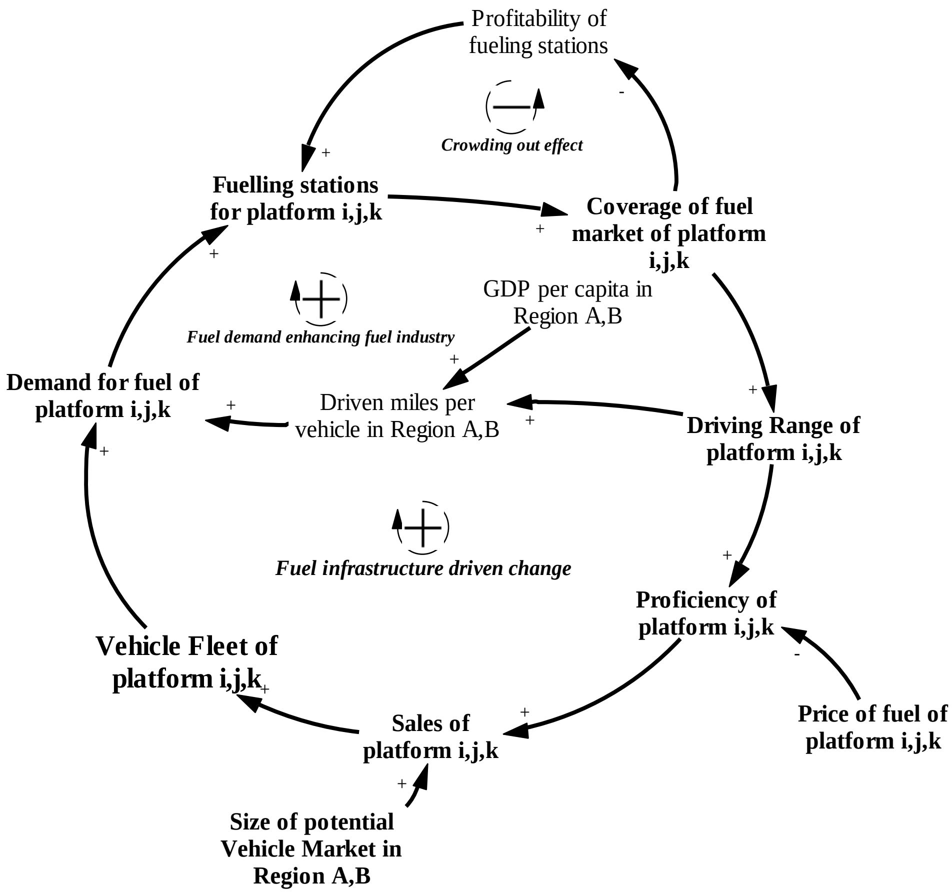


Figure 4. Fuel infrastructure driven change.

In Figure 6 we can also see that there is a delay between the diffusion of alternative platforms in the advanced region and the emerging region. This delay is caused by the social differences of consumers. In this scenario, there is a considerable gap between consumers' income level of the advanced region and the emerging region. This means that consumers of the advanced region are able to purchase the alternative platforms sooner than consumers in the emerging region. Since, in this references case, consumers only consider the purchasing price in their adoption decisions, then consumers in the advanced region adopt earlier the hybrid vehicle platform than consumers of the emerging region.

Finally, as the number of consumers driving the hybrid or the radical platform in both regions is rather limited. Then familiarity of consumers with the alternative platforms never grows in the case of the radical platform, and only grows slowly in the case of the hybrid platform. This delays the process of social learning for the alternative platforms in both regions, which prevents consumers from fully appreciating the attributes of the alternative platforms.

