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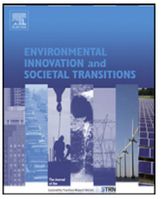

Effective public resource allocation to escape lock-in: The case of infrastructure-dependent vehicle technologies

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ABSTRACT

A multi-stage technological substitution model of infrastructure-dependent vehicle technologies is developed. This is used to examine how the allocation of public, financial resources to RD&D support and infrastructure development affects the replacement of a locked-in vehicle technology by more sustainable ones. Although consumers eventually determine which vehicle technology will be successful, intervention and financial support by public agencies can affect the technological substitution process. Computer simulations provide insights into the trade-off between investing in RD&D, i.e. the creation of new technological options (variety), and investing in infrastructure development for these technologies. The paper ends with policy recommendations.

1. Introduction

The lock-in of society into a dominant technology is one of the main barriers to the diffusion of new technologies (Unruh, 2000, 2002). This risk of lock-in is particularly high for infrastructure-dependent vehicle technologies which are characterized by high infrastructure investment costs and the presence of network externalities, two mechanisms that make it difficult to escape lock-in (Gómez-Ibáñez, 2003; Azar and Sandén, 2011). When the currently dominant technology is considered undesirable

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for society, governments may implement policy measures to facilitate the escape from the existing lock-in and the transition to a more sustainable technology.

The substitution of a dominant, locked-in vehicle technology by a new vehicle technology can be seen as an evolutionary process characterized by variety creation and selection (Nelson and Winter, 1982; Dosi and Nelson, 1994). Policymakers that seek to influence technological change can apply a wide range of instruments. These may stimulate investments in RD&D, for example, which lead to increased variety. Other measures such as favorable tax regimes, investment in new infrastructure and carbon pricing target the selection and diffusion process (van der Vooren and Alkemade, forthcoming). The government or public regulator has to decide how to stimulate the different processes.

This problem is similar to the exploration versus exploitation dilemma in studies on organizational strategy (March, 1991): First, the public budget for government intervention is limited. Second, the technological substitution process is characterized by feedback mechanisms and intervention in one part of the process influences the success of intervention in other parts. Third, the optimal level of technological variety is unknown. The literature indicates that the existence of technological diversity is a prerequisite for the escape of lock-in (Arthur, 1989; van den Bergh, 2008; Metcalfe, 1994). However, while variety is necessary to escape lock-in, too much variety may lead to increased consumer uncertainty and delayed adoption by end consumers. Furthermore, too much variety reduces the benefits of increasing returns to scale for technology suppliers (Geroski, 2000). It is thus difficult to decide upon an adequate level of variety, especially in situations where a limited budget for the creation and (long term) support of technological options is available (van den Bergh et al., 2011). Fourth, although innovations do tend to cluster in time and space (Freeman and Louçã, 2001), different technological alternatives may enter the market at different moments, which makes it difficult to evaluate the technological options.

The main research question that we will address in this paper is therefore: how does the allocation of public financial resources to RD&D and infrastructure development affect the technological substitution process of infrastructure-dependent vehicle technologies?

We address this question by building an agent-based simulation model in which alternative vehicle technologies emerge that may replace the dominant, unsustainable technology. The model allows us to compare and analyze the effects of different public resource allocations to low emission vehicle RD&D (variety creation) and infrastructure development (selection). The allocation of financial resources to variety creation, for example, through RD&D investments, may lead to the emergence of new technological options. Financial resource allocation to infrastructure development, such as the development of refuelling or recharging infrastructure in the case of vehicle technologies, is needed to support the market introduction of some of the new technological options.

The remainder of this paper is structured as follows. Section 2 provides a brief overview of the relevant literature and the agent-based model of technological substitution of infrastructure-dependent vehicle technologies is presented in Section 3. Next, Section 4 presents and interprets the results of numerical simulations with the model. Section 5 offers an interpretation of the results in the context of sustainability transitions. Finally, Section 6 concludes and provides policy implications.

2. Theoretical framework

The substitution process of infrastructure-dependent vehicle technologies is a multi-stage process (Knudsen and Levinthal, 2007). The process starts from a situation of lock-in and in the first stage the creation of alternatives (technological variety) to the dominant design is supported with financial support for RD&D. In the second stage some of the new technologies receive government support for infrastructure development before being subjected to market forces in the third stage, the stage of consumer adoption. Below, we discuss the three stages of this technological substitution process in more detail, but we start with a discussion on lock-in.

2.1. Lock-in

A dominant design refers to a technology that is the most successful on the market and becomes the standard for future designs. The emergence of a dominant design is the result of the interplay between technical and market choices (Utterback, 1994). Often, dominant technologies emerge from the competition between a number of alternative technologies (Abernathy and Utterback, 1978; Anderson and Tushman, 1990). For example, today's dominant internal combustion engine vehicles competed with electric- and steam-powered cars to succeed the old technology of horse-drawn carriages.

The determinants of lock-in can be found in path-dependent processes (David, 1985), which are the result of increasing returns to adoption (Unruh, 2000; Arthur, 1988), such as learning by using (Rosenberg, 1982), scale economies, informational increasing returns, technological interrelatedness (Frankel, 1955) and network externalities (Katz and Shapiro, 1985). The effects of these determinants are even stronger when a technology depends on the availability of physical infrastructure. Infrastructure-dependent vehicle technologies can be subject to both direct and indirect network externalities (Katz and Shapiro, 1985; Koski and Kretschmer, 2004). Direct network externalities occur when a technology is valued more highly when the number of adopters increases. Indirect network externalities occur when the availability of complementary goods increases with an increased number of users, thereby indirectly increasing the value of the technology. This is the case for cars that depend on the availability of fuel stations. Increasing returns to adoption for the old technology can hinder the diffusion of newer, possibly superior technologies (Arthur, 1988; Frenken et al., 2004).

A dominant technology forms the selection environment for the new technology. New technologies initially often show higher prices and poor performance in comparison to the incumbent technology (Rosenberg, 1976), and when these new technologies depend on the availability of a physical infrastructure (that is incompatible with the existing infrastructure), overcoming lock-in is even more difficult.

2.2. *Stage 1: public support for RD&D*

Although difficult to overcome, history shows that lock-in is often a temporary phenomenon from which escape is possible. Technology-push and demand-pull processes can give rise to new options or inventions that replace existing technologies (Dosi, 1982). Demand-pull processes occur when consumer preferences regarding technological performance change in response to dissatisfaction with the current (unsustainable) technological paradigm. Technology-push processes occur when, for example, the government supports a new technological option through adapted regulation or financial support for RD&D.

Although it is very difficult to determine *ex ante* which of the newly created technologies will succeed in replacing the incumbent technology (Kemp et al., 1999), stimulating variety is often part of policy schemes that aim to replace the current dominant technology by a preferred alternative, like in the Dutch energy transition program (Smith and Kern, 2009; Kern and Howlett, 2009; Stirling, 2010).

Public RD&D support in this first, pre-market, stage offer actors a financial compensation for their exploratory efforts. Although, such support schemes sometimes already involve elements of selection, this paper considers public RD&D support as a contribution to technological variety (see, for example, IEA (2007), on pre-award/*ex ante* selection and Knudsen and Levinthal (2007) on alternative generation). For policymakers, the question at this stage is what part of their total budget should be spent on public RD&D support in order to escape the existing lock-in (Stirling, 2010).

2.3. *Stage 2: public support for infrastructure development*

Governments can influence the rate and direction of technological change before infrastructure-dependent vehicle technologies actually compete on the market. It is especially this stage between the invention of a new technology and its deployment in large scale pilot projects where many innovations fail. This phase is therefore sometimes called the 'valley of death' of technology development.

