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Mapping the Territorial Adaptation of Technological Innovation Systems—Trajectories of the Internal Combustion Engine

Daniel Weiss [1,*] **and Philipp Scherer** [2]

[1] Chair of Innovation Management, School of Business and Economics, Freie Universität Berlin, 14195 Berlin, Germany
[2] Berlin Partner für Wirtschaft und Technologie GmbH, 10623 Berlin, Germany; philipp.scherer@berlin-partner.de
* Correspondence: daniel.weiss@fu-berlin.de

Abstract: Besides the rise of sustainable technologies, successful sustainability transitions crucially depend on the phase-out of unsustainable ones. However, the detailed dynamics of declining technological innovation systems (TIS) remain vague. Thus, based on the new TIS life cycle framework, we investigate how the technological dimension of a mature TIS adapts to increasing transformational pressures towards its decline. Considering the internal combustion engine (ICE) as a suitable research case, we measure the technological adaptation as changes in the dominant technological trajectory over time and across TIS territories. Empirically, this is operationalised by a main path analysis in patent citation networks, using 221,700 patents to cover the period from 10 January 1901 until 31 January 2019. Our results not only point to considerable shifts in the direction of technological development over time but also highlight stark differences across the three major car markets. Most notably, in contrast to USA and Japan, where hybrid powertrains have become the dominant alternative powertrains, the dominant trajectory in the EU territory points to an ongoing commitment towards diesel technology. In essence, our results highlight the importance of path dependency and connectivity of the knowledge search process as well as selective forces on the innovation system level, which have been neglected by related empirical studies. Conceptionally, our analysis demonstrates that the technological adaptation process is influenced by specific developments during a time period and heterogenous territorial dynamics within the TIS. Consequently, future TIS studies might consider spatially heterogeneous development cycles as well as possible mechanisms to establish an international trajectory towards sustainability goals.

Keywords: technological innovation system; technological trajectory; internal combustion engine; patent citation network; main path analysis; spatial development

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Citation: Weiss, D.; Scherer, P. Mapping the Territorial Adaptation of Technological Innovation Systems—Trajectories of the Internal Combustion Engine. *Sustainability* **2022**, *14*, 113. https://doi.org/10.3390/su14010113

Academic Editor: Mario D'Amico

Received: 19 November 2021
Accepted: 20 December 2021
Published: 23 December 2021

1. Introduction

The current issue of climate change and environmental pollution have led to the emergence of sustainability transition research, which aims to establish more sustainable production and consumption modes [1]. Especially in the case of the electricity and car industry, such transitions rest on the emergence of sustainable technologies and the phase-out of unsustainable ones. As a result, the technological innovation system (TIS) approach emerged as a prominent framework to investigate the development and diffusion of technologies in sustainability transitions. TIS is concerned with the development, application, and diffusion of a particular focal technology from a systemic perspective that involves various interacting actors [2]. However, the TIS concept has mainly focused on the transformational process of emerging technologies, i.e., covering the period from their initial development towards mass commercialisation. Against this background, Markard [3] proposes the TIS life cycle in order to expand the current framework by adding a focus on the decline of technologies. In particular, it adds a decline phase to the previous development concept of TIS, which halted at the stabilisation and maturation phase [4]. The latter is triggered if the TIS is not able to adapt to rising transformational pressures initiated by developments in the TIS or its context, e.g., competing technologies, loss of policy support, and changing societal expectations. Recent empirical research started to operationalise the TIS life cycle to investigate the different decline dimensions and map the adaptation process of mature TIS [5,6]. Nevertheless, we still lack a full understanding of decline dynamics, especially considering the possible differences in technological development across nations or regions [3].

Acknowledging this gap, our study explores the adaptation process of the direction of technological development in a mature TIS. Conceptually, this is represented by changes in the dominant technological trajectory, which capture technological development as a cumulative, path-dependent progression within a technological paradigm [7]. In turn, the dominant trajectory determines the direction of knowledge search and accumulation in the TIS [2,4,8,9]. Furthermore, we take the literature on the spatial development of TIS into account by examining the adaptation process across heterogenous TIS territories. Accordingly, territorial context conditions in terms of resources, regulations, and competition affect the local development of the TIS, leading to substantial differences across nations or regions [10–13].

In order to discover the dynamics of technological adaptation in mature TIS, we focus our empirical analysis on the internal combustion engine (ICE) in the car industry. Historically, the ICE-TIS has been under increasing transformational pressure due to changes in its surrounding context, the most prominent being societal concerns about environmental pollution. This has compelled car manufacturers to improve the performance and efficiency of ICEs, using gasoline, diesel, or hybrid powertrains [14–17]. Interestingly, we observe historically differentiated propensities towards different powertrain technologies across the primary car markets: a persistent strong market position of diesel cars in the European Union (EU) compared to the rise of hybrid technology as the dominant alternative powertrain in the United States of America (USA) and Japan [14,18,19]. This exemplifies that the ICE-TIS seems to have developed structural couplings with territorial elements, which heavily influenced the spatial development of the technology [9]. Based on these grounds, we ask the following research questions: First, is there an adaptation of the technological trajectory of the ICE over time due to transformational pressures? Second, do we observe differences in the adaption of the trajectories across different territories in the ICE-TIS?

In order to examine changes of the dominant technological trajectories and their underlying knowledge search processes in the ICE-TIS, we apply the method of main path analysis to patent citation networks, which identifies the most important knowledge search processes by exploiting the cumulative and path-dependent nature of knowledge development across the network [20,21]. Compared to similar TIS studies (e.g., [22–24]), this approach enables us to track the changes in the direction of technological development quantitatively.

Our empirical analysis begins with considering the changes in the USA ICE-TIS over time. The results suggest that until 2003 the prevalent knowledge search processes were concerned with improvements in fuel injection and fuel filter systems to cope with the transformational pressures in the US territory. Interestingly, after 2003, the research commitment shifted towards the hybrid powertrain, which can be depicted as a "median strategy" that allows car manufacturers to exploit complementarities between the prevailing environmental constraints, the performance demands of customers, and their own technological competencies [14,25]. In addition, our spatial analysis points to a differentiated adaptation process across TIS territories. Accordingly, for the EU, we observe a dominant technological trajectory concerned with diesel technology, while for the USA and Japan, our results point to the hybrid powertrain as the prevailing knowledge search process. Considering that, we highlight policy regulation as one of the key differences in the territorial TIS structures causing this disparity. Notably, the interpretations of our results are robust to a variety of main path algorithms and an alternative weighting index.

Overall, by recognising the path-dependent and territory-specific structure of the TIS knowledge system, our results capture an ongoing commitment of European firms towards diesel technology research. Accordingly, conditioned by the territorial context, the historical choices made by European policymakers and car manufacturers have influenced the performance and environmental trade-offs between the powertrain options and, compared to the USA and Japan, manifested the diesel engine as the most promising way forward in the EU. To our knowledge, this insight has not yet been discussed by the related empirical studies (see, for example, [14,15,26–29], as their approaches do not consider the evolution of the patent citation network structure. Given these points, our network-based approach offers reliable reference points for policies that aim to alter the direction of technological development.

Furthermore, our results are helpful to understand how the technological dimension of a mature TIS adapts to emerging transformational pressures towards the decline phase. Most significantly, we show that it is necessary to examine transformational developments not only over time but also over spatially differentiated territories of the focal TIS. Thereby, our paper emphasises the difference between the international and territorial technological trajectories of a TIS and thus highlights the need for a discussion about possible policy measures to align them towards more sustainable technology solutions [19].

Our paper is structured as follows. In Section 2, we introduce our theoretical framework, comprising the concept of technological trajectories, technological innovation systems, and the TIS life cycle framework. In addition, we describe the ICE as our empirical case and derive our research questions. In Section 3, the application of the main path analysis to patent citation networks is explained, and our dataset is described. Next, the results and robustness checks are outlined in Section 4. Lastly, in Section 5, we end the paper with a discussion of our results and conclusions for further research.