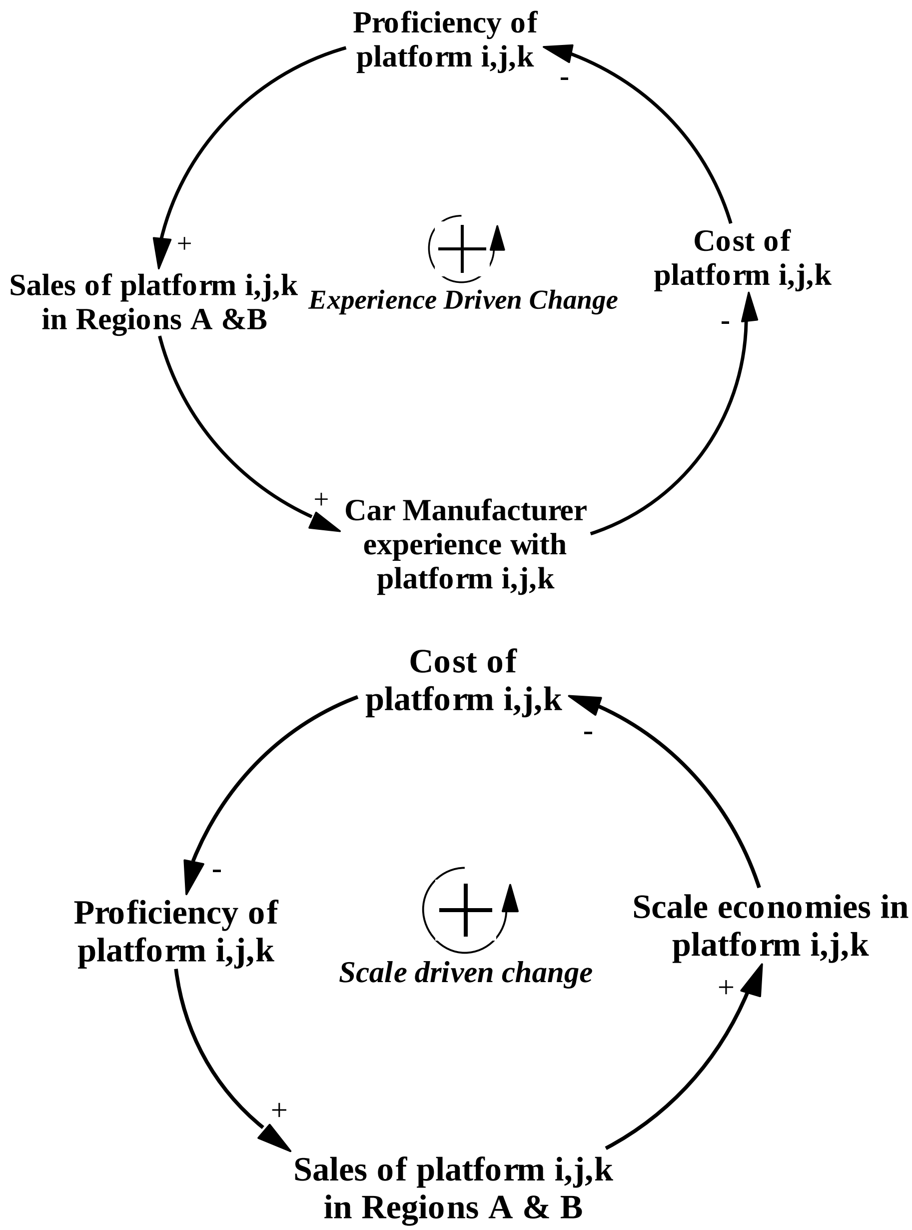


Figure 5. Causal diagrams of experience driven change and scale driven change.

4.2 Exploratory Analysis

The reference case represents only a single point in a vast space of possible scenarios that can be explored with our model and that are relevant for this transition case. Many other scenarios result when we take into account the combination of the different values that the technology and behavioral parameters of the model can take. In this regard, automakers and consumers can behave in several different ways and the technology potential and maturity of the three vehicle platforms can differ greatly.

We use the scenario discovery method (Bryant and Lempert 2010) to explore the set of scenarios that result from considering the interaction of the social and technological parameters in our model.

Scenario discovery is a methodology that can helps us illuminate key vulnerabilities and driving factors in this uncertain transition context. We have defined the exploratory analysis as follows. First, we created a data base of 1,000 different model runs by sampling (using the Latin Hyper Cube Method) over the following parameters: emerging consumers' income growth, emerging consumers' vehicle preferences (importance of purchasing price, operational cost, driving range, carbon footprint), technology potential of the three vehicle platforms (learning coefficients), and technology maturity of the three vehicle platforms (position in the learning curve). We created these scenarios by considering the whole range of values of each one of these parameters. Second, we use the Patient Rule Induction Method (PRIM) algorithm to find the scenarios of interest in our experiment, as described by Bryant et al. (2010), and Lempert et al. (2003).

The output of interest in our experimental design is the penetration of the alternative platforms in both markets. Figure 8 shows the results of our experiment taking into account these measurements. We can see that the space of possible outcomes is quite ample, but also that, on average, the hybrid and the radical platform achieve higher levels of penetration in the advanced region. Another interesting result is that there are few cases in which these technologies have a higher penetration in the emerging market. Overall, the cases that are more relevant from a policy perspective are those close to the diagonal and further away from the origin because in these scenarios alternative fuel vehicles penetrate both markets at significant levels.

Having identified the scenarios of interest, the next task was to identify the factors that were causing this behavior. Using the PRIM algorithm we studied these scenarios to analyze existing tradeoffs or combined effects of social and technological factors. Figure 9 shows two graphs in which we consider the combined effect of social factors with technological factors. The upper graph displays a case in which the hybrid platform succeeds in both markets by becoming the most popular technology. The black dots represent cases in which this result occurs, while the white dots cases in which it does not. We see that this case occurs more frequently when consumers are proficiency oriented and the hybrid platforms develops rapidly. In the bottom graph, success refers to those cases in which the radical platform penetrates in the emerging market at higher levels than in the advanced market. Here we see that the preference structure of consumers in the emerging market plays a determinant role in defining this scenario, regardless of income differences and technological maturity. In Figure 10 we also show the dynamic behavior for the cases of interest in this experimental set. Here we can see that these cases belong to the same behavior cluster, this means that even though they achieve different end-points in our simulation experiments, they show the same dynamic behavior. In the next section we discuss in more detail the meaning of these results.

4.3 Experimental Results

The exploratory analysis shows that it is possible to find alternative diffusion patterns in this transition context that do not follow the logic of the reference case, as shown in Figure 7. It has been found that the interplay of social and technological factors can significantly influence the diffusion of alternative fuel vehicles. Table 2 and

Table **3**present all the behavior clusters that are found in our exploratory analysis using the scenario discovery method.

These results show that social uncertainties associated with consumers' income levels have the following implications:

First, as the income level of consumers in the advanced region is higher than the income level of consumers in the emerging region, alternative fuel vehicles become affordable sooner for consumers in the advanced region, than for consumers in the emerging region. This stimulates the diffusion of these technologies earlier in the advanced region than in the emerging region, especially in the case of the hybrid platform. The initial diffusion of the hybrid platform in the advanced region induces its diffusion in the emerging region. For example, improvements in the performance of the hybrid platform, due to R&D, incentivize consumers of the advanced region to purchase this platform. Then, the growth of sales of the hybrid platform in the advanced region helps automakers gaining experience in its production and also achieving economies of scale, which reduces the purchasing price of the hybrid platform. This fosters the diffusion of the hybrid platform in the emerging region. The exploratory analysis show that when there is not a difference in consumers' preferences, then the hybrid platform always diffuses first in the advanced region and later in the emerging region.

