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Extending the FIP (Forecasting Innovation Pathways) Approach through an Automotive Case Analysis

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Abstract

The ”FIP” approach seeks to Forecast Innovation Pathways for an emerging technology of interest. It does so by combining empirical ”tech mining” analyses with expert opinion. Tech mining extracts intelligence from multiple sources, but especially through bibliometric and text analyses of thousands of records retrieved from global R&D publication, patent, and business/context databases. FIP blends expert opinion from multiple sources, but especially by convening a focused workshop.

SKF conducted an FIP exercise on Hybrid & Electric Vehicles (HEVs) that presents special challenges. HEVs combine multiple sub-systems, advancing at different rates technologically, with complex technical and market infrastructures. Asian automotive production and markets appear vital for the future of HEVs, and various technologies & applications (e.g., two-wheelers) warrant tracking.

Grappling with this complex innovation system helped extend the FIP approach. Enhancements included extending the previous innovation tiers framework to array multiple technological and contextual factors in conjunction. This is the first FIP workshop to split into small groups to address three priority market segments and three prime geographical regions, then regroup to review and develop consensus.Manifold factors influence HEV innovation paths, so technology delivery systems are more complex than those addressed in previous FIP studies. We reflect on FIP process development, with suggestions regarding scoping, identification of sub-systems, and possible opportunities to systematize certain analyses.

Introduction: Forecasting Innovation Pathways

A small contingent of technology analysts has been developing an approach to Forecast Innovation Pathways (“**FIP**”) over the past few years [32, 34]. This effort can be located as a particular type of Future-oriented Technology Analysis (“**FTA**” – see http://foresight.jrc.ec.europa.eu/). In 2010 they presented a 4-stage (10-step) framework, as illustrated for the case of nano-enhanced solar cells [32]. Recently they have deepened the rationale and expanded the case base by comparing FIP use for nano-enabled biosensors and Deep Brain Stimulation[34]. Several have been exploring FIP regarding Nano-Enhanced Drug Delivery [36, 37]. Each of these cases could be considered a Newly Emerging Science & Technology (“**NEST**”). Here we explore FIP in the context of Hybrid & Electric Vehicle (“**HEV**”) development. This topic poses challenges to develop the approach in terms of adaptation to diverse issues along multiple dimensions. HEVs are 1) different -- transportation technologies, as contrasted with nano- and bio-technologies; and 2) with more developed infrastructure, massive capital investment, existing global markets, and different stakeholders than the previous NESTs addressed via FIP.

FIP stands apart from other FTA approaches in its strong empirical base, combined with informal expert opinion, oriented toward elucidating “pathways” forward for R&D to translate into applications. It also combines analyses of the technical advances in conjunction with key socio-economic-organizational facets that collectively compose a Technology Delivery System (“**TDS**”) [46] to provide products to market. Pathways are particular routes for achieving that technology development. There are a range of concepts akin to TDS modeling, including technological regimes, technology architectures, and socio-technical systems. Acknowledging the variety of possible pathways for technological development is conceptually important -- for one, because it addresses the complexity of technological development [2]. Furthermore, the use of pathways assists analysts and decision-makers in recognizing that technologies are socially, and therefore, multiply determined.

As mentioned, FIP combines *empirical* and *expert* knowledge parts. The empirical part builds upon “tech mining” [31, 33] of global database search results on the topic under study.

The expert knowledge component poses its own set of challenges. In general, FTA emphasizes systematic, structured methods to elicit expert opinion – i.e., interviews, surveys, and Delphi processes. We have found that FIP work is facilitated by two different modes of tapping expertise. One is informal co-option of a local topical expert to collaborate in the analyses on an ongoing basis. In work at Georgia Tech on solar cells and biosensors, one PhD student joined on each endeavor, providing critical understanding of how the technology works. Such help reached from tuning database searches to interpreting workshop results. Such workshops constitute the second mode of gathering expert opinion. Our efforts to structure workshops to elicit tacit knowledge of diverse stakeholders on an emerging technology build directly on the work of Robinson and Propp [35]. We note that many others work to incorporate group processes to attain expert inputs and to model evolving systems [c.f., 13]. Huang et al. [15] describe adaptation of the workshop approach to advance FIP for nano-enabled biosensor development.

Fig. 1 presents the FIP process framework. On the left appear the four stages; on the right, ten finer steps are distinguished [32, 34. That is, FIP particularly compiles and analyzes information on R&D, together with business-related information, striving to identify promising applications and their potential markets. To date, the FIP approach has confronted challenges to systematize 1) configuring a TDS model, 2) "cross-charting" to link tech mining findings to potential applications [11], and 3) acquiring expert knowledge.

10 Steps (non-linear!) to Forecast Innovation Pathways (FIP)

STAGE ONE Understand the NEST and its TDS (Technology Delivery System)	**Step A**: Characterize the technology's nature
	Step B: Model the TDS
STAGE TWO Tech Mine	**Step C:** Profile R&D
	Step D: Profile innovation actors & activities
	Step E: Determine potential applications
	Step J: Engage experts
STAGE THREE Forecast likely innovation paths	**Step F:** Lay out alternative innovation pathways
	Step G: Explore innovation components
	Step H: Perform Technology Assessment
	Step J: Engage experts
STAGE FOUR Synthesize & report	**Step I:** Synthesize and Report

Fig. 1. The Forecasting Innovation Pathways (FIP)Process Framework

The FIP approach progresses through a set of four stages (Fig. 1):

1. Build understanding of the technology itself and of its TDS– i.e., the organizations involved in taking the technology to market, along with the forces and factors acting upon those innovation processes. Initial steps identify the various innovation factors that will be reflected in the vertical axis of the FIP representation. To generate these factors there is a need for an internal analysis defining technology fields, system performance, and relevant trends to monitor. This is based on a first internal round of analyses involving literature review and consultation with field experts (in this case, done internally at SKF) to define and document the main components. The guiding structure for the analysis is presented in Figure 3 (limiting there to show no more than two per topic).
2. "Tech Mine" search results in multiple databases (in this case, fundamental research publications, engineering-oriented publications, and patents; often we add business-oriented information resources too) to profile the meaningful activities. The tech mining is done via a series of searches covering the main subject (in the case of the current article: the hybrid vehicles and the electric vehicles). The searches were conducted both in the IP database and in the scientific literature databases. A semantic analysis (frequency and proximity) was carried out to determine (and confirm) the specific subtopics. We focus on identifying the key *actors* pursuing R&D, and commercialization thereof, and indications of potential *products* (applications & markets). The main tech mining results (e.g., number of documents per year, research and patent networks, specific focus areas, main player positioning) were available to the workshop participants.
3. FIP workshop with external parties representing different approaches and levels of the TDS. Informed by the preparation-phase documents (phases 1 and 2), the discussion is fashioned to highlight differences and common enablers for different product segments and regions. The role of the main stakeholders (academia, industry, local champions, government, market, regulations, etc.) is analyzed and compared for different developmental contexts (while keeping the same framework). The objective is to identify the critical links and success factors that conform to a specific innovation path.

4. Lay out potential innovation paths – by identifying various stakeholders & inviting them to participate in a workshop; summarizing the tech mining results to spotlight potential paths and issues for the participants; and conducting the workshop. Reflecting on the workshop results (that had been collected) to synthesize; pursue further analyses (e.g., technology assessment) and report.

To elaborate a bit on these stages/steps, TDS modeling entails: 1) laying out the key organizations engaged in "delivering" the intended fruits of technological advance to some marketplace, and 2) identifying the influential environmental forces that act to advance or hinder such innovation [46, 38]. Such analyses can lay bare the reasons for success or failure of a promising innovation [9]. Guo et al. [12] note many socio-technical systems modeling approaches, some tailored to particular arenas, such as energy. The present HEV case presents a far more developed TDS, entailing the need to balance wider system considerations (context) in addition to richer, micro-system aspects – i.e., how to specify & analyze sub-systems.

The stages are *iterative and non-linear*. Through these ten steps, FIP seeks to integrate empirical and expert knowledge on prior and current technological development to help uncover promising future developmental pathways.