2. Conceptual Background

2.1. The Concept of TIS, Technological Trajectories and Context

Our first technological building block is the concept of technological trajectories. Originally introduced by Dosi [7], technological trajectories describe the cumulative, path-dependent progress of a technology within a technological paradigm. The latter specifies the notion of technological progress and, thus, predefines the directions of development to pursue along with certain techno-economic trade-offs. Hence, a trajectory is directly shaped by historical choices that constitute the path dependency of technological development as current development options are dependent on past the technological development. Moreover, the historical and current choices are determined by the specific circumstances surrounding the development of a technology. This implies that switching from one trajectory to another is associated with difficulties, not only in terms of economic costs but also because of the uncertainty about future technological developments.

The notion of technological trajectories is embedded in our second theoretical building block, the concept of TIS, which is concerned with the development, utilisation, and diffusion of a specific focal technology. The underlying system can be depicted as an interacting set of actors, networks, infrastructures, and institutions that are involved in the progression of the focal technology of the TIS. In comparison with national or regional innovation systems, technological innovation systems have no definitive territorial boundary and can enclose various heterogeneous regions, industries, sectors, and countries [2,30]. The structural elements include different actors, networks, and institutions, e.g., manufacturers, research institutes, inter-organisational alliances, (supportive) public policies, or social norms and expectations [2–4,9]. The innovation process of the TIS is formed by the interactions of these different elements and follows a certain technological trajectory, which influences the direction of knowledge search and accumulation over time in the TIS [2,4,8,9].

The focal TIS itself is situated in a surrounding context, which entails all relevant factors outside of the focal TIS, such as other actors, networks, institutions, competing or complementary TIS, and social and ecological changes. The focal TIS and its context are interrelated and can influence each other in various ways, e.g., through the rise of competing technologies, major policy shifts, or changes in societal expectations and needs.

TIS and context relate to each other either through external links, i.e., the context only affects the TIS, or structural couplings, i.e., context and TIS affect each other through shared elements [9,31]. In accordance, the focal technology's trajectory and knowledge accumulation are shaped by both factors in the focal TIS and its context [8,32–34].

Next, we will introduce the notion of the spatial development of TIS to further complement our theoretical TIS framework.

2.2. Spatial Development of TIS

Although the majority of TIS studies are embedded in the context of national innovation policy design, recent works by Coenen and Truffer [10], Coenen et al. [11], Binz et al. [12], and Binz and Truffer [13] began to conceptualise the heterogeneous territorial dynamics of TIS into a spatial dimension of TIS development as a foundation for a territorial TIS analysis. As aforementioned, a TIS has no definitive spatial boundaries and thus encompasses various territories on the regional or national levels, which exhibit specific territorial context conditions that influence the local development dynamic of the TIS. These territorial factors comprise formal regulations, cultural norms, social preferences, competitive pressures, market prices, and local infrastructures. Correspondingly, the TIS is interdependent with regional and national context conditions, which might induce highly differentiated supporting and hindering forces that significantly influence the development of the local TIS structure. Therefore, a spatial analysis benefits from considering the TIS as a set of territorial subsystems that share commonalities, such as the general context and global value chains they are embedded in but are differentiated by heterogenous local specificities and technological opportunities [35].

In the next section, we will give a short overview of the TIS life cycle framework in order to elaborate on the transformation process between the mature and decline phase as the focus of our empirical analysis.

2.3. TIS Life Cycle Framework

Notably, most TIS studies are more concerned with the emergence rather than the decline of technologies and their associated TIS. However, successful sustainability transitions are not only dependent on the rise of novel sustainable technologies, but also on the phase-out of unsustainable ones. Against this backdrop, Markard [3] proposes the TIS life cycle framework, which expands the prevailing S-curve approach [4] by adding the decline of the TIS development process.

Considering the whole lifespan of a technology and its TIS, there are four idealistic phases in the TIS life cycle framework: formative phase, growth phase, mature phase and decline phase. These phases can be distinguished by examining the size and actor base, the institutional structure, and the technological performance and variation in the TIS over time. As TIS are often in a process from one phase to another, the TIS-life cycle framework puts a great emphasis on the transformational perspective. Herewith, a transformational process from one phase to another can be tracked along two major overarching dimensions: changes within the focal TIS and changes in its surrounding context. First, changes within the focal TIS comprise the number, size, or type of structural elements present in the TIS, the relationship between those elements, and their influence on each other. In particular, important changes captured by this dimension are the entry/exit of new actors or institutions, the emergence/decline of networks, new regulations supporting/withholding the focal technology, technological performance increases, and the shift from one dominant technological trajectory to another. In contrast, changes in the context of the focal TIS comprise the linkages between the focal TIS and its context and the influence of certain context events on the TIS. Here, important changes captured are disruptive events like financial crises or nuclear accidents, the rise of competing technologies, and significant price movements of critical commodities. In essence, changes within the focal TIS or its context can lead to increasing pressure, which in turn induces a transformational process that could lead a TIS into its next development phase. We explicitly define such changes as transformational pressures in this paper. In the next section, we will focus on the transformational process from the mature to the decline phase by elaborating on changes in the technological trajectories of the focal technology [3].

2.4. The Transformation between the Mature and Decline Phase

In the mature phase, a TIS is highly institutionalised and, because of a diverse set of linkages, it is highly interrelated with its context. Long-term relations between the elements constitute inherent inertia to the mature TIS, implying that there are very few to no changes in its structure and linkages. Moreover, the majority of developments of the focal technology are path-dependent and incremental [3]. This implies that there should exist a dominant technological trajectory that dictates the direction of most knowledge search processes in the TIS.

However, as Markard [3] points out, the transformation towards the decline phase is often induced by changes in the TIS context, e.g., shifts in societal expectations about the future, major economic crises or new competing TIS. Most importantly, once these pressures reach a critical point, the structure of the TIS is affected, which potentially initiates the transformation to the decline phase. This transformation could then be driven by the loss of regulatory support for the focal technology and changing expectations about the future development and/or application of the focal technology. In turn, this could lead to a decreasing flow of resources into the TIS and more and more actors abandoning the technology. As a result, context structures such as competing TIS [36] can take over the market of the once prevailing TIS. However, the transformational process from the mature to decline phase does not necessarily lead to a phasing out of the technology. In fact, Markard [3] outlines several alternative outcomes for the focal technology. Firstly, it is possible that the focal technology and its TIS continue to exist in specific niche applications, e.g., as in the case of vinyl discs. Secondly, the novel competing technologies might die out too early, implying that the existing technology prevails. Thirdly, and for our paper, the most interesting option, the decline might be delayed or even interrupted due to some kind of adaptation of the focal TIS to the transformational pressures [3].

To sum up, the TIS life cycle framework provides a novel perspective of TIS development and expands the previous framework of Hekkert et al. [4] by including the decline of the focal technology and its TIS. However, the detailed dynamics of the transformation between phases remain unclear, especially in the case of declining technologies. To address this research gap, we focus on the technological dimension of mature TIS and investigate whether the direction of technological development adapts to increasing transformational pressures. Conceptually, this should be represented as changes in the dominant technological trajectory of the focal technology over different time periods that are characterised by specific developments in the TIS context. Correspondingly, the expectations about novel trajectories establish a knowledge search process dedicated to improving the performance of the focal technology to cope with the transformational pressures towards TIS decline [8].

Additionally, considering the spatial development perspective, we expect that such transformational pressures vary across different territories in the TIS. This suggests that the adaptation process could differ depending on the territory-specific circumstances and opportunities the TIS is embedded in. Therefore, in addition to changes over different time periods, we are interested whether the adaptation of the dominant technological trajectory differs across territories. This allows us to reveal additional aspects that have to be emphasised to adequately capture important driving factors behind the transformational processes in the TIS life cycle.

In the following section, we will briefly sketch the historical technological developments of the internal combustion engine as a mature TIS which faces transformational pressures towards decline (for a more extensive review, see, e.g., [16,37,38]). Thus, we investigate the transition process from the viewpoint of a mature technology rather than an emerging one. This enables us to understand the behaviour of incumbents and derive policy recommendations specific to the mature TIS. The latter complements the insights from studies that take the perspective of the emerging competitive technology [3]. We will return to this point again in the discussion section.