Second, differences between vehicle market rates of growth are also significant in this transition context. Consumers already driving the incumbent or the hybrid platform demand a higher level of performance of the radical platform to switch to it, than consumers that for the first time decide which vehicle platform to adopt. Therefore, by the time the radical platform has improved its performance through R&D, and is able to compete with the other two platforms, this vehicle platform finds a better market niche in the emerging region because: 1) consumers have increased their income level, 2) the share of new to industry vehicle sales in considerably high and 3) the hybrid platform has not been diffused at a significant level. In the advanced region, the radical platform finds more opposition because the hybrid platform has already been diffused at significant levels. The radical platform does not always diffuse more successfully in the emerging region than in the advanced region. In fact, depending on other factors, such as: the preferences of consumers, the behavior of automakers and the development potential of the three vehicle platforms, new to industry vehicle sales in the emerging region could go to any of the three vehicle platforms.

Third, if the difference in consumers' preferences is such that consumers in the advanced region are more proficiency oriented and consumers in the emerging region are more price oriented, then, the hybrid platform always diffuses at a significant level earlier in the advanced region, than in the emerging region. In the emerging region, the diffusion of the hybrid platform shows a delay, and a lower penetration level. The more inclined consumers of the emerging region are towards price, the longer the delay, and the lower the level of diffusion of the hybrid platform. The radical platform shows a similar pattern. Therefore, in these cases, in the advanced region there is a two phased diffusion. First, the hybrid platform is widely adopted by consumer; second, the radical platform is later introduced to the market. In the emerging region, the radical platform in most of the cases fails to reach a level of sustained diffusion. In this case, the growing vehicle market of the emerging region is divided between the incumbent and hybrid platforms.

Alternative patterns of diffusion for the radical platform also occur when consumers are proficiency oriented in both regions, and when the development potential of the radical platform is higher than the potential of the other two platforms. In these cases, the diffusion of the radical platform occurs first in the emerging region, and significant diffusion of the radical platform occurs at the global level.

The analysis has also shown that the diffusion of alternative fuel vehicles becomes less uncertain when automakers behave as balanced investors. On the contrary, when automakers behave as market driven investors, the diffusion of alternative vehicle platforms becomes much more uncertain. In these cases, if consumers are price oriented, then the diffusion of these technologies fails in both regions, regardless of their development potential.

Regarding the development potential of the vehicle platforms, if the development potential of the three vehicle platforms is similar across the three platforms, then market differences have a strong influence in diffusion patterns. However, the more unbalanced the development potential of the three platforms is, the less determinant market differences become.

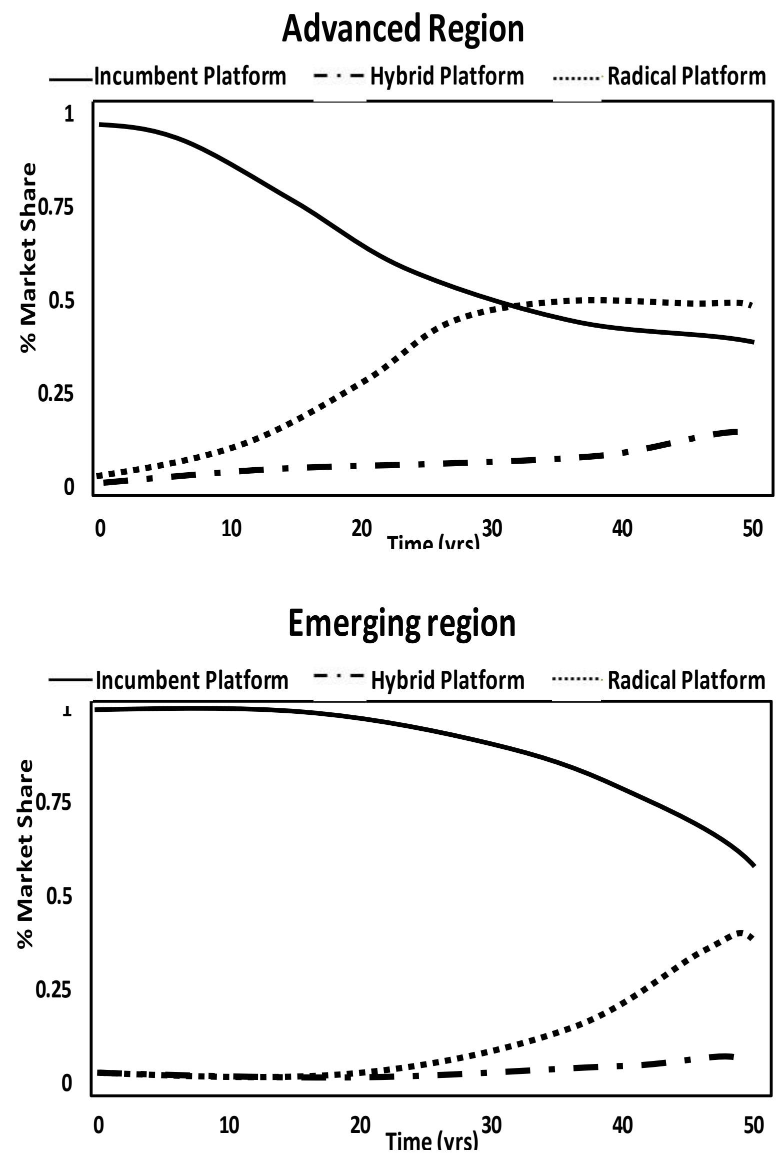


Figure 6. Reference case diffusion pattern, in this scenario the hybrid and the radical platform diffuse first in the advanced region, while in the emerging region only the hybrid platform penetrates the market.

