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Understanding the Dynamic Nature of Technological Change Using Trajectory Identification Based on Patent Citation Network in the Electric Vehicles Industry

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***Abstract*--Since the 1990s, Electric Vehicles (EV) have experienced a significant rate of growth marked by a continuing period of significant technological change. It is argued that technological changes have been taking place along ordered and selective patterns in the potential paradigmatic shift of EV evolution. A patent based method is employed in this research to observe the technology evolution and to identify the dynamic changes of technological trajectories by applying network-based methodologies to patents and patent citation. Compared with the previous literature on technological trajectory research, which conducted a historical descriptive analysis alone or considered the technology development process as a whole without dividing different phases to identify the dynamic technological trajectory, this paper highlights the dynamic nature of technological evolution in the development process and improves the accuracy of analysis of the key technological trajectories. Together with the empirical study on the technology evolution of EV, this paper not only proposes a dynamic identification method of technological trajectory, but also describes the process of technology changes in detail. In addition, this approach helps to position the development path of an object technology and thus is utilized in designing the R&D strategy for the enterprises, countries and regions.**

I. INTRODUCTION

A. Literature review

The study of technological change in complex technical systems has attracted increasing academic attention in recent decades. These literatures provide insights as to how the dynamics of technological changes is affected by different roles: network effects [21], technological interrelatedness [3], and the need for compatibility standards [12]. The concepts of technological paradigm and trajectory are widely used in the literature but at the same time the challenge of their validation from an empirical perspective is still significant due to the issue of availability of comparable data. Recent stream of literature on innovation proposes a network approach to overcome this challenge by defining technological trajectories in terms of knowledge flows within a patent citation network [4, 15, 23, 31].

Since comparable data for empirical operationalization of technological trajectory identification is not easily available even though it is suitable to be used to investigate the dynamic nature of technology because it could uncover qualitative information of the invention, one of this paper's contributions is by providing such evidence. This paper examines the patterns of technological change in complex technical systems as captured by patent citation networks. Weighted patent citation is one of the most common methods to evaluate the significance of patented innovation. It has been found in several studies that patent citation provides a reasonable proxy for their technological importance, which is highly correlated with other measures of the value of innovation such as the assessments by technology experts [20]. However, an analysis based on citation counts may have certain drawbacks [15]: Firstly, changes in one specific component would trigger changes in other parts of the system. This is because various single components need to work together in a technical system, in which innovation is distributed and takes place at the level of individual components across the system. Secondly, an analysis based on citation counts may underrate the significance of specific innovations. With the systemic characteristics, innovations appear to be incremental in nature and generally take place around well-established technical designs in order to ensure that adequate levels of compatibility are maintained [2]. Thirdly, an analysis based on simply citation counts may fail to identify the concepts and principles that could act as 'focusing devices' [27] for a sequence of inventive activities since innovation also tend to occur continuously. Both the incremental and systemic nature of innovation are conducive to the establishment of a rapid pace of technological change [3].

Our analysis is based on the study of citation network using patents in the Electric Vehicle field granted by the US patent office. The patents have been retrieved using a method of keyword search through Thomson Innovation [1], which provides a fully searchable US granted patent coverage from 1836 till present. This method was broadly adopted based on the assumption that patents represent the building blocks of a technology and citations represent an indicator of the prior knowledge underlying a specific inventive step. Thus, trajectories that have characterized technological evolution can be identified through examining the structure of the patent citation networks in a specific technological field. While Dosi has proposed that key paths of patent citation network, in a sense, can be understood as the fundamental 'technological trajectory' [13], Hummon and Doreian on the other hand have contributed a number of criteria for the identification of the main paths of 'connectivity' in a citation network [19]. Hence, our methodology for the analysis of the patent citation networks follows this seminal approach.

[1] Thomson Innovation is a patent search tool launched by Thomson Reuters, a global provider of information services across many business and technical disciplines, and the producer of the well-known patent search file, the Derwent World Patents Index (DWPI). See: http://info.thomsoninnovation.com retrieved on 7 December 2013.

The analysis of the connectivity of patent citation networks has built a continuous patent developing trajectory that traces the development of a specific technology, which has important implications for assessing the relevance of innovation in complex technical systems. First, it allows us to extract the most significant sequences of patents, thus identify the key technological bottlenecks and ‘focusing devices’, which have played an important role in the evolution of the system. In this sense, technologically significant patents should be part of the ‘main path’ of the citation networks and/or located at specifically critical ‘junctions’ within those paths. Second, it allows us to have a well-balanced investigation between quantitative and qualitative perspective by mapping technological trajectories as sequences of patents. In particular, it creates the opportunity to ascertain a restricted number of patents, which in turn can be examined in detail in order to reconstruct the strategy governing inventive activities. Third, it allows us to explain directions of improvement and trends of development in an industry or a particular technology by reconstructing the ‘main path’ of patent citation network. This not only reflects directions, processes, features and patterns of knowledge flow but also relations and patterns of citation [28].