Empirical steps D and E of tech mining (Porter and Cunningham, 2005; pertains to Stage 2 in Fig. 1) are key for FIP. Can we elicit useful, reproducible intelligence on the key *players* and potential *applications* of an NEST from data mining? We begin by tallying the most active players in the Science, Technology & Innovation("**ST&I**") datasets gathered on the technology under study. Aligning the prolific organizations to juxtapose their authored papers, patents, and mentions in business-related sources can prove informative. One finds striking differences across the spectrum of ST&I activities [c.f., 14]. "Cross-charting" is an approach introduced by Guo to relate stage-by-stage which advances are associated with which potential applications [11].

As our FIP approach evolves, the workshop remains the centerpiece of Stage 3. We prepare for these workshops by condensing the Stage 1 and 2 highlights to key on the identified actors, innovation components (advancing technical capabilities), and potential applications & markets. These are presented to the gathered parties at interest to stimulate exploration of potential paths to commercial (military, etc.) products or processes (Steps F and G). In principle, Technology Assessment (Step H) should also be initiated during the workshop.

Lastly, Stage 4 (equivalently, Step I), Synthesis and Reporting, follows. Considering the reporting, our driving motivation has been largely academic (i.e., developing the FIP approach and publishing on that). In a recent workshop on FIP with the National Research Council of Canada [30], we collectively considered varieties of reports that would vary depending on the client requesting the analyses.

In the next section we introduce our focal technology -- certain future road vehicles – namely HEVs. We selectively highlight prior efforts to produce technology roadmaps ("**TRMs**") for this industry. We describe the underlying technologies, then apply tech mining methods in conjunction with insights from automotive manufacturing and original equipment manufacturing ("**OEM**") professionals. We then describe our expert opinion methods; followed by a summary of results regarding HEV prospects. The last section highlights how this experience helps extend the FIP approach.The FIP process can be considered in terms of a first preparation phase (stage 1 and 2), followed by the FIP workshop (stage 3), and post-processing of the information from the workshop (including additional clarifications required during the development of the meeting (stage 4). For the current workshop, the pre- and post-processing phases took one month each (with a team of 9 persons working on them).

Future Road Vehicle Case

The car industry is facing a paradigm shift under the combined pressure of increasing fuel prices and increasing traffic demands globally. The drivers for that change include legislation (more demanding standards on particulate matters, CO_2, CO, HC, and NOx emissions) and economic pressures. The challenges for the automotive value chain relate to technology requirements & choices, market volume planning & pricing, and timing. Although the trends are global, there are significant regional differences in the technical requirements and business models. Electric Vehicles and Hybrid Electric Vehicles appear key for future mobility.

In this study we examine the future of these road vehicles. Our reasons for selecting this are theoretical, as well as practical. Road vehicles are among the most complex technologies that are widely and massively produced. Investigating a complex technology is a useful test case for the FIP approach. Road vehicles are also socially complex – production is coordinated across multiple locations worldwide. Manufacturers are responsive to multiple markets and regulatory factors, and must coordinate across complex supply chains. Secondly, the technology is highly consequential for the participating partners in the workshop. FIP results can be directly applied in strategy, foresight, and coordination exercises inside the companies. Furthermore, the technology is a driver of national economic competitiveness and the source of high paying manufacturing jobs. A previous industrial revolution was predicated on roads, gasoline, and the internal combustion engine. The next stage may well be predicated on the smart grid and hybrid or electrical vehicles. Understanding the technology also helps to understand the prospects for future sustainable growth. We next survey previous technology roadmaps for vehicles.

AnHEV combines a conventional internal combustion engine (ICE) propulsion system with an electric propulsion system (see Wikipedia references). HEVs may use mechanical energy recovery devices, which convert the vehicle's kinetic energy into electric energy to charge the battery. Some HEVs, known as range extenders, only use their internal combustion engine to generate electricity by spinning an electrical generator to either recharge their batteries or to directly power the electric drive motors. The definition of micro(or nano) hybrid applies to HEVs that shut off the ICE at idle and restart it when needed; this is known as a start-stop system. A plug-in hybrid electric vehicle("PHEV") is a vehicle with rechargeable batteries that can be restored to full charge by plugginginto an external electric powersource.

An electric car is propelled by one or more electric motors, using electrical energy stored in batteries or another energy storage device. More than 5.8 million HEVs have been sold worldwide as of the end of 2012, with the USA and Japan as the two biggest markets with 2.5 and 2 million HEVs respectively. Forecasting market penetration varies depending on the source. Fig. 2 shows International Energy Association estimates [16].

Phaal [29] provides a TRM of future road vehicles on behalf of the U.K. Department of Trade and Industry. The roadmap examines a range of component technologies for future vehicles, including engines and powertrains, sensors and telematics, structures and materials, and design and manufacturing processes. The roadmap takes special note of software and electronics as strong sources of value-adding for vehicle manufacturers. It also notes the role of hybrid, electric, and alternatively fuelled vehicles as a driver of future technology change. EARPA [7] also presents another automotive TRM that presents a very gradualist perspective on change, arguing for limited inroads for alternative fuels in the 2020 to 2030 time frame. The report discusses alternative powertrain technologies in detail

Over the next twenty years, the world population of on-road vehicles (including cars, trucks, and buses) is projected to more than double. Nearly a third of these new vehicles will be purchased in China; over halfwill be in the non-OECD world (Table 1). Analysts argue that this growth will primarily occur in the developing world, and particularly in the upwardly mobile nations of China and India [5]. Automotive adoption outstrips population growth there because of high income elasticity of transport in these medium income nations.

The vast expansion of vehicle adoption in medium income countries like India and China will also be accompanied by an expansion in their domestic automobile industries (Table 2). A large domestic consumer base appears highly advantageous for supporting an internationally competitive industry. As the automotive industry expands in Asia, producing another 80 million vehicles a year, there will be a corresponding boom in employment. This production may entail creating an additional 6.5 million new manufacturing jobs, and an additional 36 million employees in related manufacturing sectors. Future employment will certainly depend on the productivity of automotive workers, which has been dramatically increasing in most nations. Thus, this will eat into the potential future job growth based on otherwise extremely strong world consumer demand.

	2012	2015	2020	2025	2030	2040	2050
PHEV	0.05	0.7	4.7	12.0	24.6	54.8	49.1
EV	0.03	0.5	2.5	4.4	9.3	25.1	52.2

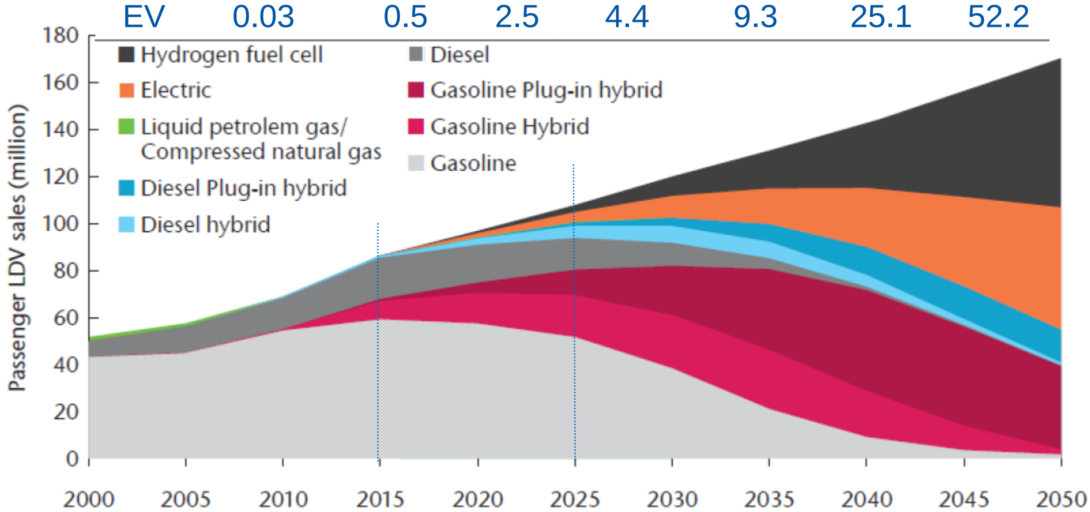

Fig. 2: Composite World Sales Forecast for Passenger Vehicles [Source IEA (2009)]

Table 1. World Vehicle Population

	2010	2030 (Est.)	Increase (Est.)
Brazil	65	84	19
China	77	390	313
Germany	47	58	11
India	21	156	135
Japan	75	87	12
South Korea	18	31	13
United States	247	314	67
other OECD	311	418	107
other non-OECD	465	542	77
Total	1015	2080	1065

Source: [5]; data from [40, 47]; units are in millions.