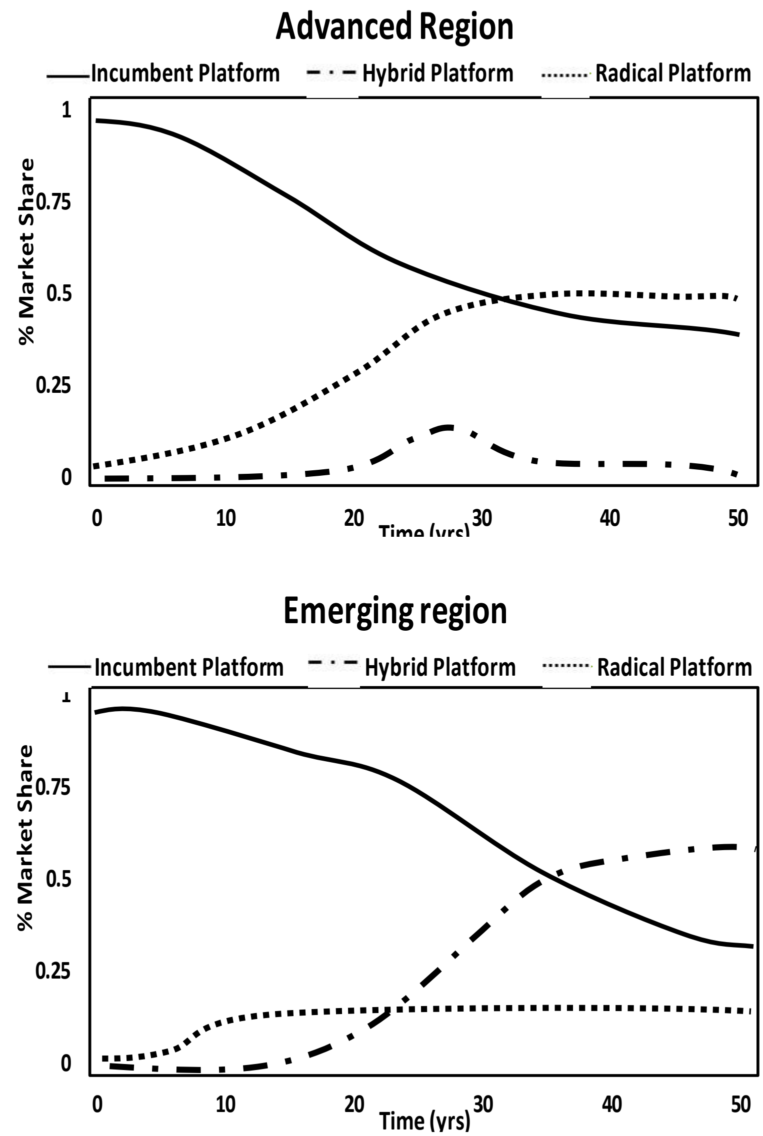


Figure 7. Alternative diffusion pattern; the radical platform fails in the advanced region, while it succeeds in the emerging region.

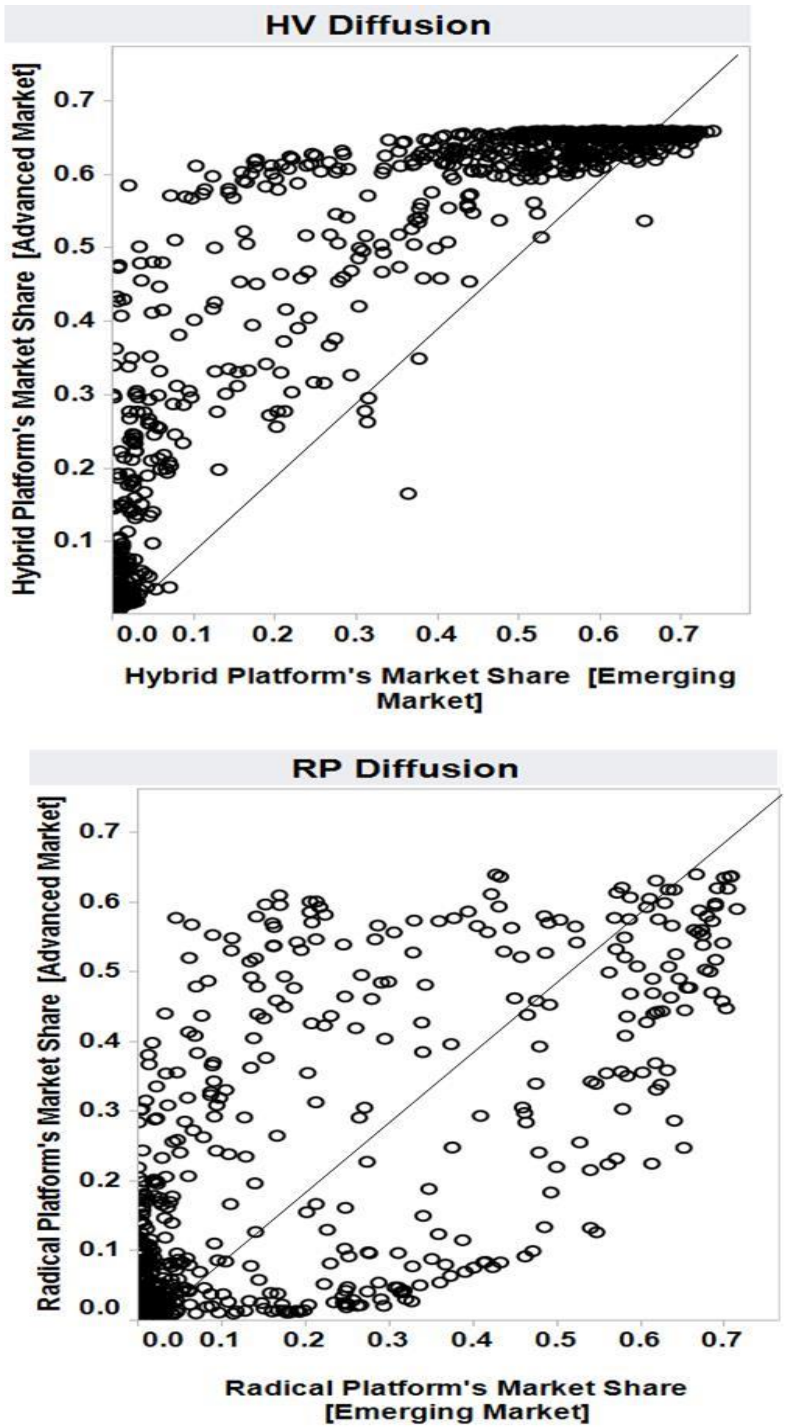
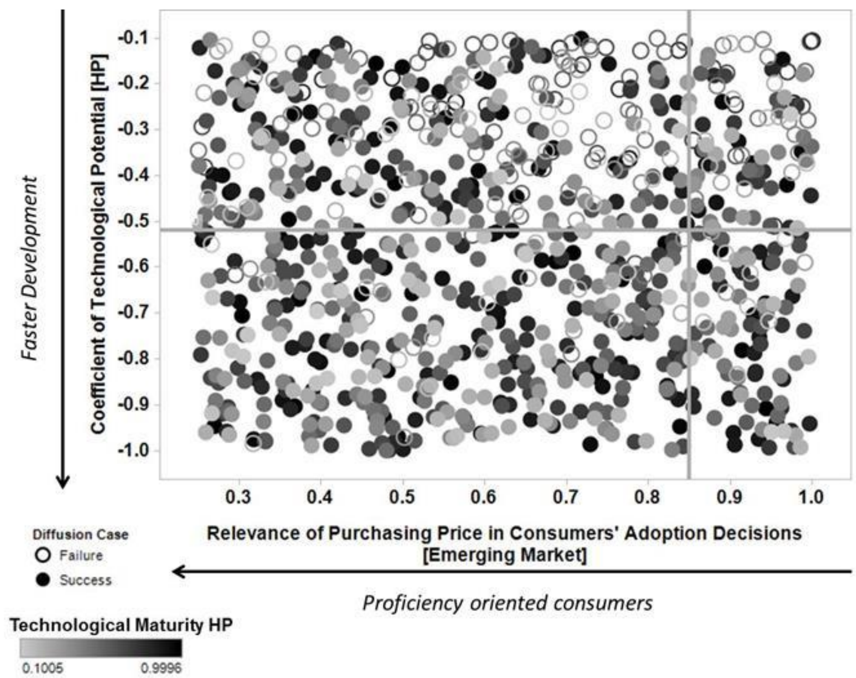