For infrastructure-dependent vehicle technologies, support often takes the form of subsidies to install (refuelling) infrastructure or the implementation of a price subsidy in order to decrease the distance-to-market for the new technologies. Given the inherent uncertainty of the innovation process, it is difficult to evaluate the different alternatives and to decide which and how many technological options to support.

2.4. Stage 3: consumer adoption

The adoption of a technology by consumers is the final stage of the technological substitution process because consumers eventually determine which technology is diffused throughout the population. In this third stage, the different alternative options for the dominant design compete with each other and with the current locked-in dominant design (Arthur, 1988). On the market the main selection criteria are the price of the technology and the degree to which the technological characteristics of the new technology fit consumer preferences (including preferences for sustainability) (Lancaster, 1971). For infrastructure-dependent vehicle technologies, the availability of infrastructure is an important factor in user preferences (Bunch et al., 1993; O'Garra et al., 2005).

This market selection environment is not static as consumer preferences evolve due to the availability of new technologies or due to exogenous forces that stress technological and service characteristics that differ from the characteristics of the current dominant design. Consumers might, for example, develop preferences for more sustainable vehicles or for vehicles with air-conditioning. Both the incumbent technology and the new technological options may benefit from this changing selection environment. When the incumbent technology successfully adapts to the changing environment this is called the “sailing ship” effect (Harley, 1973; Geels, 2002).

2.5. The allocation problem

When designing a policy scheme to support low emission vehicles policymakers have to decide how to allocate public financial resources to the development of new technologies (RD&D: stage 1) and infrastructure development (stage 2) in order to stimulate the adoption of a more sustainable technology by consumers (stage 3). The literature illustrates that this allocation decision is not trivial.

Regarding the first stage, the literature suggests that more variety creation is better because subsequent support leads to better outcomes when there is greater variety, as more variety leaves open more future options and leads to an increased probability of successful recombination and spillovers (Fisher, 1930; Metcalfe, 1994; van den Bergh, 2008; Zeppini and van den Bergh, 2011). The effects of increased variety in the next stage, where some technologies receive support for infrastructure development, are less clear. On the one hand, variety compensates for the uncertainty associated with the (future) performance of each technological option (Alkemade et al., 2009). On the other hand, as infrastructure-dependent vehicle technologies are characterized by increasing returns to scale, there are costs associated with maintaining diversity in this stage. In a model of optimizing the benefits and costs of diversity, van den Bergh (2008) finds that under increasing returns to scale, diversity is only attractive when the payoffs of diversity are sufficiently large. Other arguments, why increased variety in this stage might decrease the probability of overcoming lock-in, can be found in the increased level of competition between the alternative technological options, the increased level of uncertainty for consumers and the decreased probability of establishing a new technological standard. With regard to the level of competition moderate competition is considered to improve the chances of overcoming lock-in as rivalry among technologies gives incentives to further improve the technology (Gruber and Verboven, 2001; Koski and Kretschmer, 2004, 2005). Fierce competition among a large number of competing alternatives can slow consumer adoption of the new technology as it leads to increased consumer uncertainty. This uncertainty may cause consumers to postpone their adoption decision because of the risk of selecting a technology that fails to generate network externalities and loses the competition (Geroski, 2000). While moderate variety thus seems beneficial in the first stage, the adequate level of variety is less clear in subsequent stages. As public financial resources are limited and the uncertainty regarding future technological performance is high, deciding on how to allocate resources between the different stages is complex. In the next section we present a model that allows us to explore this resource allocation problem.

3. A model of technological substitution

The general structure of our model in Fig. 1 shows that policymakers intervene by allocating financial resources to stage 1 and stage 2. Budget allocation to public support for RD&D (B_1) results in

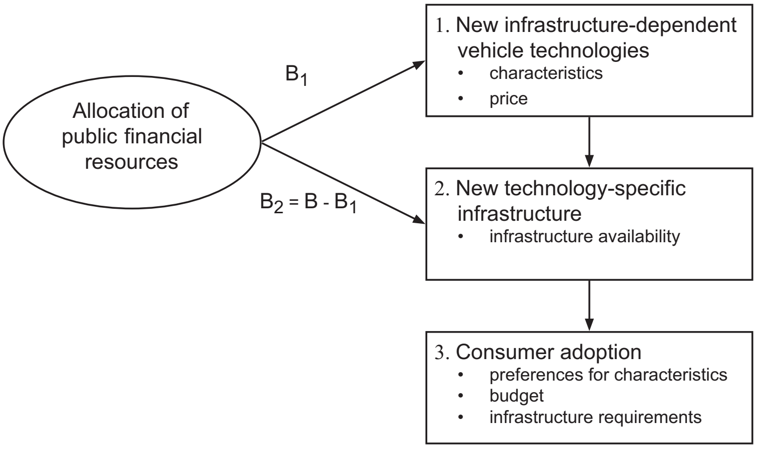

Fig. 1. Structure of the model.

the creation of technological variety. The technological options differ in initial price and performance on the technological characteristics. Budget allocation to stage 2 (B_2) leads to technology-specific infrastructure development for the newly created technological options. In stage 3 consumer adoption determines if the locked-in technology will be replaced by one of the new technologies, that is if technological substitution occurs. Below a more elaborate description of the model is given.

The model starts from a situation of lock-in into a single technological option, labeled as the incumbent technology. We define lock-in as the situation where the incumbent technology is adopted by at least 90% of the consumers. We run the model to analyze the effects of different allocations of financial resources to stage 1 and stage 2. The budget allocated to the first stage (B_1) depends on the technological variety, that is the number of technological options (I_1) that receive RD&D support, times the costs of RD&D support per technological option (c). The budget allocation $B_2 = B - B_1$ to the second stage determines how much support for infrastructure development the technological options (I_2) that are selected for infrastructure support receive. The I_2 technological options that receive infrastructure support are selected randomly, reflecting that it is difficult for policymakers to evaluate the performance of each technological option before it is actually on the market. Vehicle technologies that do not receive support will not enter the market and are therefore not available for consumer adoption in stage 3.

In the third and final stage, the infrastructure-dependent vehicle technologies compete for market share with the incumbent and locked-in technology as well as with each other. The number of consumers that adopt a certain technology determines the market share of that technology. Consumers base their adoption decision on the availability of infrastructure and on the degree to which a technology fits their individual preferences and budget. The remainder of this section gives a detailed description of the model components (technologies, infrastructure and consumers) and their interactions.

3.1. Technologies

In the model, a technology i is described by its performance on a set of characteristics $X_i \in [0, 1]$, as in Lancaster (1971) and Saviotti (1996), and by its price P. Not all characteristics are considered equally important and the way the different characteristics are valued can change over time. Furthermore new characteristics such as environmental performance can become important. These changes in the selection environment are an important driver of technological change (Dosi, 1982).

The current dominant design shows a high performance on the characteristics that are 'traditionally' considered important by consumers as it has co-evolved with, and thus has become adapted to, its selection environment. Fossil fuel-based internal combustion engine vehicles, for example, show

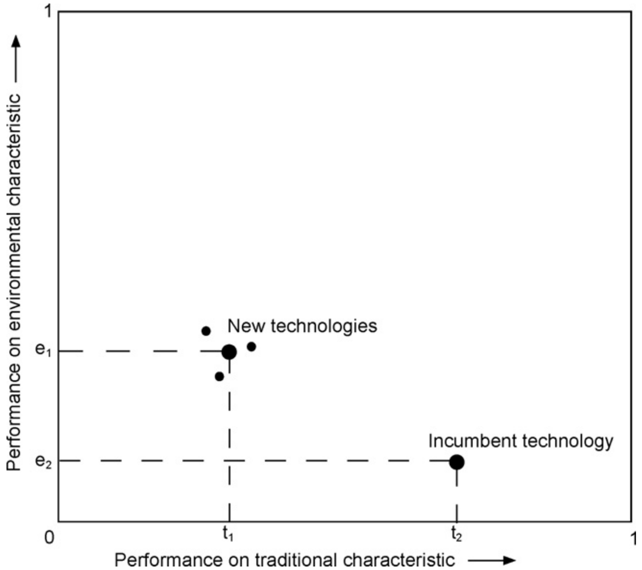

Fig. 2. The initial performance of technologies in a traditional and a environmental performance dimension.

a high performance on 'traditional' characteristics such as driving range and maximum speed. When technology-push or demand-pull factors change the selection environment, consumers may take into account a different set of characteristics in their adoption decision. In the case of vehicle technologies environmental performance characteristics like fuel consumption and CO_2 emissions have recently gained importance due to concerns about climate change. New technological options, such as electric vehicles, perform better on these newly evaluated environmental performance characteristics than the incumbent technology, possibly leading to an increase of consumer adoption of the new technologies. This is not necessarily the case however, as incremental innovation may also improve the environmental performance of the incumbent technology.