The automotive sector is currently valued at $2,519 billion (2012, USD) in turnover (OICA 2012). World GDP is estimated to be $71 trillion in 2012. Currently, the automotive sector constitutes some 3.5% of the world total. Should automotive turnover rise proportionally to the anticipated sales of new vehicles, the industry will top $5 trillion in 2030. The world economy is expected to top $128 trillion in 2030, thus automotives will increase in industrial importance. Table 3 compares the forecasted growth in the automotive sector with growth in various economies.

One billion new vehicles on the road will impact world oil consumption, ecology, and sustainability. Dargay et al. [5] note heightened environmental concern given that automotive expansion will increase most rapidly in developing economies, historically less able to manage environmental challenges.

Table 2. Millions of Automobiles Produced Yearly

	1990	2010	2030 (Est.)	Ave Yearly Growth (%)
Brazil	0.9	3.4	5.3	3.4
China	0.5	18.3	91.1	7.0
Germany	5.0	5.9	2.8	-3.1
India	0.4	3.5	27.4	9.6
Japan	13.5	9.6	0.4	-14.8
South Korea	1.3	4.3	1.8	-3.7
United States	9.8	7.8	14.8	9.0
All others	17.2	24.9	15.4	-2.9
Total	48.6	77.6	159.0	3.8

Source: Data from [27].

Table 3. Economic and Automobile Industry Growth

	Ave. Yearly Growth % (2012-2030)		Sector Relative Size in 2030 (2012=100)
	Auto	GDP	
Brazil	3.4	4.1	89
China	7.0	6.5	109
Germany	-3.1	1.3	45

India	9.6	6.7	162
Japan	-14.8	1.2	5
South Korea	-3.7	2.7	31
United States	9.0	2.3	313
All others	-2.9	3.3	33

Source: GDP Growth Estimates [26].

Tech Mining HEVs

To forecast innovation pathways, it is necessary to treat the complexity of the HEV system. That poses a need to properly define the different subsystems and technologies that contribute to it. As with any engineering system having a big social interaction, the analysis cannot be limited to the technology itself, but needs to incorporate and assess trends in mobility, infrastructure, energy (availability, management and cost), environmental, and economic concerns. Ourapproach began with gathering several experts and defining some of these factors in an interactive way with successive refinements of the hierarchical structure defining a hybrid electric vehicle. One of the peculiarities of this engineering system is that there are technologies relevant for both hybrid and for pure electric vehicles. The simplified configuration used in this case analysis is represented in Fig. 3.

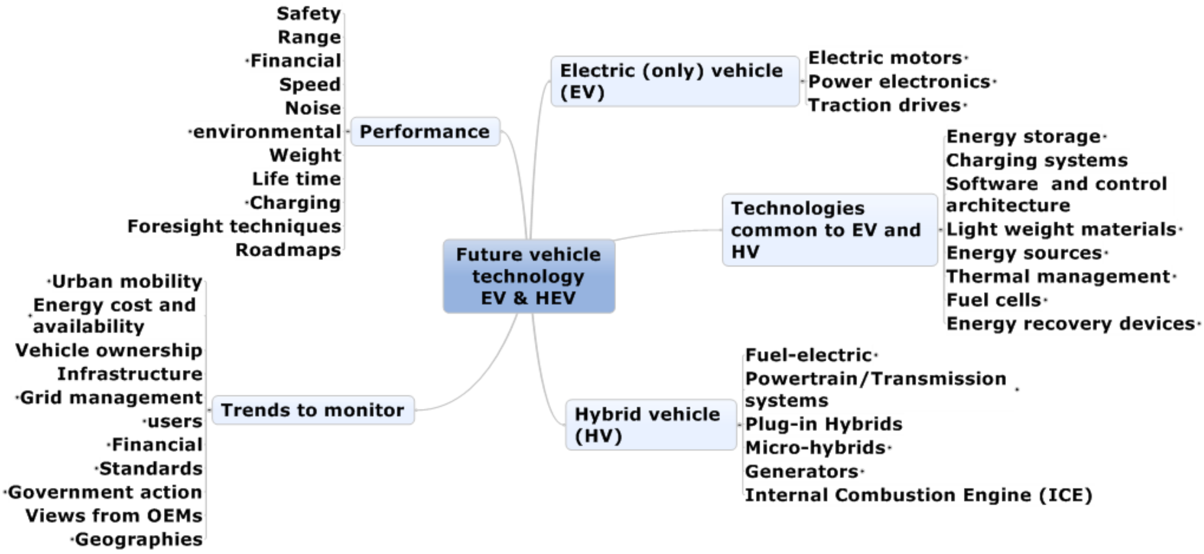

Fig. 3. Main Elements Considered for HEV Development

The nature of information available in Fig. 3 is two-foldand treated differently. The right hand side of the Figure represents the main engineering components and technologies of HEVs. The notion of HEV has been left "open" to allow the presence of different, and competing, technologies, like batteries and fuel cells. The left hand side of the Figure illustrates some of the performance criteria and trends needed to be taken into account in the FIP endeavor for hybrid electric vehicles.

The hierarchical structure used in the current exercise has two more branching levels that are not presented for the sake of clarity. We elaborate on some of the features considered in the left hand side of the Figure (the right hand side will be the object of a dedicated bibliographic analysis described later). Knowledgeable colleagues suggested a clear differentiation between the needs related to urban mobility and those for intercity (long range) mobility. This difference is not only related to the vehicles but also to the associated flexibility to update the highway infrastructure to the new vehicles and their energy needs [23, 24].The role of cities in the deployment of urban vehicles could be determinant as they are less dependent on international standards or regulation to set access limits to city centers and as the distances to be traveled are smaller and well within the current range of the vehicles already in the marketplace. The need to differentiate between private and public mobility relates to both the transportation means and their ownership modality [18].

The automotive market and its dynamics depend on the financial framework set around the vehicles and their components (e.g., batteries) [28]. The new concepts of battery leasing and swapping havebeen reviewed [25, 39]. The current trends of vehicle sharing and leasing are also important factors determining the amplitude and pace of deployment of HEVs. We need also consider new modalities of ownership [6]. An initial set of potential users (or market segments) can be identified. They include vehicles for individual and public transportation, trucks, and military vehicles. The needs, volume, timing, and technologies required for each segment are different enough to support individual FIP exploration.

Besides the classic actions of governments related to regulation, standards, and legislation, other potential fiscal actions (taxation and/or incentives) and infrastructure deployment are major influences on prospective innovation pathways. Governmental infrastructure actions could be direct or indirect depending if the state is also the owner/provider of the energy grid and highway infrastructure. A perceived need to differentiate the geographic location of HEV development vs. deployment led us to consider several micro-areas that have consistent sets of public/government demands as well as critical mass (actual or foreseen). Such factors seem particularly interesting when analyzing the TDS and the interactions between the main actors in HEV development and deployment.

Performance level aims affect the development of the HEV "system." These cover a vast range of engineering, financial, and environmental requirements to make this mobility option a preferred, or even dominant, one in the future. Would-be users are not ready to make concessions on safety [4] or comfort (noise and charging times), and they appear very reluctant to accept higher costs. The latter relates to price, total cost of ownership, and residual value of the vehicle over time. Even noting a significant body of literature about the environmental impact of vehicles, all HEV development approaches seem to be addressing economic performance (in terms of fuel efficiency and weight), as well as compliance with increasingly demanding pollution limits. Recyclability looks to be an attractive modality for both the recovery of precious elements (rare earths, precious metal catalysts, etc.) as well as enhancing the end-of-use functional part of the automotive value chain [19].Several relevant documents from original equipment manufacturers ("**OEMs**") [7, 10],international organizations [16, 42], roadmaps, and consultants [21] also aid in defining the main elements of the FIP effort for HEVs.

In order to address the right hand side of Fig. 3, we need to categorize and prioritize the complex system illustrated. This led us to organize the tech mining to identify the essential subsystems and related R&D thrusts. Only after this framing of the knowledge compilation would it be possible to proceed to a proper forecast of innovation pathways. Even though the purpose of the FIP is to include as many sources of information as useful (e.g., research literature, patents, corporate news, etc.), for the initial classification and grouping of this body of knowledge only patent information was used. Reasons for this restriction reside in utilizing the international systematic classification of patent information and time constraints. An additional restriction was imposed in the search limiting it to English language patents from the Derwent database in order to allow a more consistent semantic analysis of patents for the years 2000 through 2012.