Figure 8. Simulation experiment results, each graph presents the penetration of the alternative fuel vehicles: hybrid platform (upper graph), and Radical Platform (bottom graph). The x-axis represents the penetration in the emerging market, the y-axis represents the penetration in the advanced market.



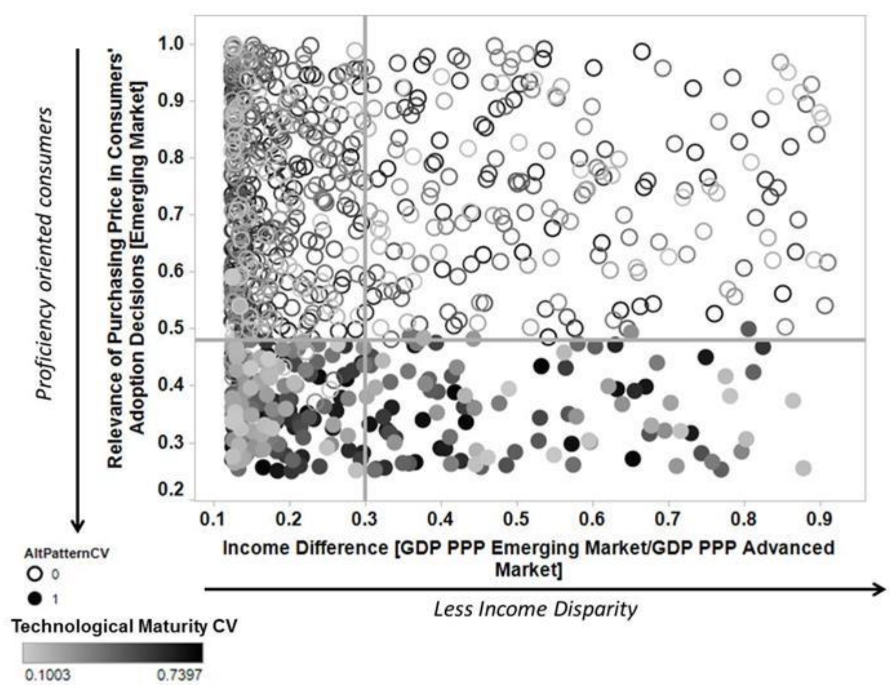


Figure 9. Trade-off analysis, the black dots represent success cases. In the upper graph success is defined as those cases in which the hybrid platform success in both markets. It displays the influence of technology potential and consumers' preferences on diffusion. In the bottom graph, success is defined as those cases in which the radical platform succeeds in the emerging market first than in the advanced market. It displays the influence of income differences and consumers preferences on the diffusion of the radical platform.