We model this process in the following way: we assume that the emergence of new technological options in stage 1 expands the set of characteristics that consumers consider in their adoption decision. Thus, consumers do not only evaluate the traditional performance characteristics but also take into account the environmental performance characteristics of a technology, although not all consumers will consider environmental performance characteristics important in comparison with the traditional characteristics. On average, new technologies are assumed to initially show a better performance on these newly considered environmental performance characteristics than the incumbent one, but a worse performance on the traditional characteristics.

Fig. 2 shows the initial performance of vehicle technologies in two performance dimensions, a 'traditional' and an 'environmental' dimension. The performance of technologies on each of the characteristics is valued between 0 and 1. The incumbent technology performs high on the 'traditional' characteristic but low on the 'environmental' characteristic. On average, the emerging technologies perform higher on the 'environmental' characteristic but lower on the 'traditional' characteristic than the incumbent technology. The initial performance is drawn randomly from a normal distribution with mean t or e. For incumbent technologies $t = t_2$ on the traditional characteristic and $e = e_2$ on the environmental characteristic. For the new technologies $t = t_1$ on traditional characteristics and $e = e_1$ on the environmental characteristic. As can be seen in Fig. 2 technologies are initialized with $t_1 < t_2$ and $e_2 < e_1$. The emerging technologies do not have the same performance on the different characteristics. Stirling (2007, 2011) identifies balance and disparity as important aspects of diversity in addition to variety. Variety refers to the number of different technological options, while balance describes the relative shares of each of the technological options. Disparity denotes how different the options are from each other. The average technological distance between the emerging technologies is higher for a higher disparity, which is the modelled as the variance of t_1 and e_1.

Upon market entry, the price of newly created technologies is assumed to be higher than the price of the incumbent technology. The initial price of new technologies P_{i0} is equal to the initial price of the incumbent technology plus a random premium ϵ.[1]

3.2. Infrastructures

Infrastructure-dependent vehicle technologies depend on the availability of a specific infrastructure, such as refuelling or recharging infrastructure, and consumers consider the availability of this infrastructure in their adoption decision. Infrastructure is technology-specific in the model presented here meaning that there is no compatibility between technology x and the infrastructure for technology y. The initial infrastructure availability for a technology is determined by the budget allocated by the policymaker to infrastructure development (B_2). This budget is equally divided among the selected technologies I_2. The initial infrastructure availability $A_{i(0)}$ of technology i is given by the following equation where κ represents the factor between financial resources and infrastructure availability and ρ represents initial investments in infrastructure availability by private firms:

$$A_{i(0)} = \kappa \times \left(\frac{B_2}{I_2}\right) + \rho. \tag{1}$$

3.3. Consumers

The consumers in the model will adopt a technology that meets all their requirements. Consumers are myopic and do not take into account the positive and negative consequences of their behavior, but base their decisions solely on past events and have no expectations about the future (Arthur, 1989). Consumers are characterized by fixed budget constraint m and infrastructure availability requirements a. Furthermore, consumers are heterogeneous and have different weights for the performance of the characteristics of a technology $x \in X$. A consumer's budget constraint m and infrastructure availability requirements a are drawn randomly from a normal distribution. The performance of a technology is valued in relation to the technological frontier. The maximum observed performance x_{max} on a characteristic x, over all technologies, is taken as a benchmark for that characteristic. The individual consumer weights φ for each characteristic x are drawn from a normal distribution with a mean equal to this benchmark x_{max}: $\varphi \sim N\left(x_{max}, \sigma^2\right)$. When the performance of the available technologies on a certain characteristic increases, the consumer weights for the performance on that characteristic increase as well, representing a technology-push mechanism. Consumer choice depends on how a consumer weighs the performance and the price of the technologies, and on the infrastructure availability for that technology. The decision making process is described in more detail below:

1. *Adoption decision:* The probability that a consumer reconsiders his previous adoption decision and seeks to purchase a new vehicle is ω in each time step, where ω is the average replacement rate. When the consumer adopts a new vehicle, his current vehicle is replaced by either a new vehicle technology or the same vehicle technology as before, which might have improved on some characteristics.
2. *Determine weights for characteristics:* The consumer updates his weights for the technology characteristics given the current state of the technological frontier as described above.
3. *Identify affordable technologies:* A consumer only considers adopting a technology when the current price of that technology is within his budget constraint.
4. *Assess infrastructure availability:* A consumer only considers adopting a technology when the current availability of infrastructure for that technology satisfies his infrastructure requirements.
5. *Determine utility:* For those technologies that fulfill all requirements, the utility the consumer derives from the performance characteristics of that technology is calculated. Utility U_i is the utility of

[1] For the initial price of the incumbent technology, see Appendix A.

consuming the set of characteristics X_i of a technology *i* (Windrum and Birchenhall, 2005; Lancaster, 1971). A simple Cobb–Douglas utility function determines the utility of each technology for an individual consumer:

$$U = x_1^{\varphi_1} x_2^{\varphi_2} \tag{2}$$

6. *Select and adopt technology:* Finally, the consumer weighs the utility and price of the technologies taken into consideration. When multiple options are considered the consumer adopts the technology with the highest utility/price ratio: $U_i/P_i^{(\varphi_1+\varphi_2)}$. The adoption decision of a consumer thus consists of both hard constraints (1, 3 and 4) and soft constraints (2, 5 and 6).

The interactions of the different model components determine the dynamics of the model and are discussed below. The characteristics, prices and infrastructure availability of infrastructure-dependent vehicle technologies change over time.

3.4. Technology dynamics

When new technologies such as low emission vehicles enter the market this can be considered a radical innovation. After market introduction these new technologies continue to evolve due to incremental innovation and learning effects. Incremental innovation in a technology occurs when the performance of that technology on one of its technological characteristics increases. This improves the competitive position of that technology and results in an increase of the number of adopters when the direction of technological change aligns with consumer preferences. Technological progress due to incremental innovation is modelled as a stochastic process in order to capture the inherent uncertainty of R&D as in Aghion and Howitt (1992) and Malerba and Orsenigo (2002). Each time step of the model innovation can only occur in one characteristic of a technology, representing a focus of the firm's innovation efforts (Moore, 1965; Nagy et al., 2011). Furthermore, innovation is path-dependent (David, 1985); once a firm has built up substantial technological capabilities in engine efficiency, additional R&D efforts in this area are more likely to lead to successful innovation than R&D efforts in areas where the firm has no prior experience. Performance increases in a certain characteristic are thus more likely if the firm's previous innovation efforts have focused on this characteristic.