Recent stream of literature on trajectory identification has pointed out a major flaw that is being static without considering the different stages in technological development process. Technological trajectory is not always a simple straight line but a diverged path due to the effects of multiple complex factors at different stages of technological development. Dosi [13] pointed that incremental innovation gives technical progress on existing products/processes of technological trajectory. However, radical innovation transforms the original trajectory into an entirely new trajectory. In practice, the emergence of new technological trajectories is contextual to the effect of innovation and market. Particularly in the case of emerging technology where uncertainty is very high, companies might choose to explore, focus or enhance capability at certain points of the trajectory. Owing to the fact that evolution of technology will result in several trajectories which are competing with one another, enterprises would choose a different trajectory in shaping their innovation strategy. Therefore, by applying major R&D efforts into these selected trajectories, eventually one would emerge as the major trajectory of technology evolution. By investigating the different stages of technological development, we are able to identify the main trajectory and changes of key technologies. Static analysis at different stage of technological trajectory is usually applied on mature technologies or emerging technologies that have achieved a certain level of stability. However, when implementation and functions of the technology are still volatile, the results of the static analyses could be doubtful. The stability of a technological trajectory would affect the formulation of R&D strategy in enterprises, especially those in emerging markets. On one hand, for mature technologies, enterprises can focus their R&D along the main trajectory, technologies which are still volatile on the other hand, enterprise could opt to invest in R&D on multiple trajectories. Therefore, simple static analysis in a single period of time would not able to detect this problem.

In order to solve the issue of dynamic changing trajectory of technology, based on works of Hummon and others, we propose a dynamic analysis of technology trajectory at different stage of technology evolution. This method would enrich the research content of technological trajectory and also provide meaningful practical implication of research in this field: micro level analysis contributes to enterprises' R&D activities while macro level analysis contributes to selection of key technologies by countries and regions in the case of emerging technologies.

B. Electric Vehicle technology

For the purpose of this paper we consider the case of Electric Vehicle (EV). The EV was invented in 1834 but due to the limitations associated with the batteries and the subsequent rapid advancement in Internal combustion engine (ICE), EV has not been heard of since 1930. Nevertheless, this industry went through a *second wave* in the early 1970s when several developed countries, compelled by the energy crisis, started the rekindling of interests in EVs. In 1990, California had a mandate on the use of zero emission vehicles. Consequently, the world went down a new road by 1997 when the first modern hybrid electric vehicle, the Toyota Prius, went on sale in Japan. Two years later, the U.S. saw its first sale of a hybrid, the Honda Insight. These two vehicles, followed by the Honda Civic Hybrid, marked a radical change in the type of cars being offered to the public: vehicles that bring some of the benefits of battery electric vehicles into the conventional gasoline powered cars and trucks that has been on the road for more than 100 years. Along the line over 20 models of passenger EVs have been introduced to the auto market [8-10]. From a technological point of view, EV presents several points of interest. First, EV represent the archetypical case of a complex system in which components must confront specific technical problems or bottlenecks before giving way to newly proposed solutions. Accordingly, the history of this technology, whose beginnings can be traced back to the early of 18^{th} century, has been punctuated by the demise and emergence of successive commercialization. Second, EV technology is a multidisciplinary subject that covers broad and complex aspect. At the same time it is also characterized by a relatively fast rate of innovation and strong uncertainty related to the availability of several technological options, which in this paper, includes hybrid electric vehicles (HEV) , battery electric vehicles (BEV), and also plug-in hybrid electric vehicles (PHEV). EV has key technologies (components), i.e., batteries and electrochemical capacitors, propulsion motor, power converters, hybrid control technology, energy source & infrastructures, and others such as ICTs related technology.

The structure of this paper is as follows. Section 2 illustrates in detail the methodology. In Section 3 we describe the construction of patent data set for this study and gives rise to the dynamic analysis of the patent citation networks using connectivity structure indicators. Section 4 concludes the study.

II. METHODOLOGY OF DYNAMIC ANALYSIS BASED ON IDENTIFICATION OF TECHNOLOGICAL TRAJECTORY

A. Selection of Patent Data set

Radical innovations are innovations that cause marketing and technological discontinuities on both a macro and micro level. On the other hand, incremental innovations occur only at a micro level and cause either a marketing or technological discontinuity but not both. Real new innovations cover the combinations in between these two extremes [17]. We argue that a focus on product/process innovation at a micro level, i.e. the component level, has the potential to unpack the relationships that matters in the localized advancement of technology in EV. Our main objective is to trace, visualize and critically discuss the dynamic processes of creation, competition, selection and inheritance of technical solutions developed by the actors in response to the problems or bottlenecks of EV.

The availability and accessibility of several patent databases has made patents analysis very popular in innovation studies. Patent documents contain a wealth of information, including but not limited to the assignee/inventors' identity, location, institutional affiliation, technological field of relevance as well as citation to prior art. Citations enable knowledge links to be traced across technical contributions in different components and therefore patent data represents a valuable source of information that can be used to plot the evolution of technologies as it illustrates how technological preferences have shifted over time [30].. While there has been some discussion in the literature as to the reliability of patent data, there is also consensus that patents granted in the US are at least indicative and could possibly offer a good proxy for technological development [1, 7, 18, 25, 32, 34]. In this study, we use citation networks to shed light on the evolution of scientific and technological knowledge connected to the emergence process of EV. The traditional approach to new car development is to re-style the body of an existing vehicle incorporating engines, gearboxes and components from other models with only minimal changes to the mechanics of the vehicle [11]. However, there are no existing power train or mechanical components to design the battery of electric vehicle around. As a result, the new product development process has to innovate these systems [26]. Xie and Miyazaki provide a principle of key words selection for patent identification which when applied shows that the most effective method of identifying patents in a specific domain through key word search is by using the patent information in the title, abstract and claims [35]. We developed our patent-identification method accordingly and proceeded as follows. After reviewing the specialized literature in EV field with the assistance of expert[2] advices, this paper extracted traces of knowledge codified in granted patent documents with the aim to identify and quantify the distributed knowledge base that has developed in the research domain of EV.