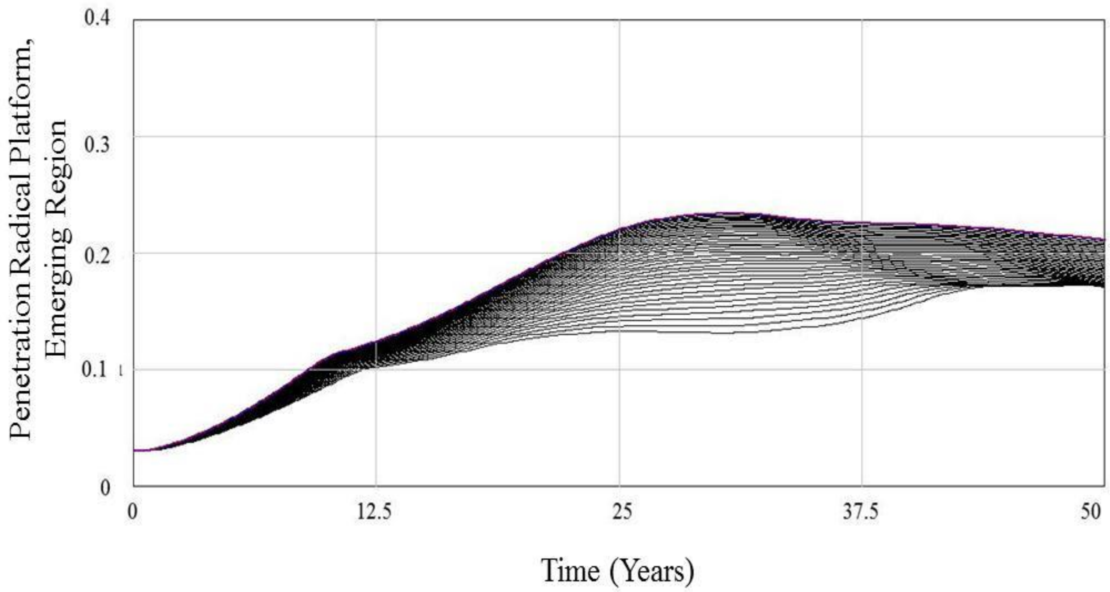


Figure 10. Example of dynamic behavior of the positive scenario cluster shown in Figure 9.

5. Policy Implications

The results of this exploratory analysis show that both regions are important for fostering a transition towards alternative fuel vehicles. It is clear that advanced economies are key players for supporting the transition towards these technologies. The early diffusion of alternative fuel vehicles in advanced economies can enhance their international commercialization by making them cheaper and increasing its performance. In principle, this improvement of alternative fuel vehicles should be enough to induce its diffusion in emerging markets. However, our analysis shows that this initial inertia in advanced economies can be exhausted, and thus threaten the global transition towards alternative fuel vehicles. This occurs because the vehicle market in advanced economies is expected to hardly grow in the future. Then, as consumers of advanced economies adopt hybrid vehicles, the second phase of this transition towards electrical vehicles can be severely slowed down due to the lack of a market niche for these new vehicles.

This increases the importance of emerging markets in this transition context. In contrast to advanced economies, in emerging markets, the vehicle market is expected to grow significantly. More importantly, in this region most of vehicle sales will be from consumers that for the first time purchase a vehicle. Thus, emerging markets have the potential of offering a complementary market niche for alternative fuel vehicles which cannot only support their diffusion, but accelerate it.

Several factors make this transition uncertain and ambiguous. Therefore, the situation previously described can only be expected to occur in a few scenarios. These cases point to the very importance of each actor in this transition case. The preferences of consumers are a key element in this transition. If consumers are proficiency oriented in both regions, then the situation described can be materialized. In the advanced economies, empirical results show that consumers are, on average, proficiency oriented (Bunch et al. 1993; Potoglou and Kanaroglou 2007). In contrast, in emerging markets this is more ambiguous and uncertain and we lack empirical data to know this in more detail. However, if the transition towards alternative fuel vehicles is to occur regardless of other contextual factors, then it is desired that consumers in emerging markets are proficiency oriented. This is quite relevant for policy makers. Here, attention must be paid to fostering the environmental awareness of consumers in emerging markets, and to implementing measures that can make consumers more conscious of their mobility carbon footprint.

There also relevant aspects of this research which are more relevant for automakers' technology policies. In this case, it has been shown that a balanced allocation of R&D resources to alternative fuel vehicles yields the most promising results for this transition case. Specifically, the results show that it is important for automaker to support the development of the radical platform before the vehicle market in emerging markets becomes as big as that of the advanced economies. If this is not done, the transition towards alternative fuel vehicles is likely to be lengthy, and less feasible.

Investing in alternative fuel vehicles might also become a matter of survival for global automakers. If consumers in both regions become more proficiency oriented, then the vehicle market will be extremely permissive to the introduction of alternative fuel vehicles. In these types of scenarios, if automakers bed their investments at maintaining the system's locked-in with the internal combustion engine, not even cheap and fuel efficient gasoline vehicles will prevent the transition towards alternative fuel vehicles. In this scenario, the most experienced and advance manufacturers with alternative technologies will benefit the most.

6. Conclusions

This research analyzes the effect of market differences between advanced and emerging markets on the diffusion of alternative vehicle platforms. A system dynamics simulation model was built to analyze this uncertain transition case. This model considers two generic regions resembling advanced and emerging markets, and three generic vehicle platforms: incumbent platform, hybrid platform, and a radical platform. The model considers also the interaction of several feedback mechanisms (social learning, R&D, learning by doing, network externalities and scale economies). It also takes into account the technology potential, maturity and spillovers of the vehicle platforms, as well as consumers' preferences and automakers behavior.

The analysis of several simulation experiments using the scenario discovery method (Bryant and Lempert 2010) shows that social and technological uncertainties can influence diffusion patterns of alternative fuel vehicles in three main ways:

First, the difference between consumers' income level between advanced and emerging markets creates a systematic delay in the diffusion of these technologies in emerging markets.

Second, the difference between vehicle markets' rate of growth has the potential of creating a strong market niche for electrical vehicles in the emerging region. On the one hand, in advanced economies most vehicle sales are replacement sales. In the emerging region, the opposite occurs, the vehicle market grows steadily, and most of vehicle sales are from consumers that for the first time purchase a vehicle. Our exploratory analysis shows that in a few scenarios if consumers consider in a more balanced way all the attributes of a vehicle (e.g. purchasing price, cost of fuel, fuel efficiency and driving range), the transition towards electrical vehicles becomes more likely in both regions. In this case, emerging markets can inject a strong impulse to the global diffusion of electrical vehicles at the global level.

Third, if the three vehicle platforms have a similar development potential, then market differences can play an important role in shaping diffusion patterns. However, the more unbalanced the development potential of the three platforms is, the less determinant market differences become.

Finally, we considered that the process of diffusion of alternative fuel vehicles can be enriched and strengthened if it is seen as a complementary process between advanced and emerging markets. Policy areas of concern are the support to the R&D of alternative fuel vehicles, the development of fuelling infrastructure for electrical vehicles and the encouragement of consumers to consider in a more balanced way all vehicles' attributes in their adoption decisions.