This is modelled as follows: the probability that characteristic $x \in X_i$ of technology *i* is selected for innovation is equal to the cumulative number of innovations in characteristic *x* of technology *i* divided by the cumulative number of innovations in all characteristics of the technology *i* ($\mathrm{Cum}_{xi}/\mathrm{Cum}_i$). The state of a characteristic after incremental innovation is given by Eq. (3), where γ is the incremental innovation rate.[2] The effects of incremental innovation are large at first, but the effects of subsequent incremental innovations in a characteristic diminish over time as in a standard learning curve (Junginger et al., 2005, 2006).

$$x_{i(t+1)} = x_{i(t)}^{\gamma} \tag{3}$$

Besides changes in the characteristics of a technology, the price of a technology can also change over time. The price of a technology decreases over time due to scale economies, learning by doing and R&D (Wright, 1936; Ferioli et al., 2009). An increase in the consumer adoption of a technology causes a decline in a technology's purchase price (Mansfield, 1988; Arrow, 1962). The effects of a price decrease on consumer adoption are twofold: first, a price decrease makes the technology affordable to a larger group of consumers. Second, it increases the utility/price ratio of that technology. Both effects may lead to increased adoption. This relationship between price and the number of adopters is given by a standard learning-curve as in Cantono and Silverberg (2009):

$$P_{i(t)} = P_{i(0)} \cdot \left(\frac{c_{i(0)}}{c_{i(t)}}\right)^{\alpha}, \tag{4}$$

[2] Incremental innovation can be unsuccessful if ($\gamma > 1$). In this case the incremental change is not adopted and the state of the characteristic remains unaltered.

where $P_{i(t)}$ is the price of technology *i* at time *t*, $P_{i(0)}$ the initial price of the technology, $c_{i(0)}$ the initial number of consumers, $c_{i(t)}$ the cumulative number of consumers of a technology and α the learning ability of a technology.

3.5. Infrastructure dynamics

Infrastructure co-develops with the size of the adopter group, due to indirect network externalities. On the one hand, an increase in infrastructure availability can enlarge the group of potential adopters, because more consumers will take the technology into consideration. On the other hand, an increase in the number of adopters of a technology leads to a higher availability of the infrastructure(s) for that technology because this attracts investors (Grübler, 1990). For example, low emission vehicles, such as battery electric vehicles, become more attractive when the availability of recharging points increase and an increase in battery electric vehicles will attract more investors in recharging points. Infrastructure availability A_i is described by Eq. (5):

$$A_{i(t)} = \max(A_{i(t-1)}, A_{i(0)} + S_{i(t)}), \tag{5}$$

where $A_{i(0)}$ is the infrastructure availability at the time of emergence, $S_{i(t)}$ is the market share of technology *i* which is equal to the number of consumers that possess technology *i* at time *t* divided by the total number of consumers *N*.

4. Simulation settings and results

The simulation model is used to analyze how the allocation of public budget to the stages of public RD&D support and support for infrastructure development affects the technological substitution process. The model is run for different conditions by varying three independent parameters: *total budget*, *RD&D costs per technological option*, and *disparity*. The total budget *B* that can be allocated to public RD&D support and infrastructure development is fixed at 1 in the simulations. Thus, an increase in budget allocated to public RD&D support (*B*1) corresponds with a decrease of the budget that is available to support the infrastructure development (*B*2) of the emerging technologies. Since, the balance between costs of RD&D and infrastructure development is not trivial, this section presents the probability of technological substitution for different RD&D costs per technological option: zero (0), low (1/30), medium (1/15) or high (1/10). These different cost levels allow us to explore scenarios where the relative balance between the costs of RD&D and infrastructure development differs. Moreover, these parameter settings allow both for conditions where there is ample support for RD&D and infrastructure development and conditions where the budget is limited due to high costs of RD&D per technological option. When the RD&D costs per technological option are high (1/10), allocating the complete budget to public RD&D support results in the creation of ten technological options; however no budget will be left to support the infrastructure development of these ten technological options. Allocating the complete budget towards the infrastructure development of a single technological option results in the development of around 30% of the infrastructure for that technological option (see Eq. (1)). The literature suggests that an initial infrastructure availability between 15 and 20% is sufficient for the wide spread diffusion of vehicle technologies (Melaina, 2003; Melaina and Bremson, 2003; Huétink et al., 2010). The exact level of infrastructure development that is sufficient for consumer adoption also depends on the technological characteristics of the vehicle, such as the range, and may thus be different for different technological options, more empirical research is needed here.

Disparity refers to the initial technological distance between the new technological options (see Section 3). Disparity is modelled by changing the variance σ^2 of the normal distribution function that sets the initial performance of the emerging technologies and can be zero (0), low (0.02), medium (0.04) or high (0.06). The average technological distance between the emerging technologies is higher for a higher disparity. The probability of technological substitution is expected to increase for a higher disparity, because in this case the technologies cover a wider area of the so-called search space (Frenken, 2006; Silverberg and Verspagen, 2007).

Table 1
Overview of all possible allocations of budget to RD&D support and infrastructure development up to ten technological options for the case of high RD&D costs per technological option (1/10). The table shows the support for infrastructure development that each selected technology receives.

Number of technologies with RD&D support (stage 1)	Number of technologies with infrastructure development support (stage 2)									
	1	2	3	4	5	6	7	8	9	10
1	0.90									
2	0.80	0.40								
3	0.70	0.35	0.23							
4	0.60	0.30	0.20	0.15						
5	0.50	0.25	0.17	0.13	0.10					
6	0.40	0.20	0.13	0.10	0.08	0.07				
7	0.30	0.15	0.10	0.08	0.06	0.05	0.04			
8	0.20	0.10	0.07	0.05	0.04	0.03	0.03	0.03		
9	0.10	0.05	0.03	0.03	0.02	0.02	0.01	0.01	0.01	
10	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

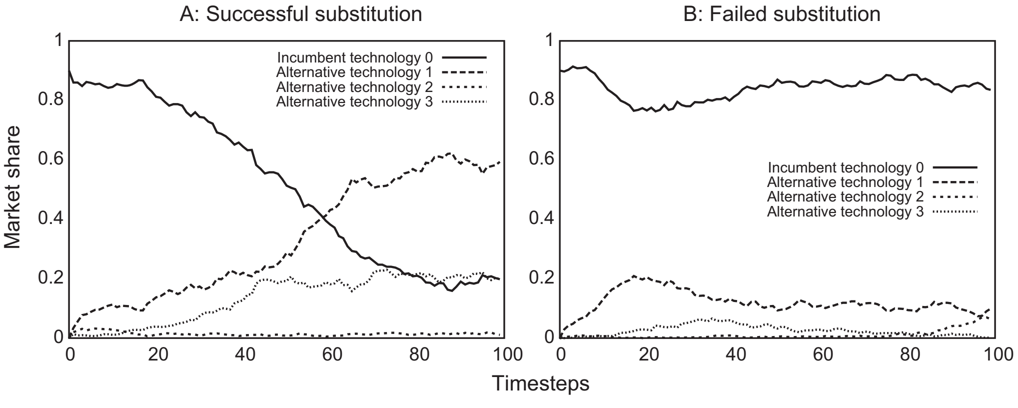

Fig. 3. Typical runs of successful technological substitution (left) and failed technological substitution (right).

Table 1 gives an overview of all possible allocations of public budget to RD&D support and infrastructure development up to ten technological options for the case of high RD&D costs per technological option (1/10). As an example, the table shows that RD&D support for two technologies leaves a budget of 0.8 ($1 - 2 \times 1/10$) to support the infrastructure development of these technologies. Policymakers can spend this budget either on the infrastructure development of both technologies (0.4 support per technology) or on the infrastructure development of one of these technologies (0.8 support). 100 model runs are simulated for each of the 55 possible allocations for 16 different conditions formed by the different disparity levels and RD&D costs per technological option.[3]

For each allocation the probability of technological substitution is calculated, that is the percentage of simulation runs in which substitution of the incumbent technology by a new technology took place within 100 time steps. More specifically, technological substitution occurs when one of the new technologies obtains a higher market share than the incumbent technology at that time. So, if the incumbent technology is replaced by an alternative technology in 10 out of the 100 simulation runs for a particular allocation, the probability of technological substitution is 0.10. Fig. 3 shows two typical runs, of a successful and a failed technological substitution process respectively.