B. Dividing the stages of technological evolution

Upon completing the selection process of the data set, we need to establish the stages of technological evolution that is the main difference between the static and dynamic analysis method. There are many ways in dividing the stages but two practical ways to achieve it is by using technology life cycle (TLC) theory [16] or by analyzing the significant characteristics or features of the technology occurring across series of time. The empirical analysis of this paper will be by utilizing a combination of both methods.

The concept of the technology life cycle was developed by Arthur [22] to measure technological changes. It includes two dimensions—the competitive impact and integration in products or process—and four stages: emerging, growth, maturity and saturation. According to Arthur's definition, the characteristic of the emerging stage is a new technology with low competitive impact and low integration in products or processes. In the growth stage, there are pacing technologies with high competitive impact that have not yet been integrated in new products or processes. In the maturity stage, some pacing technologies turn into key technologies, are integrated into products or processes, and maintain their high competitive impact. As soon as a technology loses its competitive impact, it becomes a base technology. It enters the saturation stage and might be replaced by a new technology. Ernst[14] has developed a S-curve graph to illustrate these four distinguished development stages (Fig. 1).

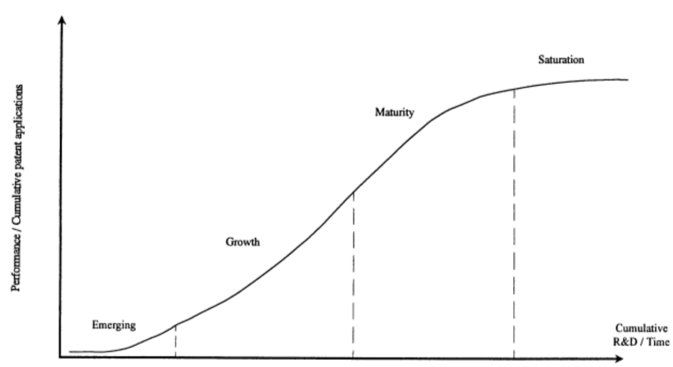

Fig 1. The S-curve concept of technology life cycle

2 One is Xie Zhongquan, who proposes an effective method of identifying patents in a specific domain. The other one is the professor of Dalian university of technology who has engaged in the basic and application research of new energy vehicle in China for many years.

Since technology life cycles illustrates the speed of technological changes, the relations between number of items in databases such as U.S. patents [33] can be used to identify the different stages in technological life cycle. In some cases, technology that has died out experiences a 'comeback' resulting in new gaps and new directions for technological evolution.

In the case where technological lifecycle is obvious, we can directly analyze significant stage of the technological evolution but for cases where lifecycle is not clearly discernable, we can analyze according to significant features across the series of time. According to annual variation of the number of patents, one can observe the trend of technological development and R&D investment. For an object technology, there will be a period for both trends aforementioned. Therefore, it indicates that, at different stages of evolution, the pattern of innovation within a technological development would be different [29]. By analyzing the variation of a certain variable, the speed and trend of development in terms of research object can be detected. In this sense, we can utilize the variation of annual number of patents to divide the stages for the next phase of our work. In particular, the years with a value of maximum or minimum that show an obvious change of quantity would be sorted to a same object stage.

C. Identification of main path

The next and important step for our research is to extract technological trajectories from different stages. A proper assessment of the technological significance of a specific patent ought to be based both on direct citations and on a general characterization of the position of the patent in the overall structure of the network of patent citations [15]. In this paper, we will follow the approach proposed by Hummon and Doreian [19] which has already been adopted for the analysis of patent citation networks in different technological fields [23, 24, 31]. According to their paper, the main paths of a network which represent the relationship between pieces of knowledge should be viewed as the 'main flows of ideas' characterizing the structure of the network. A weight is assigned to each citation links on the basis of its position in the overall structure of the network. This method is based on the examination of different 'search paths' which are sequences of links that connect the vertices of the network. An example is given in Fig.1 illustrating the fundamental method. The vertices represent the patents and the arcs represent the citations in the figure. The arcs are oriented from the cited patent towards the citing patent, hence the arrow represents the direction of the knowledge from the cited to the citing patent. A search path, for example represented by sequence A→C→D→F→H→J, which would indicate a knowledge flow from patent A to J through several intermedia patents. We use one of the indicators proposed by Hummon and Doreain, the so-called search path link count (SPLC), to measure the structure of the patent citation network. By considering all the possible search paths in the network, the SPLC is then calculated as the frequency of an arc lying on such a search path. Each search path is used only from the start points to endpoints without considering intermediate vertices as the origin or the final destination. In this case, a value of SPLC is assigned for the arc A→C. It means that this arc exists respectively on paths A→E, A→G, A→I, A→J. Once the weights to the links of network have been assigned using the SPLC procedures, Hummon and Doreian give a procedure for constructing the network of 'main paths' which is represented by the network created and formed by those paths moving from each 'start point' towards an 'endpoint' of the network. In this procedure, each node must follow the link with the highest SPLC value. In the case of a connecting tie, both links are considered as part of the network of main paths. Here, it assumes that the significance of a citation link is adequately captured by its SPLC weight. In Fig.2, the construction of the network of main paths, marked by thicker lines, does not change if we use the values of SPLC as weights of the arcs and it involves the deletion of the arcs D→E, F→G. In other words, by deleting marginal or redundant edges, this method completes the heuristic idea of identifying the most important knowledge flows in the patent citation network and then accordinglly presenting the technological trajectories traced by the patents as the carrier. Our analysis is conducted by using the software Ucinet and Pajek to illustrate the use of the indicators of inner connectivity structure for the systemic analysis of patent citation network. In addition, by intergrating the publication date of patent, the patents identified would be re-sorted along the sequence of time.