Table 2. Behavioral Clusters Hybrid Platform

Type of diffusion pattern	Social conditions influencing system's behavior	Technological conditions influencing system's behavior
A. Regional sustained diffusion of the hybrid platform. Sustained diffusion in the advanced region, failure in the emerging region	*Income differences between regions* *Vehicle market rate of growth differences between regions* *Automakers as balanced investor*	*High potential radical platform*
B. Regional sustained diffusion of the hybrid platform. Sustained diffusion in the emerging region; failure in the advanced region	*Income differences between regions* *Proficiency oriented consumers in the emerging region* *Price oriented consumers in the advanced region* *Automakers as market driven investors*	*High potential hybrid platform*
C. Global sustained diffusion of the hybrid platform. Parallel diffusion in both regions	*Income differences* *Proficiency oriented consumers in both regions* *Market driven investor automakers*	*High potential hybrid platform*
D. Global sustained diffusion of the hybrid platform. Leading diffusion in the emerging region	*Income differences* *Vehicle market rate of growth differences between regions* *Proficiency oriented users in the emerging region* *Price oriented users in the advanced region*	*Conservative development potential across platforms* *High potential incumbent platform* *High potential hybrid platform*
E. Global sustained diffusion of the hybrid platform. Leading diffusion in the emerging region.	*Market driven investor automakers*	*Conservative development potential across platforms* *High potential incumbent platform* *High potential radical platform*

Table 3. Scenario Clusters Radical Platform

Type of diffusion pattern	Social conditions influencing system's behavior	Technological conditions influencing system's behavior
A. Regional adoption of the radical platform. Initial adoption in the advanced region; failure in the emerging region	*Proficiency oriented users in the advanced region,* *Price oriented users in the emerging region* *Balanced investors automakers*	*Conservative development potential across platforms* *High potential incumbent platform*
B. Regional initial diffusion of the radical platform. Initial adoption in the emerging region; failure in the advanced region	*Vehicle market rate of growth differences between region* *Proficiency oriented users in the emerging region* *Price oriented users in the advanced region* *Market driven investors automakers*	*Conservative development potential across platforms* *High potential incumbent platform*
C. Regional sustained diffusion of the radical platform. Sustained diffusion in the emerging region, initial diffusion in the advanced region	*Vehicle market rate of growth differences between region* *Proficiency oriented users in the emerging region* *Price oriented users in the advanced region* *Market driven investors automakers*	*High potential radical platform*
D. Global sustained diffusion of the radical platform. Leading diffusion in the emerging region	*Vehicle market rate of growth differences between region* *Balanced investors automakers*	*High potential radical platform*
E. Global failure of the radical platform	*Market driven investors automakers* *Balanced investors automakers*	*High potential incumbent platform* *High potential hybrid platform* *High potential radical platform*

References

Achtnicht, M., G. Buhler, and C. Hermeling. 2012. "The impact of fuel availability on demand for alternative-fuel vehicles." *Transportation Research Part D-Transport and Environment* no. 17 (3):262-269. doi: 10.1016/j.trd.2011.12.005.

Amatucci, M., and F.Á.L. Mariotto. 2012. "The internationalisation of the automobile industry and the roles of foreign subsidiaries." *International Journal of Automotive Technology and Management* no. 12 (1):55-75.

Avadikyan, A., and P. Llerena. 2010. "A real options reasoning approach to hybrid vehicle investments." *Technological Forecasting and Social Change* no. 77 (4):649-661.

Bryant, B.P., and R.J. Lempert. 2010. "Thinking inside the box: A participatory, computer-assisted approach to scenario discovery." *Technological Forecasting and Social Change* no. 77 (1):34-49.

Bunch, D.S., M. Bradley, T.F. Golob, R. Kitamura, and G.P. Occhiuzzo. 1993. "Demand for clean-fuel vehicles in California: a discrete-choice stated preference pilot project." *Transportation Research Part A: Policy and Practice* no. 27 (3):237-253.

Colovic, Ana, and Ulrike Mayrhofer. 2011. "Optimizing the Location of R&D and Production Activities: Trends in the Automotive Industry." *European Planning Studies* no. 19 (8):1481-1498. doi: 10.1080/09654313.2011.586175.

Dawid, H. 2006. "Agent-based models of innovation and technological change." *Handbook of computational economics* no. 2:1235-1272.

Dechezlepretre, A., M. Glachant, I. Hascic, N. Johnstone, and Y. Meniere. 2011. "Invention and Transfer of Climate Change-Mitigation Technologies: A Global Analysis." *Review of Environmental Economics and Policy* no. 5 (1):109-130. doi: 10.1093/reep/req023.

Demirdoven, N., and J. Deutch. 2004. "Hybrid cars now, fuel cell cars later." *Science* no. 305 (5686):974-976. doi: 10.1126/science.1093965.

Farrell, A. E., D. W. Keith, and J. J. Corbett. 2003. "A strategy for introducing hydrogen into transportation." *Energy Policy* no. 31 (13):1357-1367. doi: 10.1016/s0301-4215(02)00195-7.

Gallagher, K. S. 2006. "Limits to leapfrogging in energy technologies? Evidence from the Chinese automobile industry." *Energy Policy* no. 34 (4):383-394. doi: 10.1016/j.enpol.2004.06.005.

Gallagher, K. S., and E. Muehlegger. 2011. "Giving green to get green? Incentives and consumer adoption of hybrid vehicle technology." *Journal of Environmental Economics and Management* no. 61 (1):1-15. doi: 10.1016/j.jeem.2010.05.004.

Geels, Frank W., and Johan Schot. 2007. "Typology of sociotechnical transition pathways." *Research Policy* no. 36 (3):399-417. doi: 10.1016/j.respol.2007.01.003.