Fig. 3 shows the emergence of three alternative technologies at time step zero, when there is lock-in into the incumbent technology. The graph on the left of Fig. 3 illustrates a simulation run where one of the alternatives becomes the dominant technology after 59 time steps, indicating successful

[3] The total number of simulation runs is 88.000 (55 possible allocations × 16 (4 × 4) different conditions × 100 runs.

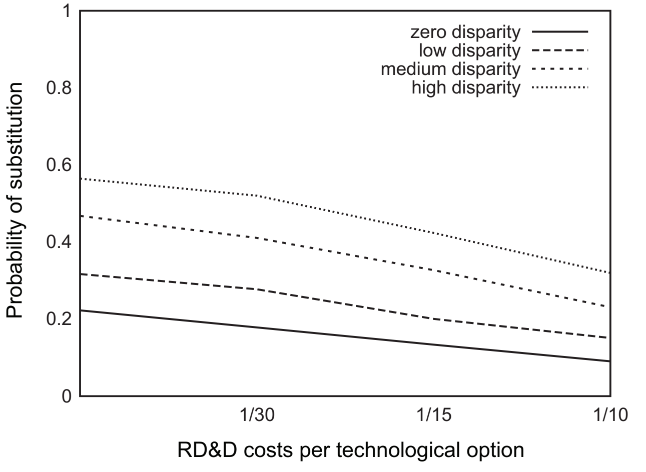

Fig. 4. The relationship between the RD&D costs per technological option and the probability of technological substitution for different levels of disparity.

technological substitution. The graph on the right of Fig. 3 illustrates a simulation run where none of the alternatives succeeded in replacing the incumbent technology as the dominant technology. Failed technological substitution may be due to, for example, sailing ship effects of the incumbent technology, bad technological performance and development of the alternative technologies, insufficient support for infrastructure development of these alternatives, or too much competition among the alternatives. A more elaborate analysis of the simulation outcomes at the level of single simulation runs in the context of sustainability transitions is presented in Section 5. This section proceeds with presenting the aggregate outcomes of the simulations.

Fig. 4 first shows the effects of the different parameters on the technological substitution process. The figure illustrates the relation between the RD&D costs per technological option and the probability of technological substitution for different levels of disparity. As expected, the figure shows a negative relation between the RD&D costs per technological option and the probability of technological substitution, because less budget is available to support the infrastructure development when the RD&D costs increase. The effects are highest for a high disparity level. Moreover, an increase in disparity results in a higher probability of technological substitution, as the technologies cover a wider area of the search space and the probability that one of the new options shows high performance increases.

In summary, the highest probability of technological substitution occurs under conditions of low RD&D costs per technological option and high disparity. Below, the effects of different allocations of public financial resources on the probability of technological substitution are analyzed. First, the effect of resource allocation to public support for RD&D is presented, followed by analyses of the effect of resource allocation to public support for infrastructure development, and the trade-off between the allocation of financial resources to support for RD&D and infrastructure development.

4.1. The effects of public support for RD&D

Fig. 5 shows the relationship between public support for RD&D and the probability of technological substitution for the different disparity levels. The RD&D costs per technological option increase from zero (graph A) to high (graph D). The *x*-axis indicates the number of technologies with RD&D support in this first stage. For each number of technological options with RD&D support, the average probability of technological substitution is calculated over all possible allocations.[4]

[4] For example, when three technological options receive RD&D support it is possible to support one, two or three of these technologies for infrastructure development. In this case averages are calculated over these three allocation possibilities.

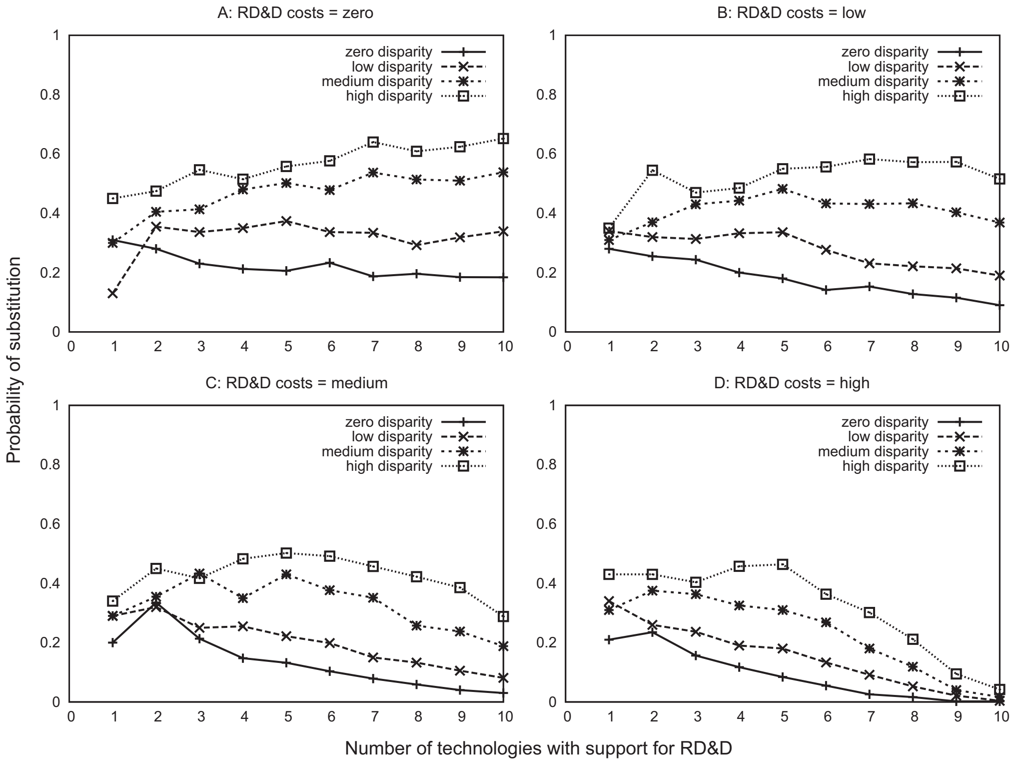

Fig. 5. The relation between public support for RD&D and the probability of technological substitution for the different disparity levels. The RD&D costs per technological option are zero (graph A), low (graph B), medium (graph C) and high (graph D).

Fig. 5 illustrates the trade-off for the policymaker related to the optimal level of RD&D support. First, when RD&D comes at no costs (graph A), there is a positive relation between the number of technologies with RD&D support and the probability of technological substitution for medium and high disparity levels, but not for lower disparity levels. When more technologies receive RD&D support the probability that a high performing technology is among them increases immediately and in the long run. These positive effects of public RD&D support are largest when disparity is high. When disparity is zero, the supported technological options initially perform similar on the technological characteristics, therefore the benefits of supporting an extra technology with infrastructure development are small.

Second, when the RD&D costs per technological option are greater than zero there are decreasing returns of public support for RD&D, illustrated in graph B (low costs), C (medium costs) and D (high costs). Graph D illustrates that support of technological options for RD&D only leads to a high probability of technological substitution when enough budget remains to support the infrastructure development of these technological options in stage 2 as well (e.g., at low levels of public support for RD&D). From graph B to graph D the optimal number of technologies with RD&D support shifts to the left for all disparity levels due to the increase in RD&D costs. Moreover, the decreasing returns of public support for RD&D are higher when the RD&D costs increase. This indicates that in domains that need large infrastructural investments, such as mobility technologies, public support for RD&D by itself is not sufficient to realize a transition. In the model, the best balance between public support for RD&D and infrastructure development is found at rather low levels of public support for RD&D.