Search strategies were developed, tested, and improved. We have carried out patent search in the Thomson Innovation platform with several high level queries for electric and hybrid vehicles. Initially we started with key word searches based on the hierarchical structure of Fig. 3. We also ran queries using International Patent Classification ("**IPC**"), ECLA, Japanese F-terms, and United States (US) classification codes. We ran separate searches and combined searches using the operator "or." We have tried to optimize the searches by using a combination of international codes, then refining with keywords and different Boolean operations. Fig. 4 shows a semantic map representing 191,915 patent applications where we can identify consistent major subsystems related to the FIP template.

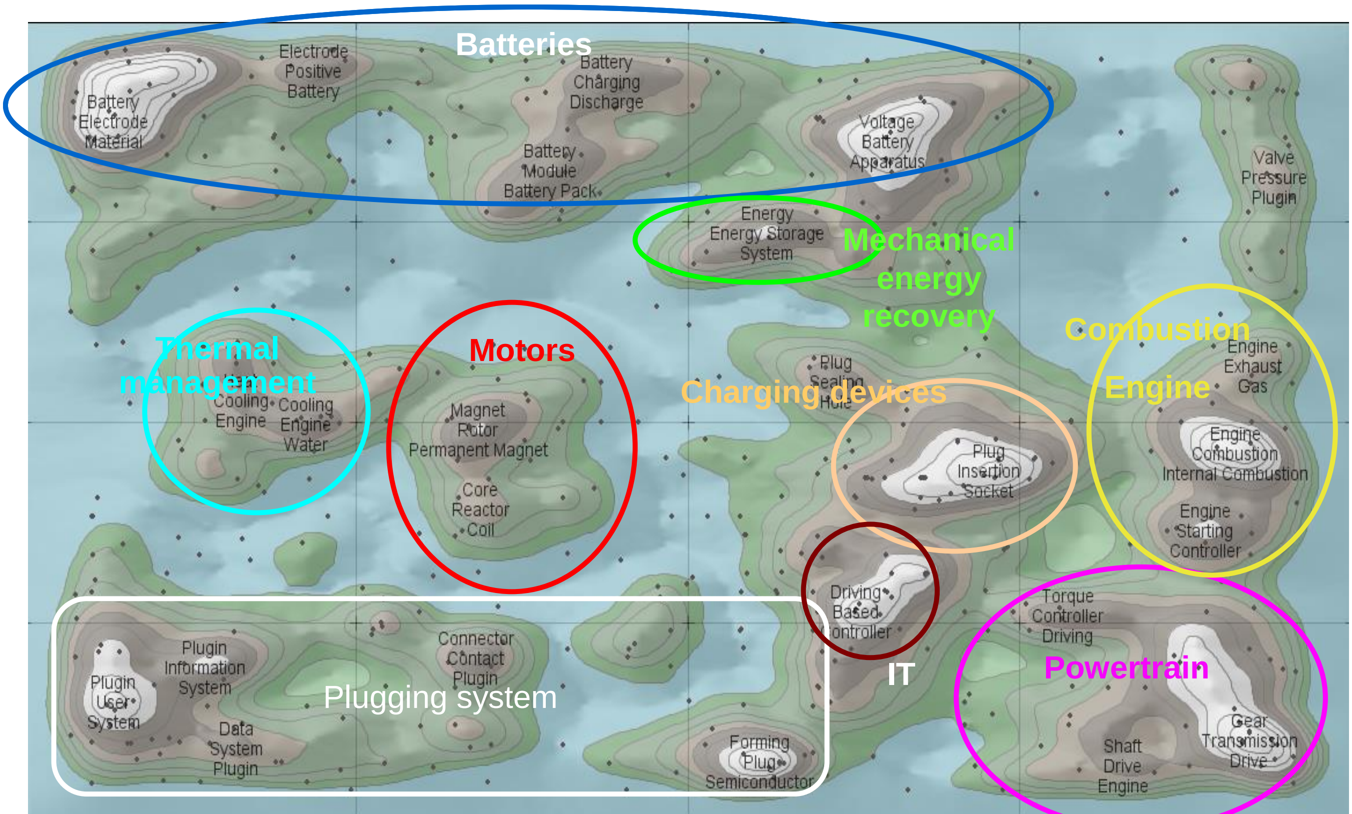

Fig. 4: Semantic Mapping of Search Results on Patents Related to HEVs

The patent analysis helps define major subsystems. From the initial Intellectual Property ("**IP**") search strategy, we moved to expand the information resources to scientific literature. We searched and retrieved electronic abstract records from three databases: EI Compendex, INSPEC, and Web of Science ("**WOS**"). The overall objective was to characterize the underlying R&D thrusts supporting the major HEV subsystems. Tech mining of the publication and patent data can also yield indicators of the maturity levels (or inversely, time to market) of constituent technology developments. Each major HEV subsystem, as well as the R&D thrusts, were covered by "landscape mapping" of the IP and scientific literature data.

This empirical work was particularly pointed to identify components important to HEV innovation (i.e., development of successful products and processes). The framework developed for the FIP effort for HEVs is presented in Fig. 5. Most elements included in the left hand side of Fig. 3 are reported in the upper innovation factors in Fig. 5, as they are closer to markets & customers, infrastructure providers, and lawmakers. This framework was used heavily during the workshop (described later) for further refinement of the HEV TDS and creative exploration of potential innovation pathways.

The number of patent applications and publications relating to HEVs is doubling every 4 years in the period considered. The fuel cell subsystem is the only one that shows a more moderated growth. Most of the R&D thrusts track the high growth trend. The recharging mechanisms have been placed in the area of infrastructure and standards as well as in the R&D thrusts -- the former as there are significant efforts to bring international standards to recharging plugs (e.g. SAE standard J1772 adopted by the US and Europe); the latter, due to a specific R&D surge to reduce charging times to a minimum compatible with high volume deployment of plug-in HEV vehicles (in many cases coupled with battery developments). University publication of scientific articles is dominated by Chinese universities in most areas, while the IP production sees the US, Japan, and Germany in leading positions for most of the key subsystems and R&D thrusts. Table 4 shows the leading universities contributing publications in each of the five key subsystems, based on journal and conference papers indexed by WOS, EI Compendex, and INSPEC. Note the prominence of Chinese research and the breadth of coverage, with many of these universities showing strongly in multiple HEV subsystems. This suggests a shared vision to some degree, rather than "silos" of unrelated research; this seems a positive factor in advancing HEV technology.