Hall, Jeremy, Stelvia Matos, Bruno Silvestre, and Michael Martin. 2011. "Managing technological and social uncertainties of innovation: The evolution of Brazilian energy and agriculture." *Technological Forecasting and Social Change* no. 78 (7):1147-1157. doi: 10.1016/j.techfore.2011.02.005.

Hekkert, M. 2006. "Competing technologies and the struggle towards a new dominant design." *Greenleaf Publishing* no. 34:29-43.

Heneric, O., G. Licht, and W. Sofka. 2005. "Europe's Automotive Industry on the Move: Competitiveness in a Changing World." *ZEW Economic Studies (32)*.

Hu, Mei-Chih, Shih-Chang Hung, and Jian Gao. 2011. "Emerging technologies in emerging markets: Introduction to the special section." *Technological Forecasting and Social Change* no. 78 (7):1101-1103. doi: 10.1016/j.techfore.2011.03.019.

Hu, Mei-Chih, and Fred Phillips. 2011. "Technological evolution and interdependence in China's emerging biofuel industry." *Technological Forecasting and Social Change* no. 78 (7):1130-1146. doi: 10.1016/j.techfore.2011.02.013.

Jacobsson, S., and V. Lauber. 2006. "The politics and policy of energy system transformation - explaining the German diffusion of renewable energy technology." *Energy Policy* no. 34 (3):256-276. doi: 10.1016/j.enpol.2004.08.029.

Kemp, R., J. Schot, and R. Hoogma. 1998. "Regime shifts to sustainability through processes of niche formation: The approach of strategic niche management." *Technology Analysis & Strategic Management* no. 10 (2):175-195. doi: 10.1080/09537329808524310.

Kohler, J., L. Whitmarsh, B. Nykvist, M. Schilperoord, N. Bergman, and A. Haxeltine. 2009. "A transitions model for sustainable mobility." *Ecological Economics* no. 68 (12):2985-2995. doi: 10.1016/j.ecolecon.2009.06.027.

Leung, V. 2011. "Slow diffusion of LPG vehicles in China-Lessons from Shanghai, Guangzhou and Hong Kong." *Energy Policy* no. 39 (6):3720-3731. doi: 10.1016/j.enpol.2011.03.081.

Ozaki, R., and K. Sevastyanova. 2011. "Going hybrid: An analysis of consumer purchase motivations." *Energy Policy* no. 39 (5):2217-2227. doi: 10.1016/j.enpol.2010.04.024.

Pavitt, Keith. 1984. "Sectoral patterns of technical change: Towards a taxonomy and a theory." *Research Policy* no. 13 (6):343-373. doi: 10.1016/0048-7333(84)90018-0.

Pavlinek, P. 2012. "The Internationalization of Corporate R&D and the Automotive Industry R&D of East-Central Europe." *Economic Geography* no. 88 (3):279-310. doi: 10.1111/j.1944-8287.2012.01155.x.

Pillania, Rajesh K. 2011. "The state of research on technological uncertainties, social uncertainties and emerging markets: A multidisciplinary literature review." *Technological Forecasting and Social Change* no. 78 (7):1158-1163. doi: 10.1016/j.techfore.2011.02.006.

Potoglou, D., and P. S. Kanaroglou. 2007. "Household demand and willingness to pay for clean vehicles." *Transportation Research Part D-Transport and Environment* no. 12 (4):264-274. doi: 10.1016/j.trd.2007.03.001.

Raven, R. 2007. "Niche accumulation and hybridisation strategies in transition processes towards a sustainable energy system: An assessment of differences and pitfalls." *Energy Policy* no. 35 (4):2390-2400.

Sterman, J.D. 2000. *Business dynamics: systems thinking and modeling for a complex world*. Vol. 19: Irwin/McGraw-Hill New York.

Struben, J., and J. Sterman. 2008. "Transition challenges for alternative fuel vehicle and transportation systems." *Environment and Planning B: Planning and Design* no. 35 (6):1070-1097.

Struben, J.J.R. 2006. *Essays on transition challenges for alternative propulsion vehicles and transportation systems*, Massachusetts Institute of Technology.

Sturgeon, T., J. Van Biesebroeck, and G. Gereffi. 2008. "Value chains, networks and clusters: reframing the global automotive industry." *Journal of Economic Geography* no. 8 (3):297-321.

Sturgeon, Timothy J., Olga Memedovic, Johannes Van Biesebroeck, and Gary Gereffi. 2009. "Globalisation of the automotive industry: main features and trends." *International Journal of Technological Learning, Innovation and Development* no. 2 (1):7-24. doi: 10.1504/ijtlid.2009.021954.

Unruh, G.C. 2000. "Understanding carbon lock-in." *Energy Policy* no. 28 (12):817-830.

Vernon, R. 1966. "International investment and international trade in the product cycle." *The quarterly journal of economics*:190-207.

Walther, G., J. Wansart, K. Kieckhafer, E. Schnieder, and T. S. Spengler. 2010. "Impact assessment in the automotive industry: mandatory market introduction of alternative powertrain technologies." *System Dynamics Review* no. 26 (3):239-261. doi: 10.1002/sdr.453.

Yeh, Sonia. 2007. "An empirical analysis on the adoption of alternative fuel vehicles: The case of natural gas vehicles." *Energy Policy* no. 35 (11):5865-5875. doi: 10.1016/j.enpol.2007.06.012.

Yucel, G., and Y. Barlas. 2010. "Dynamics of the North-South welfare gap and global sustainability." *Technological Forecasting and Social Change* no. 77 (4):594-614. doi: DOI 10.1016/j.techfore.2009.11.004.

Yücel, Gönenç. 2010. "Analyzing Transition Dynamics: The Actor-Option Framework for Modelling Socio-Technical Systems." *Delft University of Technology*.

Zhao, J. M., and M. W. Melaina. 2006. "Transition to hydrogen-based transportation in China: Lessons learned from alternative fuel vehicle programs in the United States and China." *Energy Policy* no. 34 (11):1299-1309. doi: 10.1016/j.enpol.2005.12.014.