A final outcome of the simulations is that public support for RD&D is more beneficial if the new technologies are sufficiently different (high disparity). Graph B illustrates that the optimal number of technologies with RD&D support decreases for lower levels of disparity. Similar patterns are observed in graph C and D. This indicates that the policymaker should take into account the technological

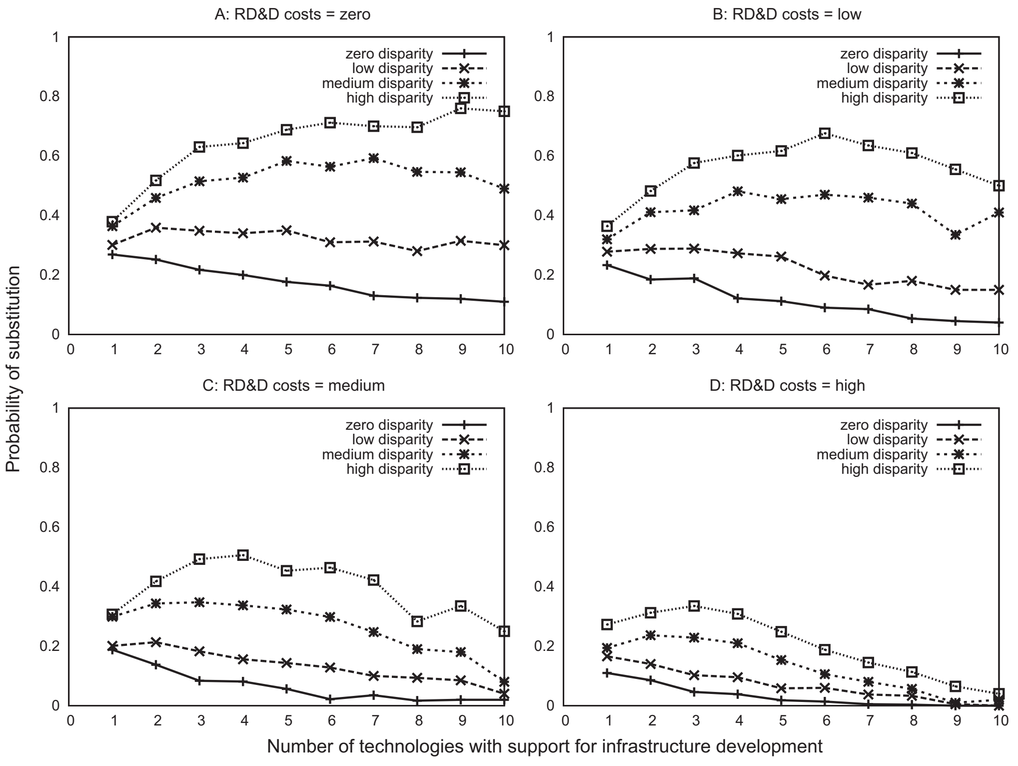

Fig. 6. The relation between public support for infrastructure development and the probability of technological substitution for the different disparity levels. The RD&D costs per technological option are zero (graph A), low (graph B), medium (graph C) and high (graph D).

characteristics of the different alternatives, adding a technology-specific element to the decision. For example, support of fuel cell vehicles and vehicles on biogas is expected to be more beneficial than support of vehicles on natural gas and vehicles on biogas, because the technological difference between fuel cell vehicles and vehicles on biogas is higher than the technological difference between vehicles on biogas and natural gas.

4.2. The effects of public support for infrastructure development

Fig. 6 shows the relationship between public support for infrastructure development and the probability of technological substitution for the different disparity levels. Similar to Fig. 5 the RD&D costs per technological option increase from zero to high for graph A to D. The x-axis indicates the number of technologies that also receive support for infrastructure development. For each level of support for infrastructure development, the average probability of technological substitution is calculated over all possible allocations.

Fig. 6 illustrates several trade-offs the policymaker is faced with. First, when disparity is zero, a negative relation between the number of technologies with support for infrastructure development and the probability of technological substitution is observed. Since the initial technological performance of the different technological options is equal when disparity is zero, the benefits of supporting multiple technologies are low. In this case the highest probability of technological substitution occurs when the complete budget is allocated to the support of a single technological option. This negative relation between the number of technologies with support for infrastructure development and the probability of technological substitution holds for all cases where disparity is zero, independent of the RD&D costs per technological option (see graphs B, C and D).

Second, when disparity is medium or high it is beneficial to support different technological options. However, there is a minimum size of the support that is needed for that support to have an effect. At some point the probability of technological substitution decreases again when more technologies are supported due to the division of the budget over more technologies. When more technologies are supported it is more difficult for each individual technology to realize increasing returns to adoption. The figure illustrates that the optimal number of technologies with support for infrastructure development also depends on the RD&D costs. For example, when disparity is high and support for RD&D comes at no costs, the optimal number of technologies with support for infrastructure development is at least ten (graph A). The optimal level decreases when the RD&D costs increase. The optimal level occurs at six supported technologies for low RD&D costs (graph B), four supported technologies for medium RD&D costs (graph C), and three supported technologies for high RD&D costs (graph D). In summary, when the RD&D costs per technological option increase the optimal number of technologies with support for infrastructure development decreases.

4.3. The trade-off between public support for RD&D and infrastructure development

Fig. 7 illustrates the trade-off between public support for RD&D and infrastructure development and provides insight into the effects of resource allocation. At the top row of Fig. 7, the disparity level is low, whereas the bottom row shows the probability of technological substitution for medium disparity. The graphs on the left show the probability of technological substitution for low RD&D costs per technological option, while the RD&D costs are medium for the graphs at the right-hand side. Each

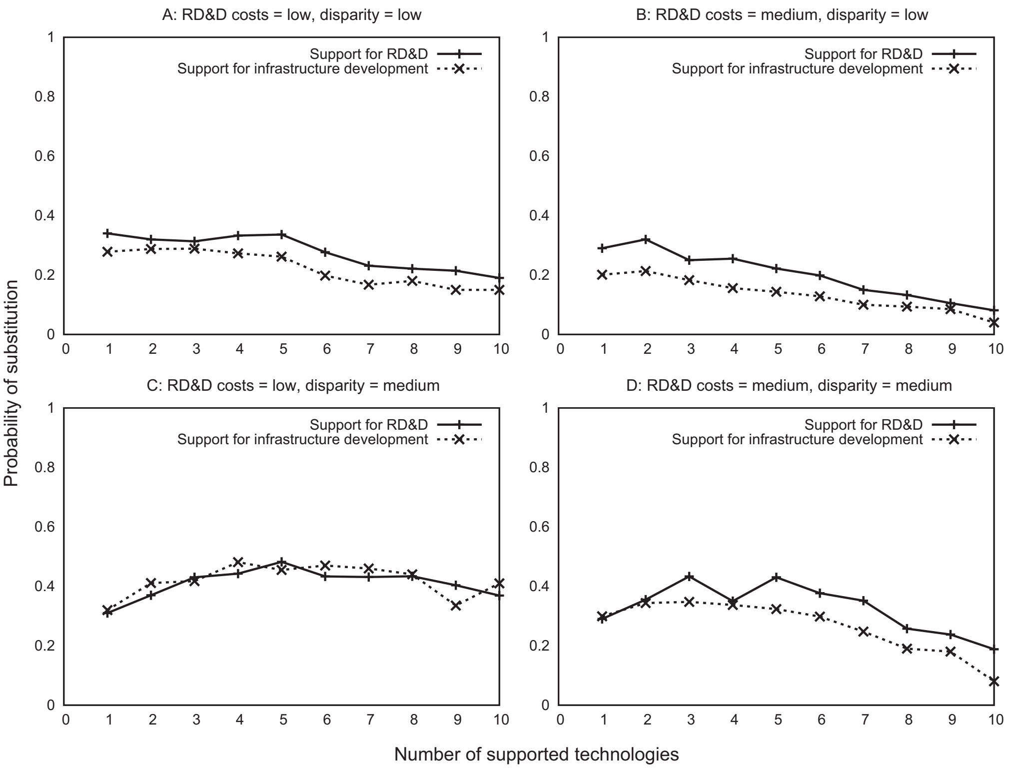

Fig. 7. The relation between the number of supported technologies and the probability of technological substitution in stages 1 and 2. For different RD&D costs and different disparity levels: low RD&D costs (left), medium RD&D costs (right), low disparity (top) and medium disparity (bottom).

graph presents the probability of technological substitution for both the number of technologies with support for RD&D and the number of technologies with support for infrastructure development.