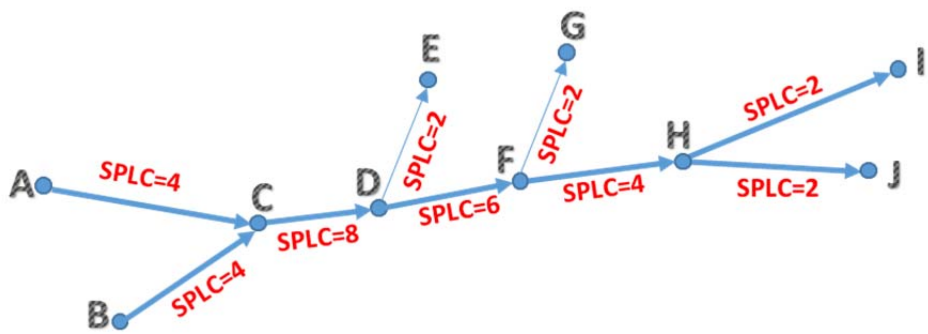

Fig. 2 Example of Calculation of SPLC and main path of the network

D. Comparison of main paths at different stages

In order to understand the stability and dynamic nature of the process of technological change and evolution, we have extracted the technology trajectories at different stages and made a comparable analysis of these various stages of trajectories.

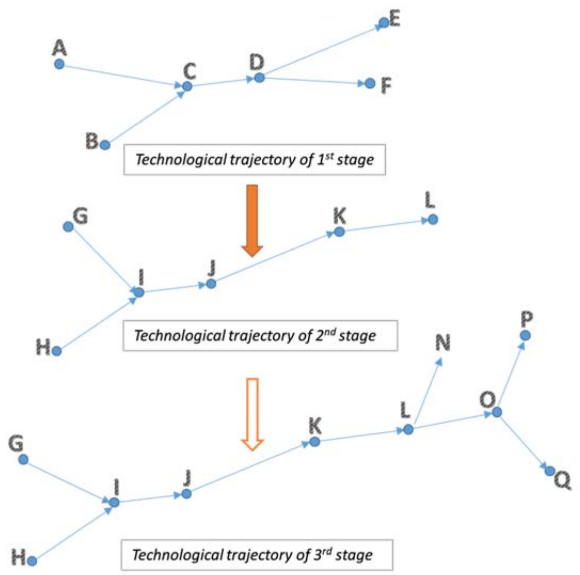

Fig. 3a. Comparison of technological trajectories in different stages

The characteristics of trajectories vary in various stages as presented in Fig.3a. On the one side, the change of trajectory is quite drastic at some stage. For example, there is no same node between the 1st stage and 2nd stage, which shows that technology has undergone tremendous changes in this situation. It may be necessary to have an interpretation of the patents and assignees in these two stages to ascertain the causes of variation and the impact of its changes on future technological developments. On the other side, the change of trajectory is incremental at a certain stage. For instance, by comparing the 2nd stage with 3rd stage, the trajectory of 3rd stage has added a few new nodes on the basis of the former one, which could be explained that the trajectory has entered a relatively stable state. In this case, technology would develop along this path for a short period due to the smaller improvement of technology in this field. Therefore, we argue that, by analyzing the technological trajectories in divided stages, we are able to understand the dynamics of development of technological trajectories and hence able to forecast the evolution of the object technology in the future.

III. EMPIRICAL STUDY ON DYNAMIC ANALYSIS OF TECHNOLOGICAL TRAJECTORY IN EV INDUSTRY

Technologies involved in the key components of EV are mostly high-tech and new technologies that are impacted by the factors in technical perspective. Therefore, by using analysis of patent citations network to illustrate the technological trajectories divided in different stages, it can provide decision support and empirical validation for latecomer countries, research institutions and enterprises who want to grasp the pattern of technology development, establish the plan of science and technology development, undertake the R&D program and apply for related patents. With the advice and experience of experts as mentioned in section 2, the EV-related inventions dataset were extracted by keyword search on titles, abstracts and claims ranging from general strategies (e.g. "electric vehicle" OR "hybrid vehicle") from the US granted patent whose publication data is later than 1863[3]. A patent data set was extracted on 25th Nov. 2013 from Thomson Innovation that contains information on 13216 patents granted in the US to EV-related inventions covering the period 1883-2013. By analyzing this dataset, a comprehensive process of EV technology development can be illustrated.. From the original data, our core analysis rests on the construction of a patent citation network composed of 13217 vertexes (patents) and 226153 arcs (citations).

A. Overview and dividing of the stages of EV technology

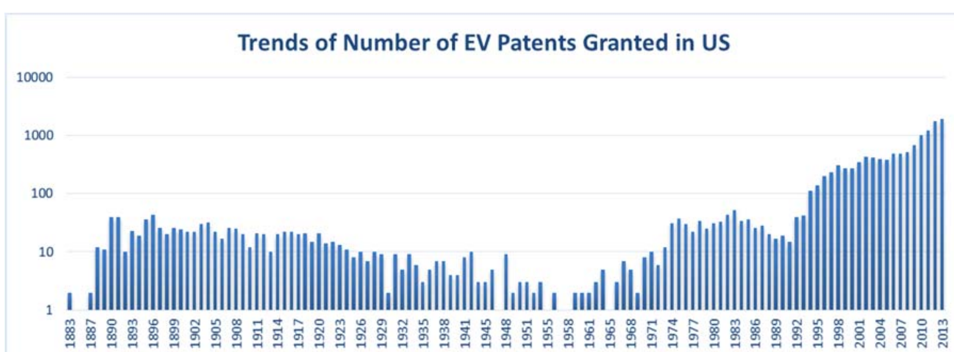

Fig. 3b. Trends of Number of EV Patents Granted In US from 1883 to 2013

[3] Thomson innovation has the world's most comprehensive collection of patent data, from major patent authorities, specific nations and proprietary sources, which include the US granted fully searchable patent data form 1863-present. See: http://info.thomsoninnovation.com/sites/default/files/assets/L-367541.pdf retrieved on 7 December 2013.