In particular, the analysis focuses on the car industry as one of the most relevant industries for ICE development [39]. To capture all possible adaptation possibilities against decline, we delineate the ICE-TIS by including all possible utilisations of combustion engines in diesel, gasoline, and hybrid powertrains. We thereby also consider hybrid applications as a part of the ICE-TIS as they also ensure the survival of combustion engines, although in a potentially symbiotic relationship with the battery electric vehicle (BEV) technology. Notably, this delineation is specific to our research case and should be distinguished by related studies considering hybrids as a separate TIS to measure, for example, knowledge spillovers between powertrain technologies [40].

Considering the aspects of the spatial development of TIS, we will focus on three car markets, i.e., the USA, EU, and Japan. These three territories have been of major importance to the development of the ICE, not only in the number of vehicles sold but also considering the amount of R&D expenditures and the number of patents granted [16,18,41].

2.5. A Short History of the Internal Combustion Engine

The success story of the internal combustion engine began in the 1910s after the technology prevailed in the competition against early forms of the electric, hybrid, and steam engine powertrains [39,42]. In the following decades, the ICE prevailed as the dominant design for car powertrains with no substantial regulatory or competitive pressure.

However, from 1960 onwards, several governments in the USA, Japan, and Europe began to implement the first regulations concerning the emission of carbon monoxide, hydrocarbons, and nitrogen oxides. Major triggers for these initial regulations took place in the wider context of the ICE-TIS. Accordingly, public concerns about the adverse effects of emissions on human health and commencing air pollution problems in metropolitan cities were increasing, exerting pressure on policymakers [38]. In addition, oil prices increased sharply during the 1970s, which in turn raised the price of fuel as a critical commodity for the ICE-TIS [15,16,43].

Even stricter regulations began to be implemented in the 1990s due to increasing concerns about climate change, e.g., the Zero Emission Vehicle Mandate in California, the European Emission Standards in the European Union, and the Japan Clean Air Program. In addition, many governments began to implement supporting policies for electric cars and the public awareness about the consequences of carbon emissions grew. Moreover, oil prices continued to rise, and more and more countries began to establish local low-emission zones. On the one hand, these aspects intensified the pressure on the technological development of the ICE in terms of emission prevention and fuel economy. On the other hand, this increased the competitive pressure by incentivising the search for alternative powertrains, which were hitherto not seen as serious alternatives to cars with combustion engines [14–16,37,44–46].

As of today, there are ever-increasing emission regulations for combustion engine cars, culminating in entire bans and phase-out targets in many countries [47]. Furthermore, the competitive pressure of alternative powertrains continues to increase due to continuous technological improvements in battery and fuel cell technology [38,48]. Basically, there are three possible technological opportunities for the ICE-TIS to cope with these pressures. The first two follow the current dominant design of the ICE and are based on further (incremental) improvements of gasoline or diesel engines (for an extensive review, see [38]). Hybrid powertrains are the third possible opportunity for the ICE-TIS to cope with increasing regulations. By using an additional electrical engine, hybrid cars try to operate the combustion engine at maximum efficiency, reducing fuel consumption and emissions, e.g., by using the electrical engine for acceleration or by warming up the exhaust after-treatment systems to their optimal operating temperature [14,49]. Thus, depending on the specific configuration of the hybrid vehicle (series, parallel or power split/series-parallel hybrid), the type of ICE used (gasoline or diesel engine), and the degree of hybridisation (micro, mild or full hybrid), fuel consumption can be reduced by up to 30% (for an extensive review see [49]).

Considering these three possible opportunities for the ICE, there are important differences in the propensity towards a specific powertrain technology across the primary car markets [14,18,19]). For example, since 1995, the usage of diesel engine cars has steadily increased in the EU [14,15,18], taking up an average market share of 42% in 2016. In contrast, diesel cars historically have been a hard sale in the USA and only reached market shares of around 1–3% [15,18,19]. The increasing aversion to diesel cars is especially vivid in Japan. In this case, the size of the diesel car fleet was similar to the EU, with a market share of around 10% in the 1990s but steadily decreased to around 1–2% in recent years [14,18]. Notably, diesel engines remain the powertrain of choice for heavy-duty vehicles in most countries, with some exceptions in local passenger and delivery transport [15,18,41]. Similar differences can be observed in the case of hybrid cars, which have experienced relatively strong sales in the USA and Japan compared with low sales in the EU market [15,50,51].

In sum, the ICE-TIS faces several transformational pressures due to changes in both the focal TIS and its context, which affect all major car markets. Arguably, as Markard [3] suggests, the associated transformative changes in the focal TIS structure seem to be heavily influenced by major changes in the context structures. Specifically, concerns about the adverse effects of vehicle emissions on human health and the climate, air pollution in metropolitan cities, increases in oil and fuel prices, and the rise of alternative powertrains have led to transformative changes in the ICE-TIS structure. As a consequence, the incumbents of the ICE-TIS are facing increasing transformational pressures in the form of emission regulations, local ICE prohibitions, and technological competition with alternative powertrains. Against this backdrop, it is still entirely unclear which powertrain technology is the best solution for the ICE-TIS to cope with these transformational pressures.

Moreover, as illustrated by the differences in the propensity towards specific powertrain technologies, there seem to be important territory-specific context conditions that influence the adaptation process to the transformational pressures. Accordingly, the mature ICE-TIS seems to have developed structural couplings with territorial elements, which influence the spatial development of the technology [9]. Therefore, following the TIS spatial development literature, our focus is to analyse the TIS in the three most important car markets, i.e., the USA, the EU and Japan. At this point, we will refrain from an international analysis of the ICE-TIS, as we expect that the respective dominant technological trajectories are much more dependent on the specific conditions in the territorial car markets, which resonates with the notion of a production-led TIS that is characterised by strong territorial couplings [13]. In doing so, we will mostly focus on policy-related factors as their importance has been frequently emphasised in the related literature [14,16,17,37,44]. Thus, we do not indeed give a complete comparison of all possibly relevant territorial context structures and refer to studies on national technological trajectories in the car industry (e.g., [19]) and territorial specificities of the largest car markets (e.g., [15,18,19,37,44,52,53].

Figure 1 summarises our analytical framework. In particular, the developments in the context of the ICE-TIS entail important trends that affect the car markets in the USA, the EU, and Japan similarly, e.g., influential factors outside of the focal TIS such as competing or complementary TIS, ecological changes, and broader changes in societal preferences and needs. However, because the territorial context conditions, e.g., national regulations, resources, infrastructure, and technological competition, influence each of these car markets separately, we expect variegated changes in the territorial TIS structures as a response to the transformative pressures. In turn, the latter shape the dominant technological trajectory prevailing in the respective territory.