The effects of RD&D costs per technological option and disparity on the optimal number of technologies with RD&D and infrastructure development support have been discussed above. Fig. 7 shows that in our simulations the optimal number of technologies with RD&D support is similar to the optimal number of technologies with infrastructure support. This means that it is optimal to support also the infrastructure development of these technologies that received RD&D support. In other words, a policymaker should not support more technological options with RD&D than can be supported for infrastructure development. This observation seems to be independent of the RD&D costs and the disparity level. The explanation for these results can be found in the decision making process of the policymaker. It is assumed in this paper that policymakers are not capable picking winners, that is, it is very difficult to determine *ex ante* which technologies will be most successful. This is modelled as random selection of the technologies that are supported with infrastructure development. This decision making process is further explored below.

4.4. Informed decision making

Fig. 8 presents the trade-off between public support for RD&D and infrastructure development for the case that policymakers do have the capability to assess the performance of the new technological options. Here it is assumed that policymakers can perfectly assess the initial performance of the technologies that received support for RD&D in stage 1, that is, they can adequately observe and

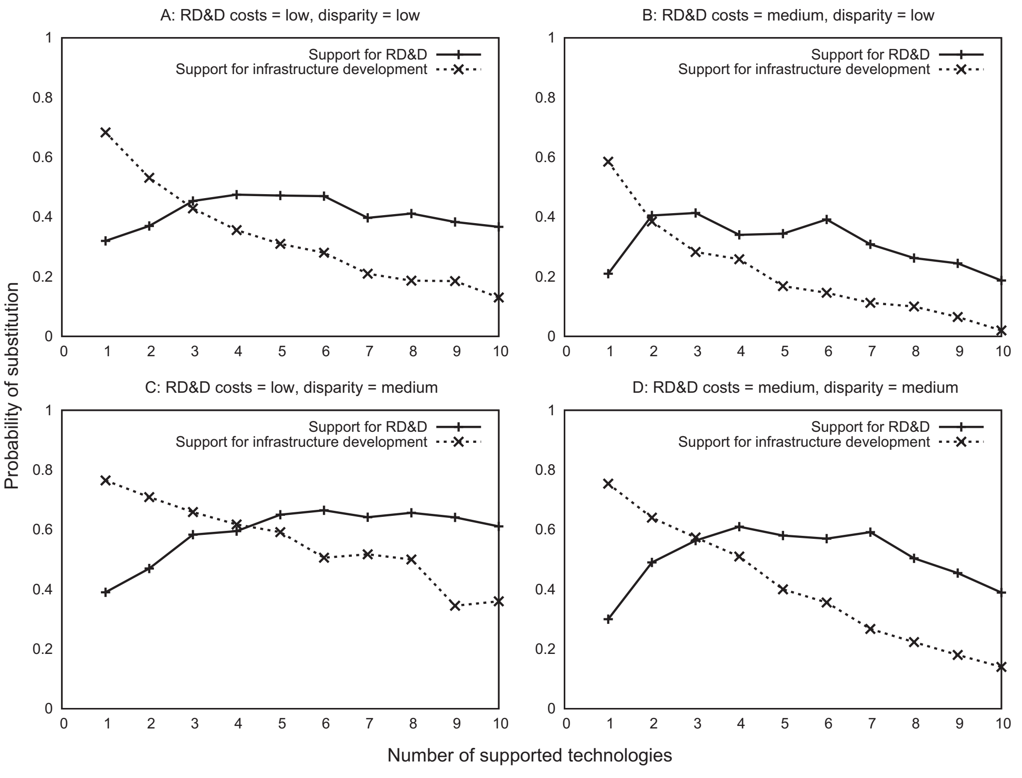

Fig. 8. The relation between the number of supported technologies and the probability of technological substitution in stage 1 and stage 2 with informed decision making. For different RD&D costs and different disparity levels: low RD&D costs (left), medium RD&D costs (right), low disparity (top) and medium disparity (bottom).

interpret the outcomes of RD&D and pilot projects when deciding upon large scale support for infrastructure development in stage 2. This is modelled by supporting the infrastructure development of those technologies with the highest initial quality/price ratio.[5]

A comparison of Fig. 8 with Fig. 7 illustrates the effects when the policymaker is capable of choosing the most promising technological options. The optimal number of technologies with RD&D support shifts to the right when policymakers can make an informed rather than random decision over which technologies to support. So, it is beneficial to support more technological options in the RD&D stage when a policymaker can evaluate the performance of these options. Informed decision making thus increases the benefits of allocating financial resources to RD&D support. Furthermore, the relation between the number of technologies with support for infrastructure development and the probability of technological substitution is negative, so that supporting one technological option for infrastructure development is most beneficial. Since, a policymaker can pick the most promising option it pays to invest in this option. However, when the disparity level increases (from low disparity in Fig. 8A and B to medium disparity in Fig. 8C and D), it becomes more attractive to support the second and third most promising option as well. There is thus a clear benefit from increased information regarding the technological characteristics and performance of the different technological options.

In sum, for an informed policymaker, the best allocation saves budget for infrastructure development for the most promising technology while the remainder of the budget is spent on the creation of technological alternatives (RD&D support).

5. Analysis of results in a sustainability transitions context

From the perspective of sustainability transitions, technological substitution is neither a sufficient nor a necessary condition for a transition to occur, as new technologies might perform worse in terms of environmental indicators than the incumbent technology. Furthermore a sustainability transition can also occur when the incumbent remains dominant but becomes more sustainable. A sustainability transition can thus be realized in different ways. Geels and Schot (2007) have provided a typology of so-called transition pathways, distinguishing four different pathways: transformation, de-alignment/re-alignment, technological substitution and reconfiguration. These pathways differ with respect to the timing and the nature of the interactions between the different actors involved. The model simulations presented in this paper started from a situation of lock-in into an incumbent technology. At time 0, the time of emergence of different alternatives, consumers start taking the environmental performance characteristic into account. The incumbent technology scores better on the traditional characteristic whereas the emerging technologies score better on the environmental performance characteristic. A sample of all simulations runs is taken to study the development of the technological characteristics.[6] Fig. 9 illustrates three typical patterns. In each graph the solid line depicts the market share of the incumbent technology. The dashed lines depict the average performance on the different characteristics weighted by the numbers of adopters of each technology. At the start of the simulations the incumbent technology dominates the market, which causes that the average performance, weighted over all technologies, on the environmental characteristic is very low in comparison to the average performance, weighted over all technologies, on the traditional characteristic.

Fig. 9A presents the case where no technological substitution and no transition takes place. This pathway in which the incumbent technology does not lose any market share and shows accumulated incremental innovations in the traditional characteristic is observed in 37.6% of the sample simulation runs and corresponds to what Geels and Schot (2007) label as the *reproduction process*.

Fig. 9B represents the case with both technological substitution and a transition. The model outcome is considered as a sustainability transition when the average performance on the environmental characteristic substantially improves and is at least as good as the initial performance of the incumbent

[5] $(x_1x_2)/P$.

[6] For each of the 880 experiments (55 allocations, 16 different parameter settings) a single run was randomly selected (out of the 100 simulation runs).