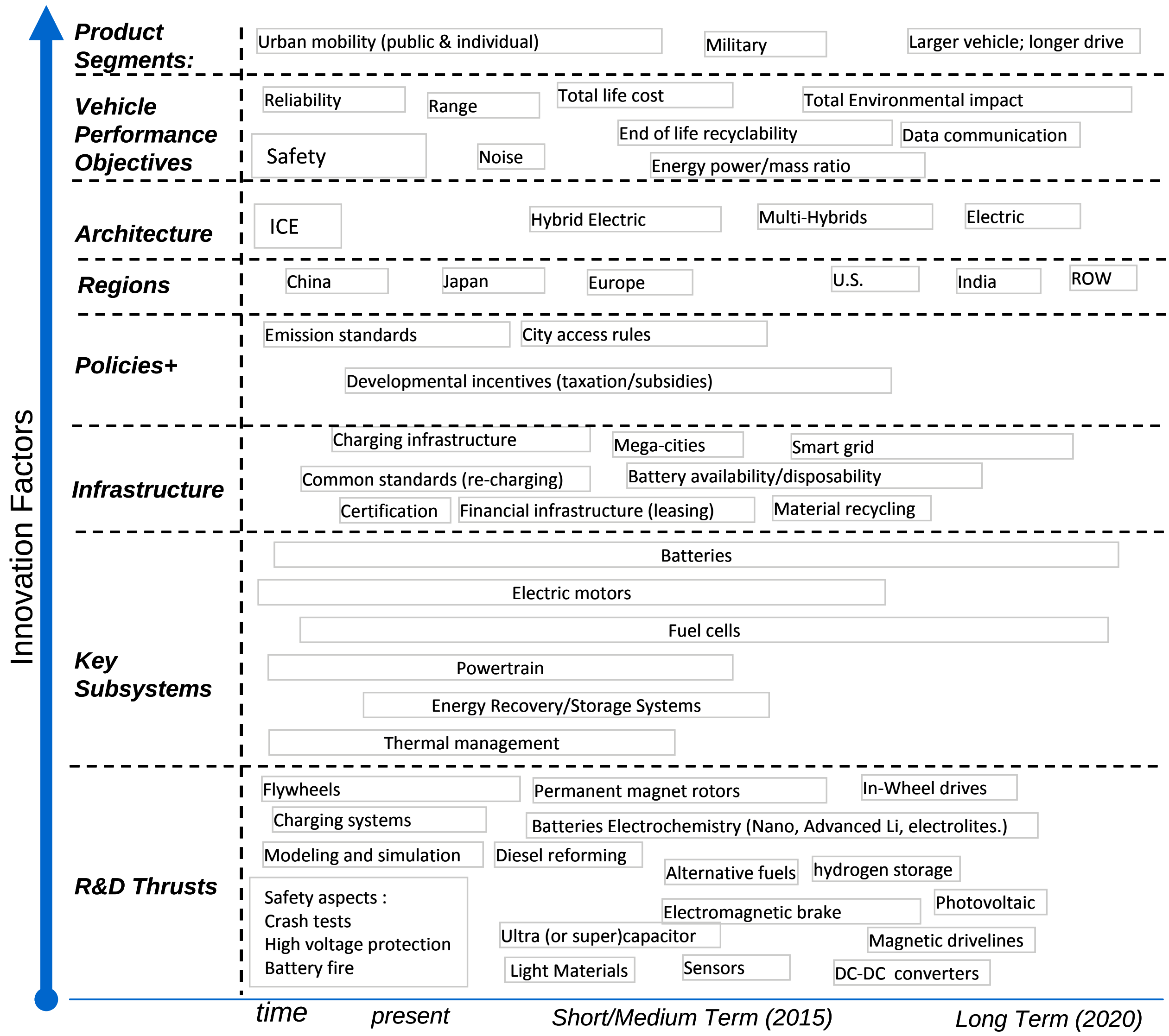

Fig. 5: Initial Forecasting Innovation Pathway Framework Proposed to the Workshop.

Table 4: Top Publishing Universities in 5 Key HEV Subsystems.

	Mechanical energy recovery	Batteries	Electric motors	Fuel cell	Powertrain
Tsinghua Univ (CN)	x	x	x	x	x
Univ Michigan (US)	x	x	x	x	x
Harbin Inst. of Technol (CN)	x	x	x		x
Shanghai Jiaotong Univ (CN)	x	x	x		x
Beijing Inst. of Technol. (CN)	x	x	x		x
Ohio State University (US)	x	x	x		x
Sungkyunkwan Univ (KR) (Samsung)	x		x		x
Jilin Univ (CN)	x	x			x
Tongji Univ. (CN)	x			x	x
Chongqing Univ. (CN)	x		x		x
Xi'an Jiaotong Univ. (CN)	x	x			
Texas A&M Univ (US)			x		x
Hanyang Univ (CN)		x	x		
Univ Tokyo (JP)		x	x		
Jiangsu Univ. (CN)			x		x

The Innovation Pathways Workshop

Innovation is a complex matter involving several distinct, but interconnected, tiers. The problem in visualizing this complexity is that it involves different actors (technology, business, legislators, infrastructure, customers) over a lengthy time period. FIP is neither a simple transfer function from NEST R&D to commercial products -- nor a product/platform roadmap -- although it needs elements from both. FIP covers broad areas of scenario analysis, macro trends, and tech mining techniques. For corporate and government decision makers there is a need to visualize several of these elements in order to identify critical paths (and links) to maximize efficiency and avoid waste of resources. As indicated by Browning and Sanders [48], you first need to visualize and understand the innovation process complexity before optimizing it.In integrated systems innovations that are characterized by novelty and complexity at multiple levels, understanding the overall process is critical. The FIP moves beyond the technology stakeholders to address the directions in which society and markets are evolving. In that sense it endorses the work of Uchihira [49] in that neither a top-down nor a bottom-up roadmap will be enough to properly derive a full view of the technology-product-market-framework developments. There is a need to work the "middle-up-down relationships." FIP provides an integrative view of the innovation drivers, indicators, and links.

The purpose of this FIP workshop is to build upon the tech mining (empirical) results by using them to fueldiscussion about their implications for the future of HEVs. The design and development of electric and hybrid vehicles occurs at the intersection of the strategic choices made across multiple international organizations, both public and private. It is therefore critical to the process to incorporate multiple perspectives, to capture the expectations and preferences of critical actors. In this section we describe the design of the workshop and its participants. In addition to our FIP team (composed of 9 SKF employees from India, China, and the Netherlands), attendees came from three companies and four universities.

Workshop participants included SKF (*SvenskaKullagerfabriken,* literally "Swedish Ballbearing Factory"). SKF is an automotive and industrial supplier originally founded in 1907. The company produces bearings and bearings units, lubrications, seals and mechatronics. It also has an extensive service wing. In 1926 SKF founded Volvo AB; the company was spun off in 1935 to become the independent company known today. Attending from SKF were a technology director and technology intelligence staff. Also attending was Tata Motors Limited, a multinational company founded in 1945. The company acquired the premium car maker, Jaguar Land Rover, in 2008. Tata Motors has auto manufacturing and assembly plants in India, but also South Africa, Thailand, the United Kingdom, and Africa. Attending were divisional and assistant general managers of Tata Motors Research Centre.Inergy was founded in 2000 as a joint venture of Solvay Automotive and Plastic Omnium, two key players in the fuel system business. The company is the worldwide leader in automotive plastic fuel systems. In 2010 Plastic Omnium took full ownership of Inergy. The company has manufacturing plants world-wide including South America (Argentina, Brazil), North America (US), Europe (Belgium, France, Germany, Poland, Romania), and Asia (China, India, Japan, South Korea). A development manager for India attended.

Academic participants included professors from Delft University of Technology; Georgia Institute of Technology; Indian Institute of Management, Bangalore; and the Indian Institute of Science, Bangalore. The professors represented a range of disciplines and degree programs, including systems engineering, management& management of technology, and engineering & public policy.

The workshop was preceded by the analytical activities of FIP Stages One and Two (Fig. 1). Introductions set the stage for further discussion. The OEM representatives each presented on HEV forecasts. Those were followed by a brief introduction to the FIP methodology and workshop agenda. Tech mining results were highlighted, identifying a set of technology components, which are layered in vehicle architecture, as well as an extended TDS incorporating key actors and societal forces. The structure and processes followed during the workshop are described in in Figure 6