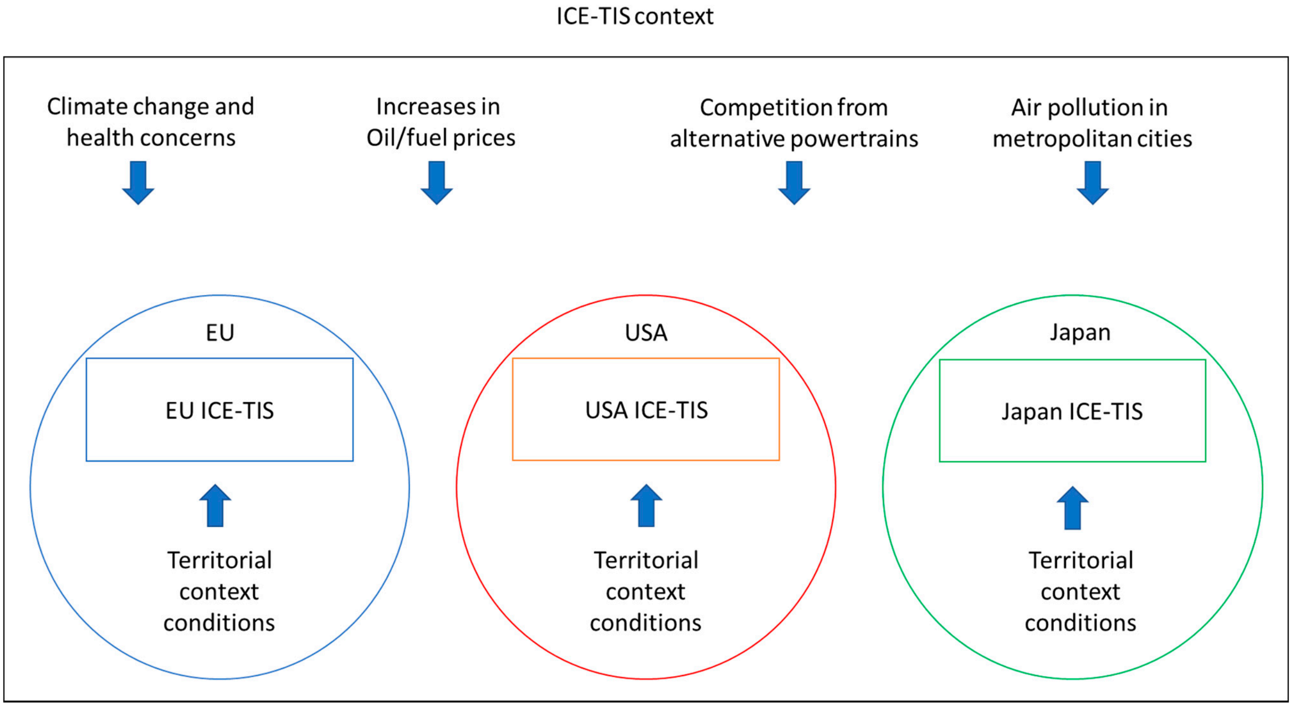

Figure 1. Analytical framework with three ICE-TIS territories and context relations.

Against this backdrop, we will use the ICE as our empirical case to gather evidence for our two research questions that are derived from the previous section: First, is there an adaptation of the technological trajectory of the ICE over time due to transformational pressures? Second, do we observe differences in the adaption of the trajectories across different territories in the ICE-TIS?

3. Materials and Methods

3.1. Method

In order to answer our research questions, we apply the method of main path analysis to patent citation networks. Extending the original approach of Hummon and Doreian [20], Verspagen [21] proposed using the main flow of technological knowledge in patent citation networks as a representation of technological trajectories. It is worth mentioning that this method has been used by several authors to reveal important knowledge search processes in a particular field using patents or scientific publications (e.g., [21,54–63]).

This methodological approach is grounded on the notion that patents can be used as an indicator to capture technological knowledge. The associated citations constitute an important source of knowledge for future patents, where the relevant knowledge flows from cited to citing patents. Hence, patents are treated as codified pieces of knowledge that use prior knowledge and provide new knowledge to the network [21,54,55,64]. Therefore, patents are depicted as throughput innovation indicators, which reflect the direct results of R&D processes. This implies that they should not be seen as innovation output indicators as they do not provide any information on whether the invention has actually been used in practice [53,65]. Nevertheless, one major advantage of patents for our analysis is that they not only measure innovative activities but also the direction of technological development. In fact, they provide highly disaggregated information about which technology fields are developing, which new technological paths are emerging, and which ones are phasing out [21,53,66,67].

However, there are some noteworthy concerns when using patent data. Firstly, a higher patent application or granting rate does not necessarily mean that a certain technological field or application will have a greater impact on the market. It merely indicates that inventions can still be patented, that organisations are working on technological developments, and that patenting might be preferred to secrecy [68,69]. By the same token, the actual number of patents might lead to a false interpretation of technological development since it varies depending on the country, industry, and the point in time under consideration. Furthermore, not all inventions are patented because some firms prefer secrecy or copyrights to protect their intellectual property [14]. However, applicable to our research case, patents seem to be perceived as effective intellectual property protection in the car industry [70].

Secondly, the usual methods to analyse patent citation networks are based on the absolute number of direct citations of each patent, which is used to weigh its importance for the development of the respective technology. However, the actual number of citations of a patent can be distorted because of differences in national patent laws [14,58,71,72], as well as biases due to self-citation and indirect, inappropriate, or false citations [20,73].

In comparison, the main path method overcomes most of these drawbacks, as the patent data are not evaluated solely by using the absolute number of patents and their respective direct citations. Instead, the method is much more focused on the flow of knowledge through the network, which depends on the number of indirect citations and how the specific patent is embedded in the network structure. Therefore, the aforementioned distortions are far less of a concern [54,55,73]. Finally, the main path method emphasises accumulation and dispersion patterns, which can reveal the evolution of the associated knowledge system and constitute a representation of the underlying internal and external selective forces shaping the technological development path [54]. Therefore, the analysis employed in this paper provides several advantages over the related literature concerned with the technological developments in the car industry (see for example [14,15,26–29]), as their empirical approaches are mostly based on citation count methods, relying mostly on the absolute number of patents and their direct citations.

In general, a patent citation network consists of a set of vertices representing the patents and directed arcs denoting the citations between two patents. In citations networks, the direction of the arcs depends on the type of citation relation. In particular, when using forward citations, the arcs originate from the cited patent and are directed towards the citing patent (is-cited-by relation). Obviously, for backward citations (is-citing relation), the direction is vice versa. This implies that citation networks are a representation of directed acyclical graphs in which the network is directed forward (or backward in the case of backward citations) in time. Consequently, when following the direction of the citations, no patent can be visited twice [20,21,73,74]. In our network, we define patents that have forward citations but no backward citations as start points and the ones that only have backward citations as endpoints [58].

In a standard citation network, all citations are by definition equally important, and each citation link between two patents has the value one assigned to it. As a first step in the main path analysis, Hummon and Doreian [20] propose using a weighting indicator to assign a traversal weight as a value to each citation link. Although there are several different weighting indicators available in the literature, they all consider not only the number of citations of a patent but, even more crucially, its position in the overall network structure [20,21,55,73]. Hence, as shown by Fontana et al. [55], it is possible that patents with a relatively low citation count can have a high traversal weight if they are positioned at pivotal positions in the citation network, such as junctions or bifurcations. Following the recommendations of Batagelj [74], we apply the search path count (SPC) for weighting our patent citation network. Intuitively, this indicator weights a specific citation link based on the frequency it is traversed when walking through all citation chains from every start point to every endpoint in the network [73]. Notably, we tested the robustness of our main results by using the SPLC indicator as recommended by Liu et al. [73], which yielded quite similar results and interpretations. Next, we will briefly explain the main path algorithms that are important for our empirical analysis.

Firstly, originating at the start point with the highest traversal weight, the local main path algorithm moves to the next vertex that is weighted the highest. This procedure is repeated at the following vertices until an endpoint is reached [75]. However, the local main path algorithm has the major drawback that the overall sum of the traversal weights in the selected path might not be the highest among all paths in the network. This implies that the selected path does not necessarily represent the prevalent knowledge search process in the network [21]. In consequence, we mainly rely on the global main path algorithm to answer our research questions. Contrary to the local main path algorithm, the global main path selects only the citation chain with the highest overall sum of the traversal weight indicator [75]. Most significantly, this path is seen as the critical path of knowledge flow in the network, constituting the dominant technological trajectory and knowledge search process [21]. Nevertheless, we follow the recommendation of Liu et al. [73] and use the local main path algorithm as a robustness check.

One important problem of the local and global main path algorithms is the possibility that the citation link with the highest traversal count, indicating an essential part of the knowledge search process, is not included in the calculated main path. Moreover, as noted by Martinelli [58], the global main path must not be unique since some paths can have the same sum of traversal weight if they do not share the same start- and endpoints. Thus, as suggested by Liu et al. [73], we complement the aforementioned local and global main path algorithms by employing key-route main paths as an additional robustness check. The key-route algorithm starts the main path computation from the link with the highest traversal weight and searches in both directions until a start- and endpoint are reached. Similar to the algorithms outlined above, this procedure can be either a local or global search process. Moreover, one can specify to compute multiple key-routes, e.g., by including the citation links with the second or third highest traversal weight [75].

To answer our research questions empirically, we employ two methodological procedures based on main path analysis. Firstly, in order to track the changes in the direction of technological development over time and to answer our first research question, we use the time-based approach that calculates the global main path in different time periods. The procedure used in the literature is to fix the starting year while alternating the ending year of each period the researcher wants to examine [21,55,56,58,73]. As a result, this procedure can be used to identify the prevalent technological trajectory in the TIS, considering the specific circumstances in each period. For the sake of brevity, we employ this approach just for the ICE-TIS in the USA. For the EU and Japan, the changes in the technological trajectory over time will be only discussed very briefly. Notably, in the time-based approach, we use the very beginning of our dataset as a starting year so as to not bias the results by leaving out potentially important patents in the past with a high traversal weight [21].