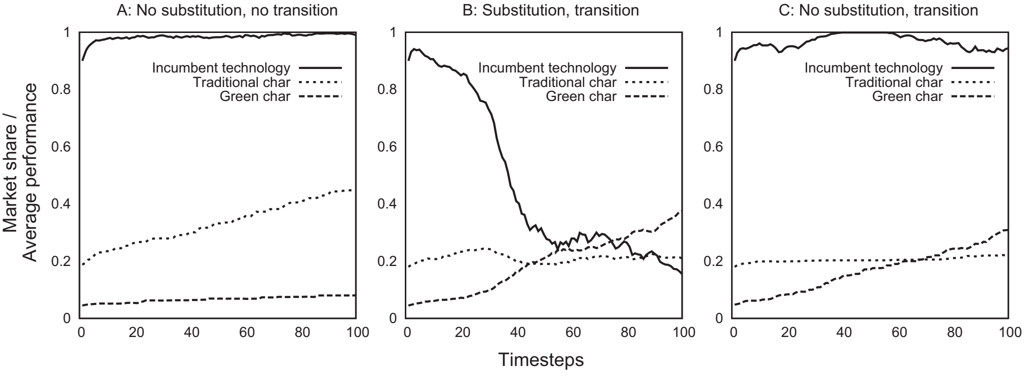

Fig. 9. Transition pathways: the solid line in each graph presents the market share of the incumbent technology over time, which determines whether or not technological substitution occurred. The dashed lines show the average performance on the traditional and environmental characteristic weighted over all adopted technologies, which determines whether or not a sustainability transition occurred.

technology on the traditional characteristic (see Appendix A). Technological substitution is observed in 36.3% of the sample simulation runs and in 64.9% of these it is accompanied with a transition. The performance on the environmental characteristic improves over time and the new dominant technology is more sustainable than the previous incumbent technology. At the same time, a slight decline of the performance on traditional characteristics is observed, as the substituting technology is not yet completely developed on these characteristics. Geels and Schot (2007) label this type of transition pathway *de-alignment and re-alignment* followed by *technological substitution*.

Fig. 9C again shows an example of a simulation where no technological substitution takes place. Nevertheless, it shows a considerable improvement in the environmental performance characteristic. This pathway is observed in 26.1% of the sample simulation runs and corresponds to the *transformation pathway*, *"the regime actors respond to landscape pressure by modifying the direction of development and innovation activities"* (Geels and Schot, 2007). The alternative technologies cannot take advantage of this pressure because they are not yet sufficiently developed. One might also link such a transition to the *reconfiguration pathway* in which the new regime also grows out of the old regime, only here the regime's basic architecture changes as is often the case for sociotechnical systems.

6. Conclusions and policy implications

In this paper, we have presented a model of technological substitution focused on infrastructure-dependent vehicle technologies. The focus was on how the allocation of public financial resources to public support for RD&D and infrastructure development affects the replacement of a locked-in technology by a new technology. Although consumers in our model eventually determine which technology will be successful, policymakers can affect the probability (and speed) of the technological substitution process. We have analyzed the effects of resource allocation to these stages by performing numerical simulations. More specifically, the simulations provided insight into the trade-off between the allocation of a limited budget towards the creation of new technological options by supporting RD&D on the one hand, and the support for infrastructure development of these technologies on the other hand. The results of our model indicate that for infrastructure-dependent vehicle technologies, an increase in public support for RD&D does not necessarily lead to a higher probability of technological substitution (or a transition). Supporting the RD&D for different technological options is usually costly, and these costs should only be made under conditions where it is possible to benefit from the increased technological variety. According to the model analysis, support for RD&D of different technologies is most useful when it meets three conditions: first, the supported technological options should be sufficiently different with respect to their technological performance in order to cover a wider area of the so-called search space. The analysis of the results show that such disparity increases the probability that a technological option will be developed that successfully competes with the incumbent technology.

A second finding is that policymakers should allocate substantial financial resources to the public support for infrastructure development of the infrastructure-dependent vehicle technologies. So, public support for RD&D in stage 1 is only rewarding when each of the created technologies is also substantially supported for infrastructure development in stage 2. The results illustrate that supporting many different technologies, each with a modest support for infrastructure development makes it difficult for any individual vehicle technology to realize increasing returns to scale.

A third important insight is that if policymakers are able to adequately evaluate the different technological options supported in stage 1, and because of that are able to pick the most promising options for support of their infrastructure development, then the policymaker can reduce the number of technological options with support for infrastructure development and increase the number of options with RD&D support. As uncertainty is inherent to the development of new technologies, this knowledge is usually not available.

The foregoing conclusions only hold when there is a strict dependency of vehicle technologies on the availability of a particular physical infrastructure. Policies aiming at the technological substitution of infrastructure-dependent vehicle technologies should include all stages of the technological substitution process as well as a clear prescription of how results from early stages feed forward into later stages.

Acknowledgements

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Appendix A.

Parameter values.[a]

Parameter	Interpretation	Values
Stages		
B	Total budget for policy intervention	0.3
B_1	Budget allocated to variety creation (stage 1)	$<B$
B_2	Budget allocated to selection (stage 2)	$B - B_1$
I_1	Number of created technologies in stage 1	$\leq B/c$
I_2	Number of selected technologies in stage 2	$\leq I_1$
c	Costs of variety creation	$\in[0, 0.03]$
Consumers		
N	Number of consumers	1.000
φ_x	Consumer weights for characteristic x	$\sim N(x_{max}, 0.1)$
m	Budget constraint	$\sim N(0.4, 0.1)$
a	Infrastructure availability requirement	$\sim N(0.4, 0.2)$
ω	Replacement rate	1/3
U_i	Utility of consuming the set of characteristics of technology i	$\in[0, 1]$
Technologies		
X_i	Set of service characteristic x of technology i	$\in[0, 1]$
x	Performance of characteristics	$\in[0, 1]$
x_{max}	Maximum observed performance on a characteristic x	$\in[0, 1]$
i	Index for technologies	
A_i	Infrastructure availability for technology i	$\in[0, 1]$
κ	Factor between financial resources and infrastructure development	1/3
γ	Incremental innovation rate	$\in[0.97, 1.02]$
α	Learning ability	0.05
P_i	Price of technology i	$\in[0, 0.5]$
$c_{i(t)}$	Cumulative number of adopters at time step t	
$S_{i(t)}$	Market share of technology i at time t	$\in[0, 1]$
Cum_{xi}	Cumulative number of innovations in characteristic of x of the technology i	
Cum_i	Cumulative number of innovations in all characteristics of the technology i	

Incumbent technology		
$x_{e(0)}$	Initial performance of environmental characteristic	$\sim N(e_1, 0)$
$x_{t(0)}$	Initial performance of traditional characteristic	$\sim N(t_3, 0)$
e_2	Mean of initial performance of environmental characteristic	0.05
t_3	Mean of initial performance of traditional characteristic	0.2
$c_{i(0)}$	Initial number of cumulative adopters	900[b]
$P_{(0)}$	Initial price of incumbent technology	0.2
Emerging technologies		
$x_{e(0)}$	Initial performance of environmental characteristic	$\sim N(e_2, \sigma^2)$
$x_{t(0)}$	Initial performance of traditional characteristic	$\sim N(t_2, \sigma^2)$
e_1	Mean of initial performance of environmental characteristic	0.1
t_1	Mean of initial performance of traditional characteristic	0.1
σ^2	Disparity: variance of initial performance of characteristics	$\in[0, 0.06]$
c_{i0}	Initial number of cumulative adopters	1
ϵ	Random premium (price)	$\in[0.025, 0.125]$
ρ	Initial infrastructure investment by private firms	0.04

[a] The source code of the NetLogo (Wilensky, 1999) simulation model is available from the authors upon request.

[b] Lock-in is defined as the situation where the incumbent technology is adopted by 90% of the consumers.

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