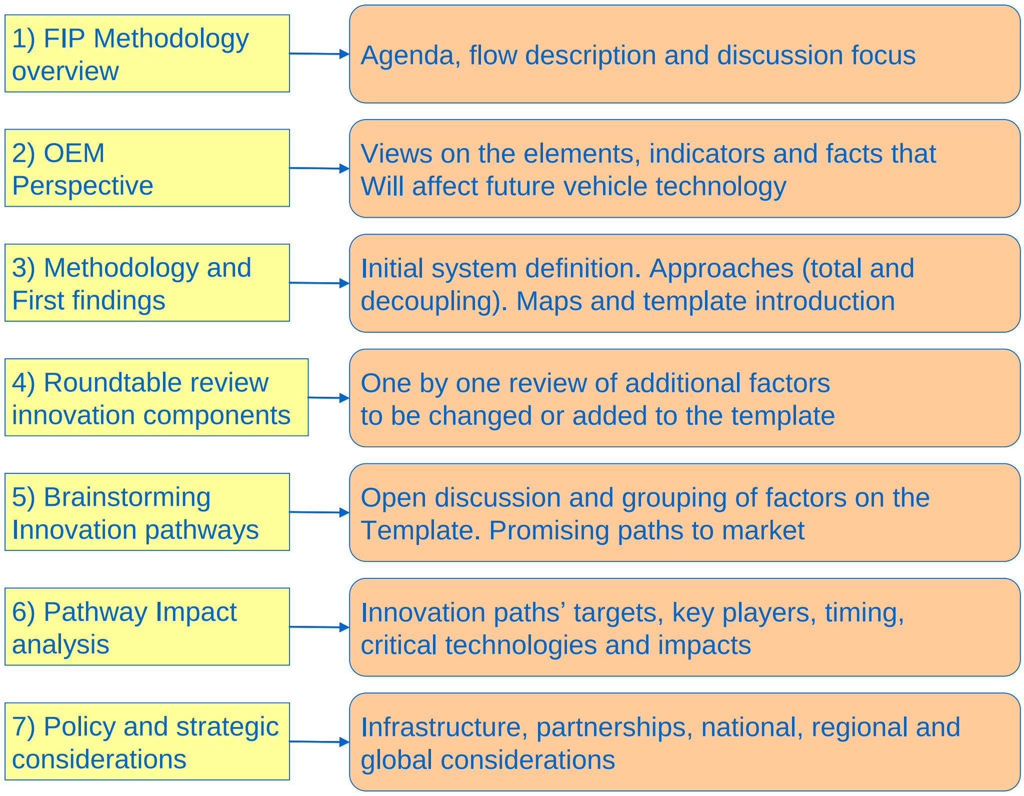

Figure 6. Sequence of Workshop Activities

The participants were given the opportunity to extend or revise the initial FIP diagram (Fig. 5). Six teams were formed, grouping industry, academic, and tech intelligence analysts in each team, as feasible. Each group then "brainstormed" to devise pathways through the diagram. These pathways represent alternative product segments, technology architectures, and implementation pathways. The reflection process involved a simple group consensus and voting procedure, which identified elements critical to multiple pathways. The group as a whole then discussed policy and strategic management issues. The resulting diagrams were mined for public and private sector impacts. The one-day workshop then concluded. The next section details workshop results.

Results of the Workshop

To generate more specific analyses, each group was asked to focus on either one of*threekey market segments* identified, or on one of *three macro geographic areas* (EU-US, China-Japan, or India). Each group focused on the relationships among the different elements in the FIP, as well as on the sequential interactions of the main actors in the TDS in implementing particular innovation pathways (transitioning from Fig. 5 to Fig. 7). Findings and propositions were then jointly discussed during the next workshop segment. Findings are summarized below for each of the three target segments and for the three target regions.

1) Urban mobility: The use of electric or hybrid cars in urban areas seems to be a trend affected by available parking places, smog & noise contamination, and the continuous growth of the global urban population. The main elements of an urban HEV FIP include:

- The trend seems to be geography independent. City governments are critical and highly influential
- Wide variety of criteria to be satisfied and potential technologies to fulfill diverse needs.
- As urban areas become bigger, vehicle range becomes an issue.
- Speed is not a critical variable; urban speed is already low and will probably evolve into lower levels
- Infrastructure (either refueling stations or electric charging/smart grid) are critical

The TDS developed during the workshop includes the following observations:

1. Technology and engineering development evolve (and co-evolve/compete) to produce vehicles with sufficient performance specifically targeted for urban areas. Ownership models could evolve or change (e.g., city, not citizens, owning urban-only HEV vehicles).
2. Alignment takes place between government (mostly local but can also be regional, national and, more rarely, international) to implement restrictions on either emissions or city access.

3. Infrastructure should be developed according to the guidelines derived from points (1) and (2), engaging energy providers.
4. Vehicles are commercially launched.

2) Military vehicles: While not prominent in the general public view, there is significant development in the field of military HEVs to ease demands on the logistic chains confronting armies, especially in geographical areas of difficult access. Many OEMs are also pursuing government funds to develop and integrate key subsystems, and those can be replicated for other market segments. Some military considerations for HEV development:

- Focus on faster rate of discharge on the storage energy favors super-capacitors and flywheels (batteries are considered to not be fast enough). This reflects aneed to have a vehicle idle (main engine off) with all sensors activated, to then react rapidly to a hostile event, drawing only on the stored energy.
- Integration with other operational sensors (sights, firing mechanisms) is important. Specific and more demanding standards apply than for routine non-military contexts.
- Efficiency -- in mountain areas, the fuel logistics may bring the effective price of a gallon of fuel to be in the range of$250-400/gallon.
- No road infrastructure assured
- Preference for range extenders and energy recovery devices.
- Anticipated government support for development and acquisition is essential. Possibility of cascading down resulting military technological developments to civilian applications is high.
- Military as lead user can be considered a global factor.

The TDS developed during the workshop includes:

1. Users (the military) can support both R&D activities and vehicle supply procurement
2. Most development cost activity is supported by national funding, but vehicle manufacturers drive development. They do this directly or indirectly via the tier suppliers (mostly for specific subsystems).
3. No specific infrastructure needed, easing deployment and logistics.

3) Larger long range vehicles (trucks): This case needed some additional distinctions. Trucks for urban and suburban areas vs. long distance ones: the former are normally smaller and shorter range vehicles, most of the elements of the urban mobility apply. Several main FIP elements derived for larger, long-range truck-specific innovation paths are summarized here:

- Although fuel cell vehicles are creditedwith longer range than battery electric vehicles, that option seems excluded when it comes to trucks for national transport due to the difficulties related to the upgrading of the highway infrastructure associated with their fuel. The regular electric grid seems more suitable.
- Solutions based on advanced ICEs and hybrids seem to be dominant for the near future.
- Geography limited to large countries with consolidated central governments (e.g., US, India, China); Europe does not seem to qualify well in this category.
- Highway infrastructure and charging units are considered to be critical. Time frame is therefore longer than for the previous two cases.
- Data communication seems relevant for optimization of long-range vehicle fleet utilization.
- For medium size trucks (or even large Sport Utility Vehicles -- SUVs) not needing long range, propulsion options are similar to those in urban areas. Fuel cells may be preferred for their longer range and faster recharging for both individually owned or public transport vehicles.

TDS factors of note, posed to be favorable to development of an innovation path:

1. Government (e.g., national) sets long term and planned targets for emission controls.
2. Legislation is communicated to energy providers (electricity and grid), as well as to vehicle manufacturers. End-users are made aware of the new emissions so that they plan fleet renewal.
3. Parallel developments on grid optimization and vehicle design
4. Interactions between vehicle manufacturers and infrastructure providers lead to definition of highway infrastructure and product planning and scheduling.

Three of our workshop groups focused on specific macro geographic areas to see the differences in both the FIP and TDS for HEV progression. The findings reveal important differences in sequencing, infrastructure priorities, access to resources, and pace of development.

4) Europe and the United States: This geographic area of highly industrialized countries contains most of the major current HEV players. These Western powers show some strengths and weaknesses associated with the lack of a clear technology winner and delay in deploying national infrastructures. The FIP main elements can be summarized as follows:

- Very complex set of both needs and markets/government regulations.

- Vehicle complexity tends to be higher (as well as development costs) leading to high prices
- No clear infrastructure prioritization due to competing technologies and their associated lobbying.
- Pure electric vehicles seemlimited to urban mobility; hybrid vehicles look to be the volume winners.
- Taxation, rather than incentives, seems to be the main financial mechanism for national governments to shift to new mobility options.
- City government could be critical in local deployments.
- Safety, comfort, and cost are of paramount importance for end-users.
- Complexity leads to delays in implementation
- Mega-cities not growing so prominently as in some other regions

Prime TDS events and interactions are:

1. At least two main competing approaches (well-to-wheel for fuel cells vs. electric vehicles); R&D activities and lobbying reflect these conflicting interests.
2. Central point of intersection of the lobbying actions is the government -- to modify, in a controlled way, the emission standards or access rights. This recognizes trends toward less polluting vehicles, butconfounds technology selection.
3. Standards are best communicated as a planned deployment that will be gradually imposed on end-users.
4. Two main competing solutions (fuel cells vs. batteries) support specific R&D. Vehicle manufacturers hedge their technology bets by a portfolio of propulsion options.
5. Highway infrastructure remains in the hands of the current incumbents (well/hydrogen) companies. Distribution infrastructure is in the hands of the production/distribution companies.
6. Many options being generated with no clear winner leads to lack of major investments in infrastructure, mainly limiting HEV deployment to local (city) levels.

5) China (group invited to consider Japan too, but focused mainly on China)**:** Major and new road vehicle players operate in this geographic area with the highest market expansion. Even if the FIP is generally similar to the Western model, the TDS interactions seems radically different, leading to different deployment rates. Main elements of the FIP are:

- Similar to Europe-US, but without having end-of-life recyclability as an important demand.
- Several megacities emerging
- People used to driving at lower speed, requiring less power to weight ratios, conducive to HEVs
- Government having the financial capacity to subsidize development and market introduction.
- Main foci on urban mobility and military vehicles.