Secondly, for the spatial development analysis of our ICE-TIS, which answers our second research question, we propose the following approach. We start by extracting patents for the USA, EU, and Japan from our initial dataset by considering patents that are granted from the respective national patent office. The underlying assumption is that, because there is a high cost of patenting and patents are solely protected in the territory they are actually filed in, firms only consider filing for protection in countries in which they expect potential market value and development opportunities for the invention [53,76]. Based on these datasets, we then calculate global main paths for each territory. In turn, this enables us to make comparisons between the technological developments in the territorial TIS.

3.2. Data

We delineate the patent data associated with the ICE-TIS by using the International Patent Classification (IPC). In particular, we consider patents contained in the class IPC F02 that refers to “combustion engines”. Thereby, we cover a wide array of possible applications of combustion engines. The IPC codes include all utilisations of combustion engines in diesel, gasoline, hybrid powertrains to cover every historically relevant powertrain option for the ICE-TIS. By using such a broad definition of our TIS, we mitigate concerns about biasing our selection of main paths by selecting a narrower delineation. The employed IPC codes for our data shown in Table 1 are taken from Aghion et al. [77]. As the IPC codes are well-defined for the ICE, we prefer this method over extracting patents by means of relevant keywords since the latter approach involves several drawbacks that make an exact delineation more difficult [14].

Table 1. IPC codes for internal combustion engines.

IPC Patent Class	Definition
F02B	Internal-combustion piston engines; combustion engines in general
F02D	Controlling combustion engines
F02F	Cylinders, pistons, or casings for combustion engines; arrangements of sealings in combustion engines
F02M	Supplying combustion engines in general with combustible mixtures or constituents thereof
F02P	Ignition, other than compression ignition, for internal-combustion engines; testing of ignition timing in compression-ignition engines

To make our dataset more manageable, we only include granted patents to eliminate multiple counting [65] and one patent per patent family, as the latter depicts a group of closely related patents that share basically the same core technology [72,73,78]. Following Hummon and Doreian [20], Fontana et al. [55], and Martinelli [58], we use forward citations to construct our patent citation network. Our data are based on the DOCDB database provided by the European Patent Office (EPO), which we accessed through www.patentinspiration.com on 3 January 2019. To prepare the data for the analysis, we corrected for strong/cyclical components by removing mutual citations of two patents. In doing so, we deleted the citation of the patent that was granted later. Moreover, we deleted isolated patents, which have no citation link with any other patent. The prepared dataset consists of 221,700 patents, covering the period from 10 January 1901 until 31 January 2019, with 323,374 forward citations. Notably, the citing relations of US patents are not strictly sorted according to their granted date because citations can be added by the USPTO before the patent is granted [71]. Thus, it is possible that a patent is cited by a patent that is granted later but has an earlier application or priority date. However, this does not disturb our main path analysis as the flow of knowledge between the patents is still intact. Next, we extract 123,515 patents with 209,615 citations for the USA, 44,977 patents with 40,302 citations for the EU (for the EU we included patents from the EPO and the national patent offices of the member countries), and 51,714 patents with 51,330 citations for Japan in order to analyse the technological trajectories across the different territories. It is worth mentioning that we do not only observe a stark disparity in the number of patents across territories but also in the ratio of citations to patents as well [68]. In fact, the latter reflects the differences in the incentives to disclose prior knowledge due to specific national patent laws. Most likely, this systematic difference in the citation frequency could lead to a biased main path analysis when examining the international ICE-TIS using patents from all countries.

4. Results

Figure 2 depicts the time evolution of the global main path for the USA ICE-TIS. Notably, we only focus on the three most recent trajectories from 1978 to 2019, as these outline the key developments in the US car market.

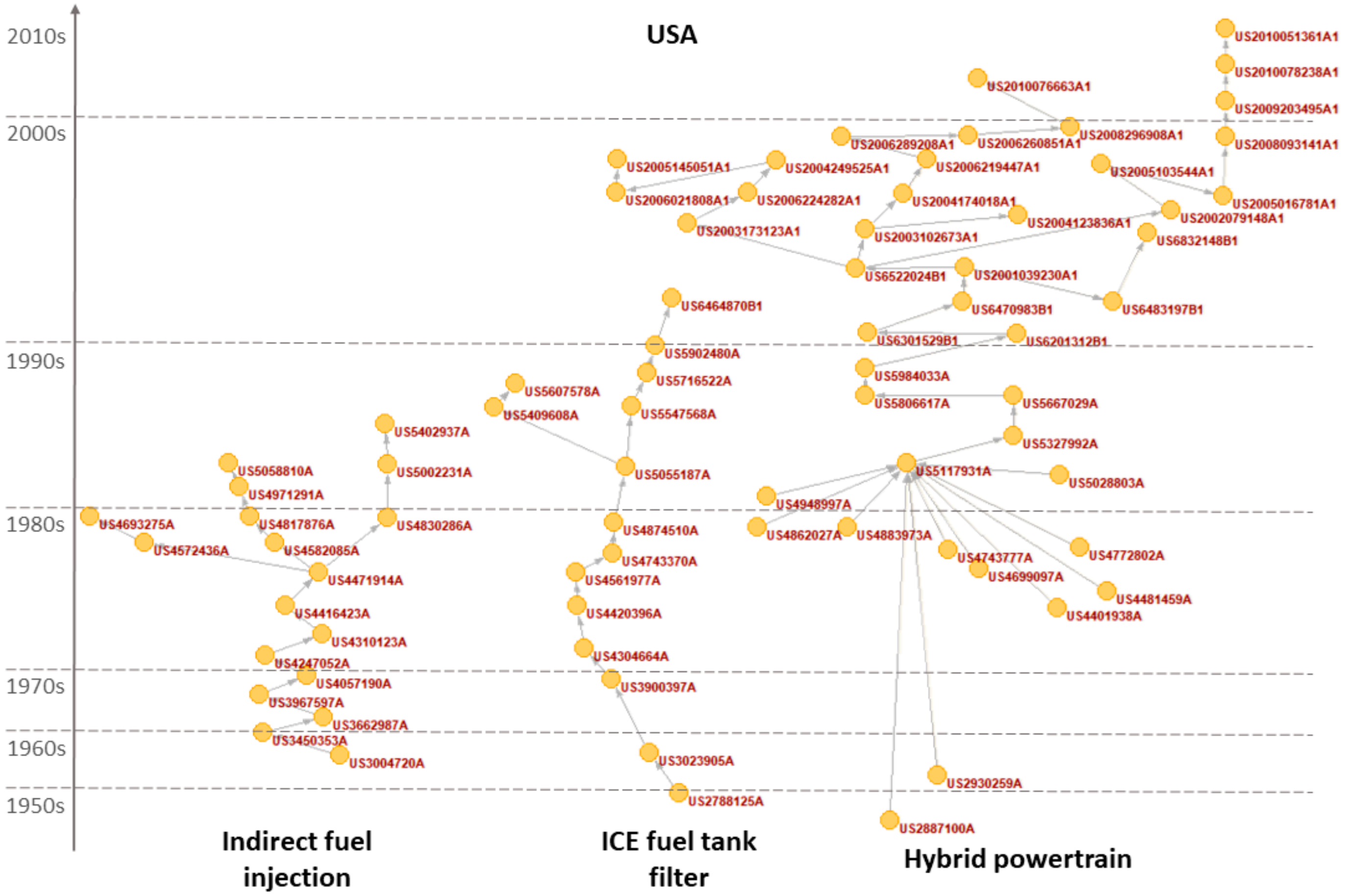

Figure 2. Dominant technological trajectories of the USA ICE-TIS. The circular nodes represent the patents, and the arrows depict forward citations from the cited to the citing node.