Figure 3b which illustrate the trends of number of EV patents granted in the US shows that the research in EV related technology begun and patents have been applied since the 18th century. For the increasing trends of patent documents, the number of granted patents reached a local maximum value in 1896 and 1983 respectively. And the annual volume of patents was on a rising trend hovering more than 20 from the year of first local maximum to 1924. Then, a standstill of patent publication has lasted for a long period till the 1970s, in which the number remained below 10 and even no patent was granted in some years. Interestingly, after 1994, the number exceeded 100 for the first time and with a highest ratio of year-on-year increase , the number of granted patents has increased rapidly.

According to the historical perspective, as early as 1834, Vermont blacksmith Thomas Davenport developed a battery-powered electric motor. He used it to operate a small-model car on a short section of track, paving the way for the later electrification of streetcars. Though EV technology was pioneered in Europe (The 1899 La Jamais Contente set a world land speed record) they were more established in the U.S. by the early 1900s. In fact, by 1900, almost 30% of passenger vehicles were electric. Based in Cleveland, Ohio, Baker was one of the largest manufacturers of electric vehicles in the country. However, advances in gasoline vehicle technology after the turn of the century quickly made range-limited electric cars obsolete. Due to the limitations associated with the batteries and the rapid advancement in ICE vehicles, EVs have almost vanished from the scene since 1930 [9].

As a consequence, while considering both the patent trends and these events, we can break the entire process of EV development into two waves: first wave from 1834 the year EV was invented to 1930, and then second wave from 1948[4] to 2013 as the main research period of this paper.

Based on the theory of technology life cycle, we can induce that the process of technology changes in EV field is still in the growth period, in other words, the inventive themes and number of publication of patents have significantly expanded in this period. We have found that EV has gained its popularity by dint of investigating the inventors and assignees who have paid more attention to EV research and become more and more active in R&D actions. This characteristic indicates that the EV industry is an emerging industry in a high-speed growth phase, which has attracted a number of enterprises and research institutions engaging in the R&D activities. Overall, it is a timely opportunity for enterprises to enter this industry and conduct R&D actively due to the vigorous vitality of EV technologies.

By analyzing the increasing trend of EV patent's literature and technology life cycle in EV field, we divide the second wave of EV technology evolution into four stages: (I) the first stage is 1948-1983, in which the annual number of patents has increased slowly until it reaches a local maximum by 1983; (II) in the second stage 1984-1993, the patent volume experienced a small drop phase; (III) When the number exceeded 100 firstly on 1994, EV technology evolved into its third stage, until 2006 with a higher year-on-year increase jumped to 25.4% compared to past 3 years of negative growth; (IV) in the fourth stage, 2007-2013, technological development enters a rapid phase with a growth spurt of patenting number. From 1997, EV reached a significant milestone of its second wave, when Toyota Prius was introduced to the Japanese market, two years before its original launch date, and prior to the Kyoto global warming conference held in December. Until 2013, Toyota Motor Corporation announced that cumulative global sales of its hybrid vehicles topped the 6 million unit mark [5]. EV technology has evolved from scientific and technological oriented period to market oriented period in the second wave of its development. In this period, with rapid technological development, R&D investment of pioneers including enterprises and countries has increased dramatically. Therefore, it has a far-reaching significance to grasp the changing nature and trends of the technological trajectories in the future development of the industry as a whole.

B. Analysis of dynamic changing process of technological trajectories

Patent citation network needs to be constructed first in order to track the trajectory of EV technology development. After cleaning and sorting the retrieved patent dataset, the citation networks is created through extracting the cross cited relations. Then, the visualization of these citation networks in different stages are implemented by utilizing the software Netdraw. Batagelj [5] has developed an algorithm to analyze the connectivity of citation network and thus computationally identify the most important part of a citation network i.e. its main path with a maximum value of SPLC. A number of Pajek's functions are used here to find and extract main path from large networks [6] and show visually the relationships among them. While a main path providing a parsimonious longitudinal examination of how a citation network evolved through their citation patterns - such as convergence or divergence overtime - which are described in Batagelj's research, these four main paths present the technological trajectories in the divided four stages and thus provide a visual mapping of a broader longitudinal connectivity within the citation system of EV related patents. Fig.4a and Fig.4b illustrate the evolution of the four main paths (i.e. the technological trajectories) of EV technology evolution over time 1948-2013 calculated on nested subsamples, in which each node is named using patent publication number.

In order to understand the changing nature of EV technology, we analyzed the comparable trajectories divided in four stages of evolution process and thus found that:

[4] The records with regard to patent citations data of USPTO we retrieved from Thomason Innovation can be reviewed from the year of 1948.