TDS development appears driven heavily by the State:

1. Government apt to either fix new standards or plan mandatory levels of hybrid electric vehicles.
2. Research (public and private) aligns with the indications of government.
3. Our FIP exercise reflects no big involvement in the well-to-wheel approach (for hydrocarbon fuels).
4. Research, vehicle development, and infrastructure deployment highly coordinated.
5. Vehicles develop with a high degree of commonality based on a selected technology platform.

6) India: The Indian case is particular, with several well-developed and competitive car OEMs, an infrastructure needing urgent and massive updating, and a growing/young potential market. Some solutions and influential roles are unique for the Indian subcontinent as reflected in the following FIP and TDS highlights:

- No clear choice regarding the energy sources and the means to store energy (batteries vs. fuel cells vs. mechanical storage)
- Electric and fuel infrastructure not ready for volume adoption of alternative fuel vehicles.
- Main direction seem to be toward hybrid vehicles (whatever the configuration). Pure electric is not considered a viable option due to the lack of reliability of the current electric grid.
- Special interest for urban public transportation as a driver for vehicles (and technology). Cities will be the starting point of any national deployment with potential (slow) migration to suburban/rural areas.
- The need for some “infrastructure-free” recharging stations opens a distant window of opportunity to photovoltaic charging.

The logic for the TDS and further deployment:

1. Actions started by strong national champions
2. Agreement with the Government that influences the development of the energy supply network (from generation to final distribution)
3. Vehicle OEMs optimize time to market by use of tiered supply network for lean product development.
4. Vehicles and infrastructure are gradual but coordinated.

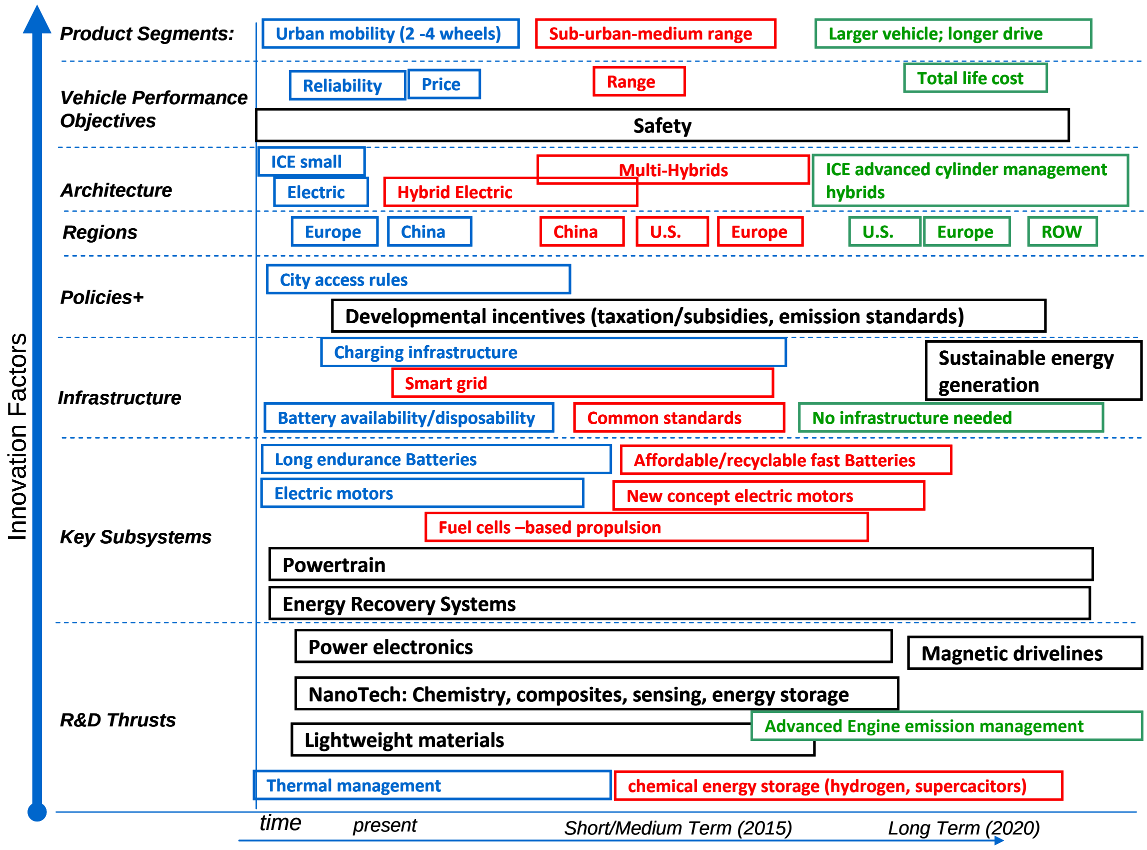

Figure 7. Final Workshop FIP analysis.
Legend: Black bold -- valid for all segments and solutions; Blue -- urban mobility pathway; Red -- medium range vehicles; Green -- long range/heavy vehicles (trucks).

Perhaps the most relevant evidence of the implications of the FIP applications and derived learning is shown in Fig.7. While maintaining the horizontal rows unchanged, the elements within have changed and start to be grouped to point toward innovation paths, even for such a complex system as HEVs. The figure suggests several levels of analysis with implications for technology management.

The most relevant outcome of the workshop and its aftermath processing is the development of a new segmentation proposal for the market that differs from the currently accepted one. This shows the potential of FIP and also confirms the opening statement that the automotive industry is facing a paradigm shift. The segmentation is based on distances and has main elements of the technologies available for the vehicles and the required efforts to create long-distance infrastructures. This segmentation is consistent with, but extends, the work by McKinsey [50].

The second relevant conclusion (indicated in black in the above mentioned Figure) is that some elements of the FIP are common to all the segments and/or geographies. They include the role of government and legislation, safety, and the need to diversify energy sources.In the more specific technology arena, it is interesting to see that the FIP process was able to discriminate between general technology enablers (energy recovery devices, power electronics, weight reduction, drive trains) and others that are not general for all configurations (e.g., batteries).

The following 3 levels derived from the Figure show three innovation path with a good level of consistency. In the dynamics of the discussions, it also emerged that not all of them are independent from each other.

The FIP endeavor suggests three potential innovation paths. A long distance, big vehicle innovation path seems to go through an infrastructure-independent hybrid vehicle with advanced ICE variable geometry. The other two paths seems more sequential than alternative. The overall consideration is that cities will have an initial vital role in the deployment of new energy vehicles.Central city constrictions limit infrastructure options. The blue path of Fig. 7 should develop first. In other words, the red path assumes that most of the elements in the blue path are previously achieved on a local level.

Conclusions Regarding HEV Developmental Prospects

The six technology delivery systems were somewhat different. The common point of all TDS was the important role played by the government in a general framework under which the different HEV technologies and engineered systems can be developed. All the cases (either by product segment or by national geographies) tend to show a rather passive behavior of the end users (except for the military). The passive role of the consumers is not uncommon when a radically different service or good is launched. This could also lead to new segmentation and ownership concepts. The final alignment between different players will ultimately determine the success and timing for the introduction of HEVs and EVs.

As part of the group discussion, a new product segment was identified as having sufficient differentiators to be considered in isolation from the others -- electric two wheelers (motorcycles). This segment presents the following characteristics:

- No need for smart grid or big electric generation increases, even being an electric-only sector
- Range and cost are critical, more than speed and reliability
- Main areas of deployment are in Asia with the US and Europe as potential followers
- The in-wheel drives lead to cheaper and lighter vehicles and provide design freedom for new concepts.