In the picture, the trajectories are ordered horizontally according to the periods in which the trajectories were calculated, with the left trajectory being the earliest one. In addition, we ordered the patents according to their granted date on the vertical axis, with the oldest patents at the bottom. Furthermore, to provide a more concise picture, we excluded the endpoints of each trajectory that have a common ancestor because they have no forward citations and thus do not contribute to the SPC weighting [21,74]. The first trajectory on the left was calculated for the time period 1978–1995. It entails patents about ICE fuel injection and fuel metering systems. Specifically, almost all patents in the trajectory are specialized on fuel injection valves and nozzles for gasoline-manifold fuel injection (e.g., Patents US3662987a, US3967597A, US4057190a, US4247052A, US4310123A, US4416423A, US4572436A, US4582085A, US4817876A, US4830286A, US5002231A).

The other patents in the trajectory do not focus on indirect fuel injection and contribute to general improvements of injection nozzles and valves. By and large, this technological trajectory represents the knowledge search process associated with the period of changeover from carburettors, which have been the standard in the car industry since the late 1800s, to much more environmentally friendly electronic fuel injection systems [43,52]. As already mentioned, the first ICE emission regulations in the major car markets and a sharp increase in fuel prices constituted considerable transformative pressures on the ICE-TIS during this period. In particular, the Clean Air Act of 1968 represented the first nationwide emission regulation in the US and was followed by a sharp increase in emission limit values in 1977 [15,16,38,43]. The companies with the most patents in the trajectory, indicating a major partaking in the knowledge search process, are Bosch from Germany, General Motors from the USA, and Weber SRL from Italy.

The second trajectory, covering the period from 1996 to 2002, comprises patents about fuel tank filters that are important for gasoline engines (e.g., Patents US2788125A, US3023905A, and US4874510A), diesel engines (e.g., Patent US4304664A), or both (e.g., Patents US5547568A, US5716522A, US5902480A). Notably, this time period comprised increasing regulations and fuel prices in all major car markets. In the USA, this development was spearheaded by the California Air Resources Board, which introduced the ambitious low-emission vehicle program [38]. To cope with this increasing transformational pressure, car manufacturers reduced emissions further by using higher fuel injection pressures, shorter injection duration, and ethanol fuel. In turn, these technical advances increased the sensitivity of the fuel injection systems to fuel impurities [79–81]. Hence, the knowledge search process of this trajectory is concerned with filtering performance (e.g., Patent US4743370A and US4561977A) as well as material composition and design of fuel filters (e.g., Patent US5902480A and US5716522A). These two trajectories are representative of the historical observation that in the last decades, car emissions were mostly reduced by improvements in fuel injection systems and associated components [38]. The companies with the most patents in this trajectory are Nifco from Japan as well as General Motors and Kuss Corp from the USA.

In contrast, the third trajectory, which prevails from 2003 to the beginning of 2019, suggests a knowledge search process that is focused on hybrid vehicles as a solution to overcome the transformational pressures. While battery and fuel cell electric vehicles did not experience significant market sales until the late 2010s, hybrid vehicles experienced major success with the introduction of the Toyota Prius I in the USA and Japan during the turn of the millennium [15,16,49,82]. Against this backdrop, most major car manufacturers, including General Motors, Ford, Nissan, Hyundai, BMW, Mercedes, and Volkswagen, entered the market with their own hybrid vehicles in the late 2000s [16,45]. Correspondingly, the patents in the trajectory are concerned with technical inventions associated with the different hybrid configurations, i.e., series hybrid (e.g., Patents US2008296908A1 and US20062260851A1), parallel hybrid (e.g., Patents US5984033A and US6201312B1) and powersplit/series-parallel hybrid (e.g., Patents US5667029A and US2005103544A1). Interestingly, the majority of patents comprise improvements that are particularly important for powersplit/series-parallel hybrid vehicles. This can be seen as an indication that the search process is focusing on this hybrid configuration as the most promising one in terms of efficiency and emission reduction.

The hybrid powertrain trajectory points to a notable shift from the previous technological trajectories, which solely rely on the dominant ICE design. Therefore, the hybrid powertrain trajectory can be regarded as a "median strategy" that lies in-between the trajectories for fully electric and diesel/gasoline cars. Accordingly, using the median strategy enables car manufacturers to exploit complementarities between the prevailing fuel infrastructure, environmental constraints, performance demands of customers, and their own technological competencies [14,25]. Thus, the hybrid powertrain is not only more efficient than using only a combustion engine, but it also has an advantage over fully electric vehicles because it is compatible with both the dominant ICE design and the existing fuel infrastructure [14,49,83,84]. Consequently, this trajectory cannot only be seen as an effort to cope with emission regulations and local prohibitions of ICE vehicles in the ICE-TIS but also as a response to the increasing transformational pressure due to the rise of competing for TIS, i.e., battery and fuel cell electric cars, in the context of the ICE-TIS. As expected, the companies with the most patents in the hybrid trajectory are Toyota as well as Aisin from Japan, reflecting the technological lead of Japanese car manufacturers [15]. Additionally, this supports the suggestion that Japanese companies have created entry barriers to the hybrid vehicle market through patenting [85]. In comparison, there are only a few patents of US firms (e.g., US5806617A and US5667029A) and no patents of European manufacturers.

Overall, considering the first research question, we can clearly observe an adaptation process of the dominant technological trajectory in the USA ICE-TIS over time. Specifically, the adaptation was driven by transformational pressures, which were initiated by substantial changes in the context of the TIS. We have summarised the results of the global main path analysis for the USA ICE-TIS in Table 2.

Table 2. Evolution of the dominant technological trajectory of the USA ICE-TIS.

Time Period	Trajectory	Main Objective	Changes in TIS	Changes in Context
1980–1995	Indirect fuel injection	Transition from carburettors to fuel-efficient injection systems.	First ICE emission regulations (e.g., Clean Air Act).	Concerns about adverse effects of emissions on human heal, air pollution in metropolitan cities, increase in fuel prices.
1996–2002	ICE fuel tank filter	Increasing performance of fuel filters for advanced fuel injection systems.	Extension and intensification of emission regulations (e.g., Low-emission vehicle Program).	Emerging climate change concerns across the broad society, further increases in fuel prices, commencing a search for alternative powertrains.
2003–2019	Hybrid powertrain	Sharp reduction of fuel consumption and emissions.	Extension and intensification of emission regulations and introduction of low/zero-emission zones.	Continuing climate change concerns and increase in fuel prices, increasing competition from fully electric powertrains.

Next, we will compare the dominant technological trajectories of the territorial ICE-TIS in the USA, the EU, and Japan in order to shed light on the spatial development and to reveal how the adaptation process differs across the most important car markets. Our focus here is to highlight the key differences in the territorial TIS and territorial context conditions influencing the respective trajectories. For the sake of brevity, we will focus on the analysis of the most recent trajectories and only briefly sketch the preceding trajectories in the EU and Japan.

Figure 3 depicts the global main paths for the EU, USA, and Japan. The dominant trajectory for the USA is depicted on the left and is equal to the latest trajectory in Figure 2. As before, the trajectory represents the knowledge search process concerned with the application of the ICE in hybrid vehicles (e.g., Patents US2008093141A1 and US2005016781A1). Likewise, the trajectory for Japan in the middle of Figure 3 consists of patents for hybrid vehicles (e.g., Patents JP2006118681A and JP2010202151A). Notably, almost all patents in these two trajectories are from Japanese firms, demonstrating their dominant position and technological advantage in the hybrid vehicle market [15]. Next, we consider the development of the Japanese trajectory over time. When taking patent data up to the end of 2000 and 1990, the respective results point to knowledge search processes that are concerned with diesel technology. Indeed, these trajectories represent the high share of diesel cars in Japan during the 1990s, which we already pointed out in the historical description of the ICE. By the same token, the succeeding shift to the hybrid powertrain trajectory exemplifies the choice of policymakers to phase-out diesel cars on the Japanese car market.

The most recent trajectory in the EU is in stark contrast to the latter two since it deals with fuel filters and fuel heaters that are specialised for diesel vehicles (e.g., Patents EP2514958A1 and EP1101519A1). Interestingly, this exactly reflects the territorial differences in the propensity towards the specific powertrain technologies outlined earlier. Most patents in the EU trajectory are held by Mann & Hummel from Germany and other European applicants. In comparison, there is only one patent from USA and Japan, respectively. This further indicates that the primary knowledge development for diesel engines seems to be advanced almost exclusively by European firms. Notably, this result is reinforced when observing previous trajectories for the EU territory. Taking patent data up to the end of 2000, we again reveal a knowledge search process that is concerned with diesel technology. Moreover, for data up until the end of 1990, the dominant technological trajectory entails advancements in fuel injection, potentially relevant for both diesel and gasoline engines. In consequence, the knowledge search process in the EU seems to have been systematically focusing on diesel technology for several decades.