[5] Toyota News Release. "Worldwide Sales of Toyota Hybrids Top 6 Million Units". Toyota USA. Retrieved 2014-01-15

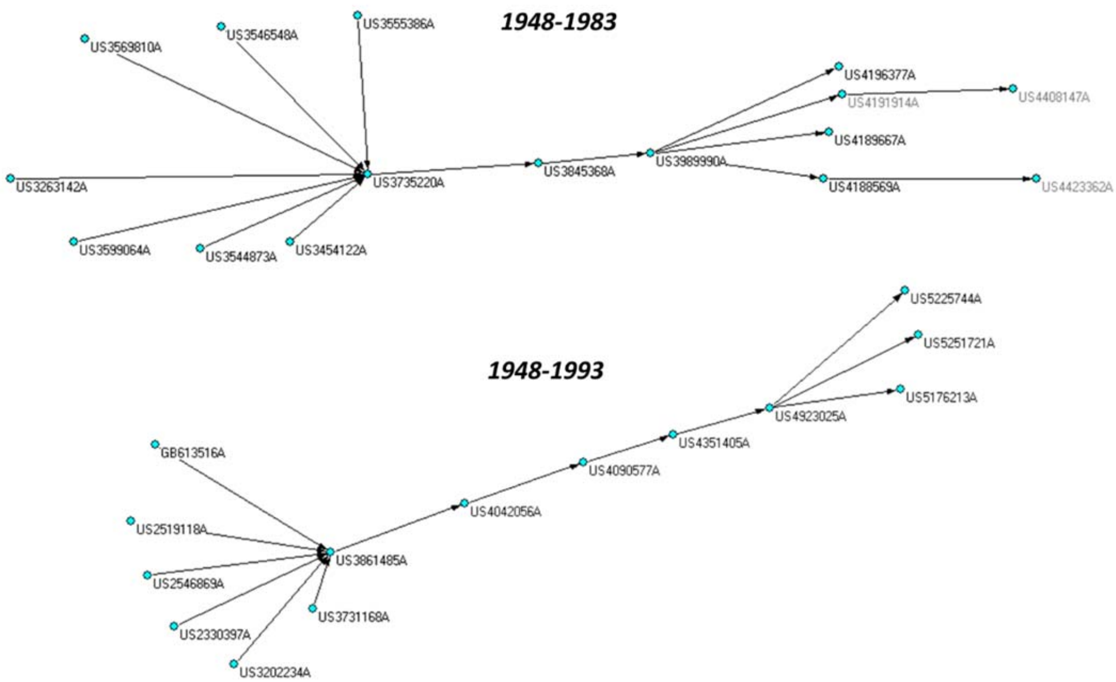

Fig *4.a*. The evolution of the main path over time 1948-2013

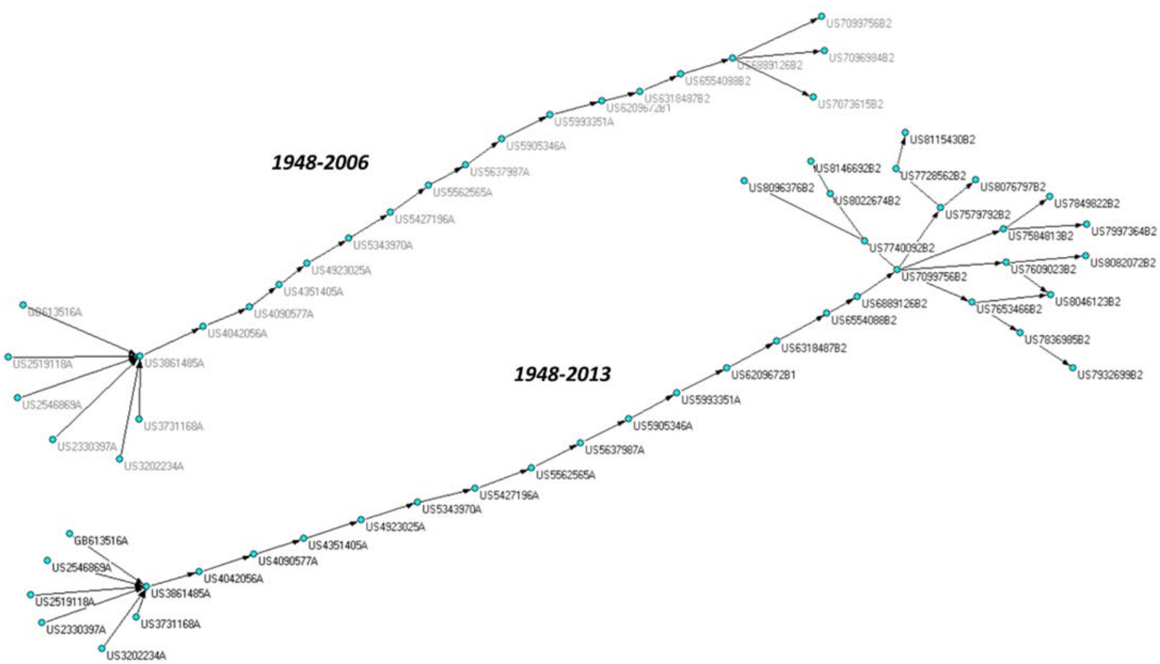

Fig *4.b*. The evolution of the main path over time 1948-2013

The patents in the first technological trajectory up to1983 are linked to the emergence of a fully electric propulsion motor with the small granted number. Due to the emerging characteristic of this stage, the technology is yet mature and focused on basic research. A major problem of early motor was the achievement of a basic level of reliability for the control system. The assignees of the first stage were mainly manufacturing enterprises such as Westinghouse Electric Corp and Lucas Industries Limited which engaged in the manufacture of key component and invested in the R&D of feedback control. The enterprises including both motor industry and aerospace industry also occupy positions on the trajectory which indicate the significance of technological background of control circuits for electric traction. In this stage, a series-connection characteristic during acceleration up to a predetermined nominal speed was given to the motor by dint of the control circuit. From the point view of knowledge flow in this stage, technology convergence of control circuit for electric motor (patent US3735220) and divergence of feedback field control for EV (patent US3989990) appear in the process of constructing main path.