For the case of future HEV vehicles, the FIP exercise has generated the following insights:

- All OEMs hedge their technology bets. There is no clear winner as of today.
- Two main technology development philosophies emerge: a) internalization of main components (e.g. some Japanese, German, and US car-makers developing e-motors) or b) development via alliances (e.g. Indian car OEMs working with German partners on fuel cells and e-motors).
- Expect newly emerging players and unorthodox alliances in the complex HEV system. Most of the patents found related to e-motors for vehicles did not involve the world leaders in industrial electric motors. The field of batteries also sees new entries from the world of computing.
- Thermal management of storage devices seems to be a critical issue for both efficiency and safety.
- Pure electric cars in the near future seem apt to be a niche market (4-6%), mostly for urban mobility (individual cars, motorcycles, and light trucks), but possibly expanding to much larger percentages in the long term. Discrepancies between the participants and the literature sources & tech mining mainly pertain to the timing to reach that status and if there will be a dominant HEV technology.
- Hybrid (not pure electric) vehicles seem to be the clear choice for near future volume production.
- Customers seem not to be requesting HEV vehicles. End-users will likely buy according to the following criteria: safety, cost, comfort, performance, and taxes/access.
- Vehicle architecture is shifting towards higher electrification (independently of the energy source). This will affect development of the software and control logics embedded in the vehicles and the platform engineering.
- The long distance road infrastructure tends to favor electric grid over hydrogen storage options.
- Lack of standards is limiting HEV market potential.
- Speed will be less of a requirement in urban and suburban mobility. Range and the reliability of that range will likely increase in importance.
- Vehicle cost is a key performance dimension to be monitored. Batteries could account for a third of the vehicle cost and are therefore critical.
- Strong central government seems in position to indicate development guidelines and lead to faster deployment of new energy-conserving vehicles.
- Developments in HEVs will depend on both technology developments and proper economic & political framing. Range, life, and cost are critical. The latter is related to competitive fuel price for realistic cost comparisons.

These results also suggest the importance of legislative and regulatory policy drivers of automotive innovation. Prolonged higher fuel prices, stimulated in part by expanded automotive usage, will make it politically more feasible for nations to require higher fleet economy standards. The U.S. Energy Information Administration projects fuel prices of greater than $150 per barrel as a nominal scenario for 2030 [8]. A diminishment of the European automotive sector may also make it more feasible for Europe to continue leading in environmental regulation. On the other hand, with China being the leading consumer of future road vehicles, Chinese national policies will have the greatest potential impact on the world fleet of automobiles. China recently rolled out a plan to produce two million electric and hybrid vehicles, combined, by 2020 [3].

In summary, future road vehicles offer a significant case for investigation. The coming twenty years will see more than a doubling of vehicles on the road. Many of these new vehicles may be produced and utilized in China and India. These vehicles will create significant new economic and employment opportunities, but will also heavily strain the existing conventional fuel market and create significant new transport emissions. Electrical and hybrid vehicles appear to be an increasingly important part of this future.

The Indian focus of the analysis was especially valuable. Literature scanning and industrial knowledge identified the significant role India may play in the development of future road vehicles. Workshop participants included two Chinese nationals as well as two US nationals. Despite this, further depth and breadth of participation from these nations would have been welcomed. China is in the ascendancy in automotive manufacturing, while Japan may be seeking to further specialize or differentiate itself. The United States and Europe face very different futures. The US may benefit from a high-tech vehicle manufacturing base, with rich energy reserves. Europe may find it ever more feasible to demand higher performing, greater sustainability vehicles – particularly when such vehicles are being manufactured elsewhere.

Investing in electrical/hybrid vehicles is a critical decision for industrial participants, and the future success of the technologies are far from certain. Hybrid vehicles represent a significant transitional step toward full electrics. Further choices involve determining to what extent hybrid vehicles represent a robust strategy that will deliver a payoff regardless of what the economic, technological, or legislative environment may bring. There are other transverse technologies that underpin future road vehicles of any stripe. This workshop identified energy recovery and storage systems as particularly robust future investments for OEMs.

The FIP Process: Assessment, Enhancement, and Needs

The FIP approach aims to explore and assess potential paths to commercialization of complex engineering systems. This exercise expanded the FIP *template* of innovation tiers by time (Figures 5& 7); this worked well in facilitating discussion (workshop), pointing toward identification of dependencies and emergent behaviors. It offers a good model in terms of level of detail and general issues for future FIP analyses, with suitable tailoring to the topic.

As we began to work with SKF on the FIP process, at least four analytical process issues surfaced. One was *scoping*. Emerging technologies enter onto stages that vary enormously in terms of scale and status. Setting a doable, useful scope for an FIP exercise entails more than constructing a crisp database search strategy. Exploring relationships of an emerging technology with encompassing systems involving technology and/or contextual factors is vital. The HEV case shows how multifaceted “FIP” can be – i.e., determining how to array developmental options regarding global location of production and of use; diverse targets (urban, military, long distance); vital non-technological factors (e.g., ownership options of vehicles and batteries); modes (4- vs. 2-wheel); infrastructure forecasting (roads, power sources, etc.); and so forth.

Another issue concerns technological and/or organizational*subsystems*. The target emerging technology may well have vital subsystems developing somewhat separately. It may be critical to forecast developments in each subsystem, to forecast plausible, promising combinations that could effect viable new products or processes. Tracking subsystem development trends, barriers, and incentives – plus interdependencies – appears important to FIP. We see adding a new, early stage to the 4-stage FIP process (Fig. 1) after Stage 1 to address “Scoping” – to distinguish larger (encompassing systems of interest) and smaller, vital subsystems to analyze.

A third issue is understanding the NEST and its associated Technology Delivery System (TDS). Until now, we have not formulated a *systematic approach* to accomplish these base tasks. Access to 1) commercial technology reviews and market research reports, 2) scholarly review and forecasting/foresight articles, and 3) Technology RoadMaps (TRMs)can contribute to a more informed, and hence more valid, FIP. We recommend adding these to Stage 1 as checklist items.

A fourth issue lies in identifying potential *applications*. Tech mining provides a wealth of data, but no easy ways to identify, no less assess, plausible links from R&D activity, through capability enhancement, to products, processes, and services with market potential. Cross-charting, mentioned, seeks to chain items together, but to this point it is a highly subjective process. We are exploring text analytics to help identify actions and their implications, particularly with respect to possible applications [1, 20, 22, 41, 43].

The FIP *workshop design* entails selecting the correct a) number and b) mix of participants, and provision of the correct amount of c) time to these participants to attain useful insights. The workshop design was successful on two of these three criteria. A moderate number of strategically well-qualified participants permitted a frank and open discussion of the relevant issues. An expanded mix of participants would have lengthened the workshop, and might have compromised the capacity for high-level attendees to join. Nonetheless, we desired to incorporate a broader span of views. Very valuable additions to the workshop might have included legislators, consumers, advocacy groups (e.g., environmental), and regional market experts. Workshop process options surfaced here too, including small group breakouts, voting mechanisms, and consensus building tools.

Further consideration of the design of systematic processes and outputs for FIP is needed. The FIP approach is young and evolving. Our efforts to synthesize tech mining findings to inform the workshop are relatively ad hoc. In particular, we see value in devising templates to help compile information for easy processing by a range of individuals in a very short time. This relates to determining what form FIP outputs should take. As noted, most of our prior work has not had a “real” user requesting the analysis, so this case analysis for SKF breaks new ground. More work is needed to assess the best form and content of information to provide to the workshop participants..

We have not worked through Stage 4 of the FIP framework seriously. We believe technology assessment is important, but was not addressed effectively in any of the FIP studies to date. We need to test the efficacy of inclusion of such impact assessment within the FIP workshop vs. afterwards (by analysts and/or on a participatory basis).

FIP explorations with the National Research Council of Canada in 2012 indicate that summarization, visualization, and direct communication of FIP findings need to be considered with care. Robinson's visual renditions of our several innovation pathways have been found captivating and strategic [35,Fig. 3; 32,Fig. 9]. Likelihood estimates and strategic management decision options are important communication dimensions yet to be developed.

In this case exercise the FIP process provided valuable insights. Previous roadmapping work identified critical technology components. The FIP process enriched this identification process with technology indicators and metrics. It integrated those technological elements with contextual factors and forces (TDS modeling). Our sense is that the HEV analysis provided an extremely rich set of factors to consider in gauging potential future HEV development pathways. We still need to integrate consideration of those factors to lay out specific innovation pathways and critical factors.

This FIP experience also yielded an appreciation of decision-making in uncertain and multivalent environments. The management of complex technologies (including road vehicles) will be a critical organizational competency of the twenty-first century. MOT approaches, including the FIP process, will need to support building and enhancing competence at strategic decision-making.

In the case of alternative energy vehicles, there will be a clear diversification of the sources of energy that will influence mobility in the future. The changes will go beyond the technology sphere. It seems to fair to say, based on the FIP process, that the vehicle future has already begun.

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