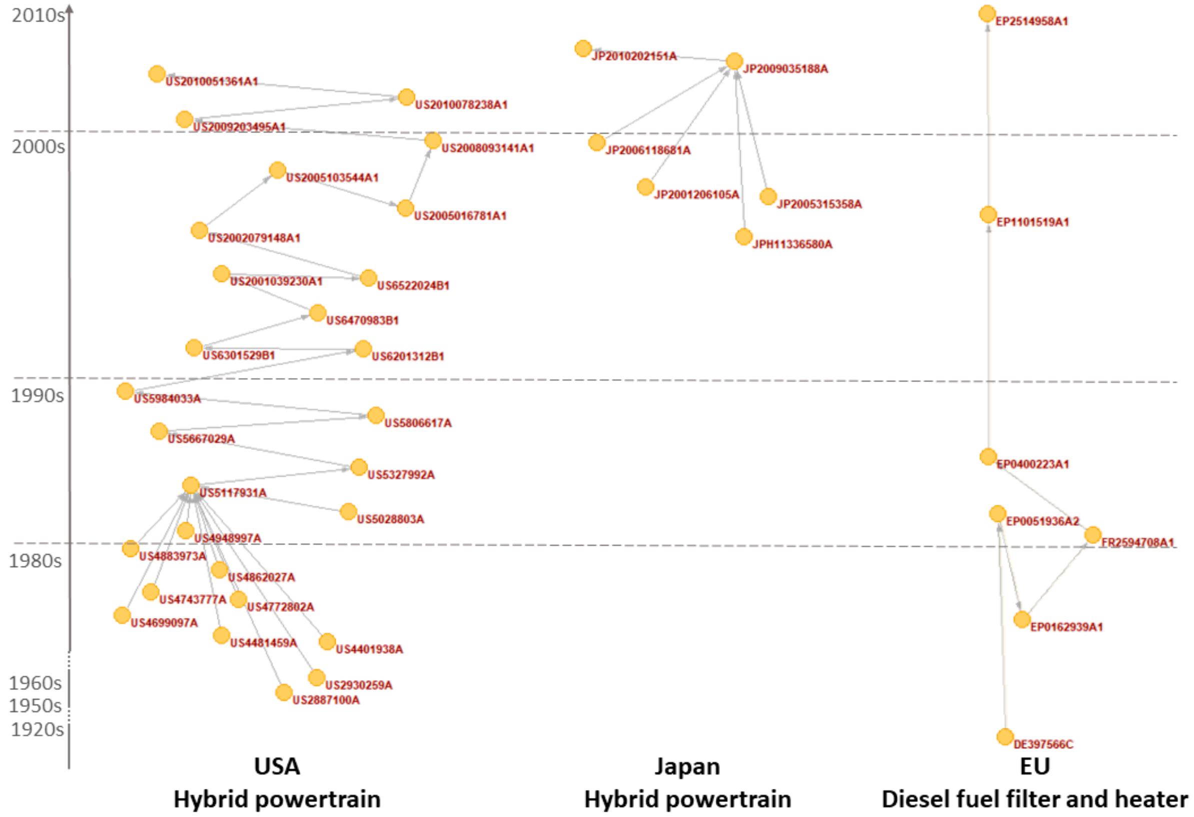

Figure 3. Dominant technological trajectories across three territories of the ICE-TIS. The circular nodes represent the patents, and the arrows depict forward citations from the cited to the citing node.

The major drivers for this disparity across these TIS territories are found in the different political approaches towards the emission regulation of the ICE. Accordingly, the Euro 2 legislation implemented vehicle emission standards which allowed for far higher emissions for diesel cars compared to gasoline ones. In fact, the latter faced threshold values for nitrogen oxide and hydrocarbons that were 40% higher [18]. This double standard has since continued, and even the most recent Euro 6 standard introduced comparatively less stringent diesel emission regulations [86]. In addition, several national support programs for diesel engines were implemented, with a prominent example being the benefits for diesel cars in France [87]. In essence, there was certainly a tendency among European policymakers to support local car manufacturers developing diesel technology [15,18,19]. Although the circumstances that induced this policy support towards diesel technology are certainly complex, the literature points to several considerable factors: the intense lobbying activities of European car manufacturers in the course of the voluntary agreement between the European Automobile Manufacturers Association (ACEA) and the European Commission in 1998, the declining sales of the European Oil industry in the energy sector, and the resistance of European car manufacturers towards hybrid powertrains [18,87]. Hence, European car manufacturers embarked on the diesel trajectory and continued to deliver continuous performance improvements since diesel has been considered to be the more attractive powertrain to comply with EU regulations compared to hybrid or fully electric vehicles [19,87]. In contrast, emission regulations in the USA and Japan were far more stringent and constituted a considerable barrier to European diesel technology [19]. In particular, the USA followed a more fuel-neutral approach inhibiting any customer incentives to buy diesel cars. By the same token, Japan, which targeted a phase-out of diesel cars, even began to impose stricter emission standards on diesel than on gasoline vehicles in the early 2000s [44,86].

Moreover, high fuel taxes have induced a cost advantage for diesel cars in the EU, as they are generally more fuel-efficient than gasoline cars. Additionally, in many EU member states, diesel fuel is considerably cheaper than gasoline. In comparison, lower fuel prices in the USA and the absence of a significant price difference between diesel and gasoline have mitigated consumer preferences towards fuel-efficient diesel cars [14,15,18,41,44]. Therefore, facing the higher price, the relatively minor advantage in driving cost, and the complex technology involved, hybrid cars are considered a less appealing powertrain choice compared to the diesel engine in the EU [15]. On the contrary, due to the missing competition of diesel cars and significant policy support through policy programs, hybrid vehicles have gained an impressive market position as the dominant alternative powertrain in both the USA and Japan [15,52,85].

In sum, regarding our second research question, we observe a striking difference in the adaptation process of the ICE-TIS across major territories, which is in line with the TIS spatial development literature. Most significantly, these findings highlight how different territorial context conditions can have a major impact on the development of territorial TIS structures. Thereby, the transformational pressures induced by the context changes provoked variegated changes in the ICE regulations, which, in turn, caused a substantial disparity in the direction of technological development. The results of the global main path analysis in the three territorial TIS are summarised in Table 3.

Table 3. Comparison of the dominant technological trajectories across three ICE-TIS territories.

Territory	Trajectory	Territory Specific Adaption of TIS Structures to Context Changes
EU	Diesel fuel filter and heater	Emission regulations put diesel at an advantage over gasoline and hybrid powertrains. Several national support programs for diesel. Cost advantage of diesel cars due to lower fuel prices. Lobbying activities of car manufacturers.
Japan	Hybrid powertrain	Advanced Clean Energy Program favouring hybrid cars. Phase-out of diesel cars due to comparatively more stringent regulations for diesel cars. Denigration of diesel technology.
USA	Hybrid powertrain	National Low Emissions Vehicle Program favouring hybrid cars. Fuel-neutral ICE regulation approach. No cost advantage for diesel cars due to the absence of a fuel price difference from gasoline.

Robustness

Following Liu et al. [73], we check the robustness of our global main paths by calculating the corresponding local and key-route main paths (the results of the robustness testing are available upon request). We calculated forward local main paths for the USA ICE-TIS in 10-year steps from 1960 onwards. For the EU and Japan, we computed the local main paths using the whole territorial data sets (all forward local main paths were calculated with 0.00 tolerance). In sum, the results affirm the previous answers to our research questions.

Additionally, for the USA ICE-TIS, we computed key-route main paths across the top ten citation links with the highest traversal count in 10-year steps from 1960 onwards. In brief, the key-routes affirm our initial results, as they basically reveal the same substantial changes in the trajectories. Similarly, for the territorial TIS, we derived key-route main paths embedding the five highest valued citation links over the whole time period of our data set. Notably, we chose fewer key-routes as the territorial sub-samples consist of a considerably lower number of patents and associated citations. Again, most of the key route paths confirm our initial results. One noteworthy exception is the key route main paths for the EU territory because, in addition to a diesel fuel filter and heating trajectory, we derive two hybrid powertrain trajectories. However, the latter two are mostly driven by Japanese car manufactures, which again supports our result that European manufacturers are more important for the development of diesel technology than for the hybrid powertrain. In either case, we find no evidence against our initial interpretations based on the global main path algorithm.