The second trajectory, calculated between 1984 to 1993 adds to the previous trajectories' few patents. A radical change has taken place in the new trajectory , compared to the previous one, and the technological development in this stage is more simplified which focus R&D on drive and control system. However, the patent volume has a small drop. For the assignees in this period, the ones, such as Westinghouse Electric Corp and Lucas Industries Limited exit from key roles in previous trajectory; the others join in, for example, Warner Swasey Co, Aisin Aw Co., Ltd., Automobile Corporation of America. Regarding the development of technology, from electric motor vehicle to hybrid powered drive system, comprising solar celled hybrid vehicle and hybrid car with electric and heat engine, it addresses the issues of hybrid drive system.

Owing to the particular breakthrough in related fundamental technology, technological trajectories in the two stages above have experienced significant variation in which the EV industry was still in an emerging stage with lower clarity of direction. In other words, at this stage, a stable and predictable trajectory has not been formed but several trajectories were competing with one another.

The inclusion of patents up to 2006 expands the trajectory of the last stage with a higher year-on-year increasing rate of granted patents. Minor changes of technology occurred in the stage of 1994-2006, which experienced the improvement from an electric motor to a gasoline and battery-powered system, the optimization of hybrid car with electric and heat engine, and the process of development of a hybrid vehicle comprising an internal combustion engine, a traction motor, a starter motor, and a battery bank. Furthermore, Warner Swasey Co and Aisin Aw Co., Ltd quit from the trajectory and the carmakers join the main path such as Nissan Motor Co., Ltd, Paice Corporation, Toyota Motor Corporation, General Motors Corporation. It points out that on the one hand, the foci of R&D shifted from basic or component technology to the whole vehicle system, and on the other hand, the giant enterprises played a more and more important role in this trajectory which have solved certain focal issues of hybrid vehicle and led the application to a direction of advanced hybrid vehicle.

The last trajectory, adding the data up to 2013, almost completely goes along the previous one but with a more diversified direction of application for hybrid vehicles. Technology changes at this stage are primarily incremental changes in the performance or application based on the improvement of former products or technologies. In fact, some elementary technical problems have been solved in this stage where the technological trajectory has been emerging out of stability in a short-term and the industry has entered the period of growth. We can conclude that mixed power propelled vehicle is the principal stream of EV. Enterprises can go along this trajectory for continued R&D and strive for grasping the core technology of electric motor drive system and entering in to the trajectory as early as possible. After examining the assignees of this stage, accordingly, we induce that the pattern of R&D in this stage is transferring from a mode of internal R&D inside of big enterprise to a mode of open cooperation among different organizations, which could be translated that it highlights the importance of competence for enterprises to acquire, assimilate and use external knowledge.

A look throughout the changing trajectories of the four stages brings about the dynamic nature of technological change: technological trajectories are constantly changing accompanied with processes that the old technical bottlenecks are addressed and technologies are utilized to further fields. Stable technological trajectories did not appear in the prior two stages but gradually formed in the latter two stages which may still be volatile in the future. A final remark in support of the dynamic change observed in Fig.4 regards the analysis of the assignees of the patents among the trajectories. Indeed, some enterprises are observed in different stages such as Toyota which not only kept an active role in the basic research stage but also owned several basic fundamental technologies of EV. Its main technological competence includes those technologies related in motive power output, and solution for hybrid-vehicle control, while it occupies the upper position of different trajectories. After continued investment in R&D for many years, these enterprises already have a certain accumulation of EV technology which provides the foundation for sustainable development in the future.

C. Findings

As a finding of this paper, we put the trajectory for the period 1948-2013 here again and consider the second wave of technology development as a whole shown in Fig.5. The figure should be interpreted in a cumulative way, starting on the left side with the period 1948-1975 (indicated A) in which several components/technologies converged to a main junction that is an EV with battery, constant speed motor and variable transmission. As longer time periods are considered, more nodes and branches are added to the early trajectory. For instance, the trajectory for the period 1948-2006 is the union of the trajectories indicated by letter A and letter B, in which a technological accumulation of hybrid automobile drive technology has taken from electric battery-driven technology.

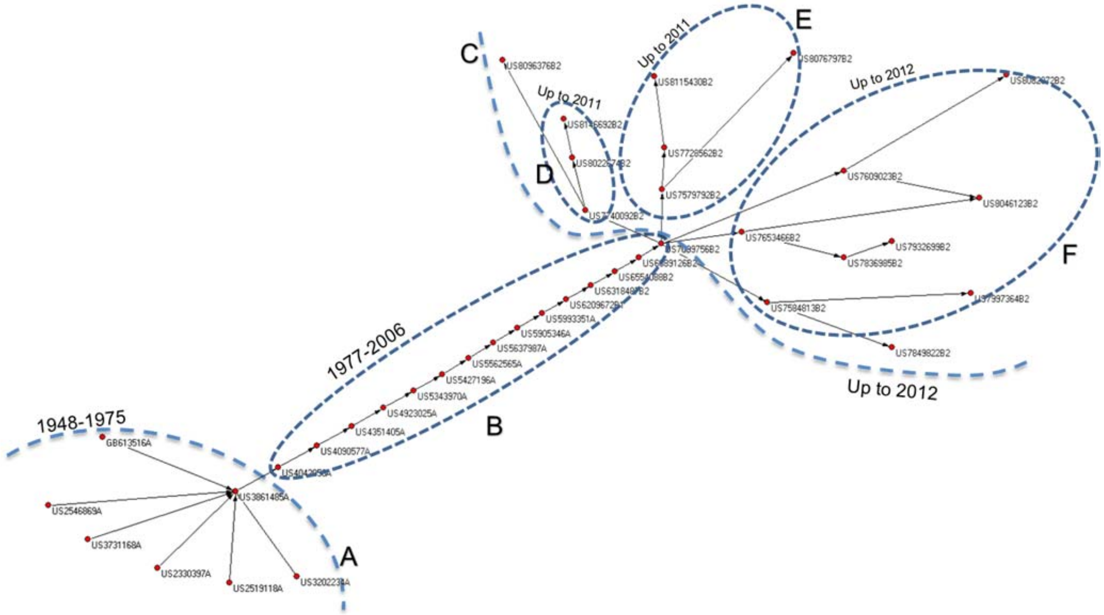

Fig.5 Union of the main paths calculated on a nested USPTO dataset, represent the technological trajectory of EV technology in the second wave

By the re-construction of the main path of 1948-2013, we found out that three trajectories that are listed in Table 1 compose the second wave of EV technology development. This finding, which is in consonance with the conclusions of prior literatures and the fact of developed market, not only provides an evidence for empirical operationalization of technological trajectory identification but also verifies a proposed dynamic analyzing method to investigate the nature of technological changes.

TAB.1 TECHNOLOGICAL TRAJECTORIES OF EV TECHNOLOGY IN ITS *SECOND WAVE* DEVELOPMENT

Trajectory - A	1948-1975 Path of electric motor driven vehicle
Trajectory - B	1976-2006 Path of Hybrid power driven vehicle
Trajectory - C	2007-present heterogeneous trajectory of mixed EV D. plug-in hybrid propulsion with energy storage E. Energy transferring and controlling F. Power sysetem or battery controlling

The emerging technologies are mainly driven and brought about by the actors including big enterprises with technical strength, laboratories and individuals engaged in basic research. Actors who have successfully occupied the focal node of technological trajectories would have a dominant position in the competition of technology and market share. Therefore, many research laboratories, manufacturers of equipment and raw materials, producers and regional associations are trying to positively influence the content and process of technological development. Accordingly, manufacturers of equipment and raw materials, such as a chemical firm[6] using high-capacity silicon negative-electrode material to enhance capacity of lithium-ion battery, adjust their innovation strategies based on the implications from these technological trajectories, so as to be consistent with the requirements of market in the future. In particular, by analyzing the assignees of technological trajectories, we are able to comprehend not only the changes of actors who played key roles and dominant position in the development of the industry, but also the changes of real products and using each technology through the major business of these assignees.

Additionally, when we discuss the dynamic nature of technological trajectories in a broader view, the pattern of R&D corresponding to the mode of cooperation of patentees in an object technology field also appears. Actors existing on the key nodes of the trajectory include not only single R&D institution or enterprise but also multiple organizations or enterprises cooperating with one another. Consequently, it indicates a cooperative R&D mode and we may analyze the stability of their cooperation when a certain institution or enterprise appears more than once in a trajectory, which cooperates with the same or different organizations to apply patents.

6 The R&D Center of Sekisui Chemical Co., Ltd. has developed a high-capacity film-type lithium-ion battery using a coating process that has simultaneously tripled its capacity (compared to other Sekisui Chemical products), increase its safety (as a result of standard safety testing, e.g. no problems with nail penetration tests or crush tests) and speeded up production by ten times. See detail in: http://www.sekisuichemical.com/about/whatsnew/2013/1239025_17313.html retrieved on 18 December 2013.

IV. CONCLUSIONS AND IMPLICATIONS

The limited empirical literature on technological changes tends to use the approaches of analyzing technological trajectories to explain the technological development process of most industries but not for evolutionary process of an object technology with a dynamic changing condition due to the limitation of considering the development process as a whole. This paper proposes a dynamic analyzing method based on identification of technological trajectories by the use of patent citation network. It describes not only the explicit structure and implementation steps in detail but also discusses the validation through empirical examination in EV technology research and development. Additionally, this paper provides comparable evidence for empirical operationalization of technological trajectory identification and verifies a proposed dynamic analyzing method to investigate the nature of technological changes which are measured by the theory of technology life cycle and divided into different and non-static phases..

The aim of this paper was to investigate the micro-dynamics of technological changes in the EV industry by looking at the dynamic nature of evolution regarding technological trajectory. By investigating the evolutionary process of EV technology, we have a conclusion in terms of dynamic nature of technological change that is twofold: first, the technological trajectory experiences a significant variation when there is no obvious change of the granted patent number, for example in the early emerging phase, however it retains a relative stability as the number increases drastically; second, the actor who occupy the key node of trajectories in the early or germination stage of technology development does not necessarily play a key role for a long time, but the actors, which achieved the key position of trajectories in the maturity stage, are the ones owned a prolonged impact on the development in the future. Therefore, the development of technology is influenced by the dynamic changing nature of technological trajectories. Integrating the dynamics to analysis of technological trajectory can be used to understand the nature of technology evolution with a higher accuracy and the trends of progress in the future. Accordingly, it could be applied to design the scientific and technological development strategy for enterprises, countries and regions.

This paper also makes a trial effort to identify the history of an object technology. We have traced two historical waves and a dynamic development process of EV technology from the early emerging stage to the relative mature phase that are clearly showed in this paper. Therefore, our approach has made a contribution to the field of history of technology that helps to position the dynamic development path of an object technology history.

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