5. Discussion and Conclusions

After illustrating our results to answer the proposed research questions, we now want to discuss the implications of our work. To a great extent, our results are in accordance with the conclusions of the related empirical literature. Similar to Frenken et al. [26], Oltra and Saint Jean [14], Sushandoyo et al. [15], Köhler et al. [27], Liesenkötter and Schewe [28], and Borgstedt et al. [29], our evidence points to an increasing interest in the hybrid powertrain among major car manufacturers, with Japanese firms taking the lead in the knowledge-generating process. However, because these works are not encompassing the evolution of the patent citation network structure, they do not capture the path dependency and connectivity in the knowledge search process. Thus, by neglecting the selective forces on the innovation system level, they fail to grasp the stark contrasts between the territory-specific knowledge systems, which is exemplified by the ongoing commitment of European firms towards diesel technology research. Accordingly, conditioned by the territorial context, the historical choices made by European policymakers and car manufacturers have influenced the performance and environmental trade-offs between the powertrain options and manifested diesel engines as the most promising way forward in the EU ICE-TIS. Notably, this illustrates how different historical choices, e.g., the different regulatory approaches described in the previous section, have shaped the current technological development in the respective territory, leading to significantly different outcomes in the choice of powertrain. To our knowledge, this insight has not yet been illustrated in the empirical literature. Given these points, our work suggests that superficial patent citation analyses are insufficient and have to be complemented by a system-based approach. Only then is it possible to offer reliable reference points for policies that aim to alter the direction of technological development.

Our results relate to recent work on knowledge spillovers between the BEV, hybrid, and ICE powertrains [40]. In particular, using patent data from 2008 to 2016, the study reveals a symbiotic relationship between the ICE and hybrids, meaning that both powertrain technologies benefit from each other’s knowledge development. Interestingly, this corresponds to the hybrid powertrain shift we observe in recent years in the USA and Japan. As the authors note, the relationships and behaviour of technologies depend on the respective environment in terms of technical difficulties, infrastructure, and regulation that change over time and space. Accordingly, our spatial perspective constitutes an additional dimension governing technological relations as illustrated by the diesel trajectory in the EU. The latter suggests that the knowledge spillover between hybrid and ICE are less pronounced in this territory because the environment is more favourable to ICE, which motivates manufacturers to pursue knowledge exploration in their own TIS instead of exploiting other technologies [40]. Moreover, the authors reveal a parasitic relationship, with BEVs benefitting from hybrids, and an amensalism in relation to ICE, again in favour of BEVs. Transferring these insights to our results, the shift to the hybrid powertrain seemingly benefits the development of BEVs and, therefore, might actually undermine the survival of the ICE as an increasing diffusion of hybrid is increasing the user acceptance of BEVs in relation to electric charging [84,88]. Arguably, these elaborations need empirical evidence by combining the two approaches to derive complementary insights, especially considering the spatial development perspective.

Going back to the theoretical framework, our contribution demonstrates that the adaptation of the technological dimension is indeed influenced by the developments in the TIS and its context during a certain time period. In addition, we proposed a methodological approach to show that the adaptation process is dependent on the spatial dimension as well. Thus, our results imply that spatially heterogenous TIS life cycles must be considered in future research, a conception Markard [3] already hinted at. Moreover, from a policy standpoint, this suggests that an alignment of the territorial dynamics towards a more sustainable international technological trajectory becomes necessary. Possible mechanisms are put forward by Bohnsack et al. [19], e.g., international policy diffusion and ICE regulation harmonisation.

Methodologically, we introduced and expanded main path analysis to consider trajectories in TIS over time and space. The approach contributes to the toolbox of empirical methods for TIS analysis and allows to identify and compare technological trajectories from a quantitative perspective to capture TIS directionality. Specifically, it relates to the recently introduced functions of decline by capturing guidance during a possible TIS phase-out. However, this needs further conceptualisation, as the functions of decline are still preliminary [89]. Although we focused on the recent TIS-life cycle framework [3], measuring the direction of technological change also contributes to the functional TIS analysis as a possible indicator for the guidance of the search function [30]. Future research could build upon our study and apply the method to additional data and context structures, especially considering differences across sectors [90]. Moreover, our approach can be combined with related research to consider additional indicators for emerging technological dominance in TIS [91].

Last but not least, we want to highlight the following important limitations of our paper. Firstly, we only investigated the adaptation process of the technological dimension of a mature TIS. Apparently, a complete analysis of a TIS transformation process has to include additional dimensions, different TIS phases [3], a sectoral or industrial segmentation [9,90,92] and a variety of empirical research methods to give a comprehensive picture. We also only focused on the USA, EU, and Japan as our TIS territories, leaving out other upcoming car markets, such as China and India, that should be considered by additional work. By the same token, further analysis is necessary to identify a possible shift of the technological paradigm in the car industry. A possible approach to doing so is proposed by Martinelli [58]. Moreover, future research has to expand our spatially oriented framework to capture the changes in the dominant technological trajectories of the international TIS. Thereby, researchers could shed light on the influence of transnational linkages (see, e.g., [92,93]) on the direction of technological development during a TIS life cycle.

Secondly, our research should not be taken as a forecast of the future development of the ICE-TIS. In our empirical investigation, we used patents as an indicator for codified knowledge that only measures inventions that have yet to successfully evolve into innovations [65]. Thus, we left out the role of tacit knowledge and market demand in shaping technological development. Another important point is that we only focused on the most significant main paths in the citations network, which are indeed a stark reduction of the overall complexity of the network. Other procedures that capture a greater complexity, like the network of local main path [21], the conceptional trajectory map [94] and the technological juncture analysis [62], are available in the literature. Subsequent works could extend our analysis with additional main path analysis approaches and complement the findings with more innovation output related data to account for the alignment with market demand. Relatedly, we explicitly took the perspective of a mature technology and investigated how it adapts to increasing decline pressures. Future research could consider emerging competitive technologies, e.g., BEVs and fuel cell vehicles, and investigate their development dynamic in relation to the incumbent ICE-TIS. This can be further complemented by adjacent frameworks like the multi-level-perspective that provides a dedicated focus on niche-regime dynamics [95].

Finally, further research is needed to establish a causal relationship between the changes in the context, the TIS structure, territorial particularities and the choice of the dominant technological trajectory. Arguably, among a wide range of possible factors in the territorial TIS structures, we emphasised policy regulations as the primary driver for the difference in the technological trajectories across the examined territories. However, there are certainly other important factors in the territorial TIS, such as the initial bad image of the diesel engine in the USA and Japan or the denigration of diesel technology by major Japanese carmakers [18,19,87], which could be responsible for the disparity in the technological trajectories. Additionally, there is also further potential to put a greater emphasis on context structures like competing or complementary TIS or a stronger focus on the ICE-TIS itself by means of a finer delineation between the gasoline, diesel, and hybrid powertrains. This would allow to further differentiate the influence of context changes on the respective technological applications and their interrelated development dynamics [40]. Besides examining other factors, the linkages between the focal TIS and its context have to be investigated in greater detail as well [3].

Author Contributions: Conceptualization, D.W. and P.S.; methodology, D.W. and P.S.; software, D.W. and P.S.; validation, D.W. and P.S., formal analysis, D.W. and P.S.; investigation, D.W. and P.S.; data curation, D.W. and P.S.; writing—original draft preparation, D.W. and P.S.; writing—review & editing, D.W. and P.S.; visualisation, D.W. and P.S. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data presented in this study are available in the DOCDB database provided by the European Patent Office (EPO).

Acknowledgments: We wish to thank Carsten Dreher and Julia Simper, who reviewed previous drafts of the manuscript and provided valuable insights and constructive feedback; The publication of this article was funded by Open Access Publication Fund of the Freie Universität Berlin.

Conflicts of Interest: The authors declare no conflict of interest.

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