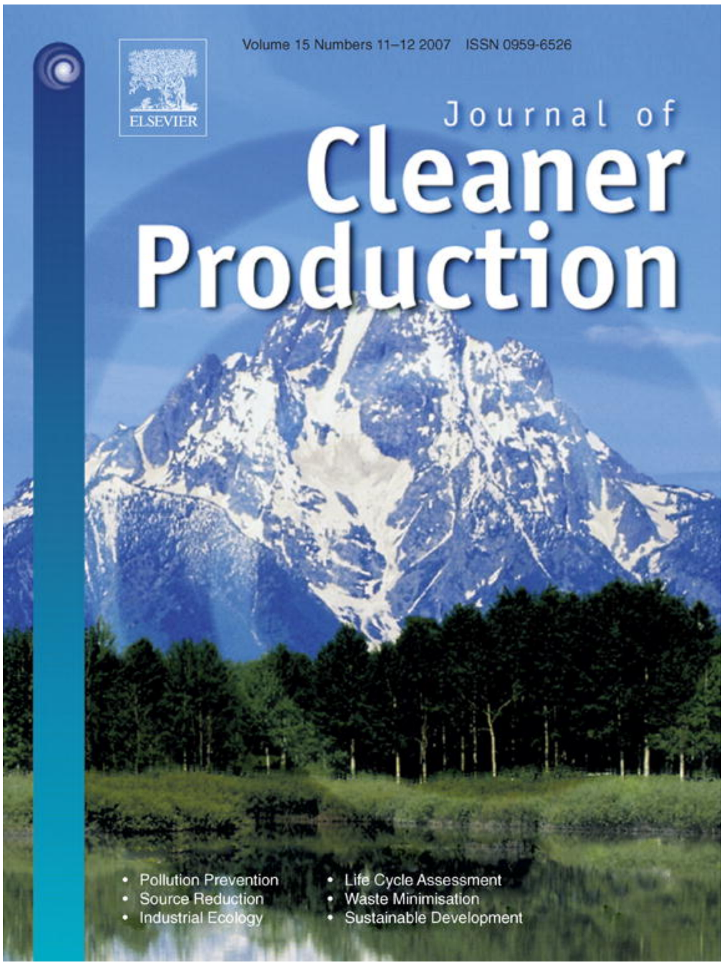
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Sustainable mobility: from technological innovation to societal learning

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Abstract

This paper addresses a persistent and worsening societal dilemma worldwide: the ecological unsustainability of the automobile as the primary means for providing personal mobility. The solution to this problem will require input from all segments of society, and must include technological innovation, changes in the physical infrastructure and land use, and social, cultural, and institutional changes. A fundamental rethinking of the entire system of personal mobility is necessary. Governments can play a significant role in promoting change: by stimulating technological innovation through regulations, incentives and subsidies, by investing in the infrastructure, by providing leadership, and by organizing and supporting a debate with a focus on the system as a whole: its spatial characteristics, the motives for transport, and the alternatives that are presently not developed. From the technological perspective, one of the much-discussed solutions is a hydrogen-powered automobile. We argue that the future of this approach is questionable, and propose a fundamental re-framing of the significance of hydrogen: from viewing it as a solution to the personal mobility problem to seeing it as a medium for transporting and storing energy that has been generated elsewhere (preferably by renewable resources). A new and radically different way of seeing the problem of individual mobility, and of the roles of various stakeholders in finding solutions, is also necessary. This is the essence of higher order learning. To facilitate such learning among various societal groups, we advocate a combination of multi-stakeholder visioning processes, scenario building, backcasting exercises, and small-scale socio-technical experiments. These approaches may be practiced at various levels, from local to national, with experimentation probably being best suited for a smaller scale. An ongoing process of visioning future mobility in the Boston Metropolitan area illustrates how such approaches may be used.

Keywords: Higher order learning; Social learning; Sustainable transportation; Technological innovation; Hydrogen fuel cells; Visioning; Backcasting; Boston scenarios

1. Introduction

This paper addresses a persistent problem of our society: the ecological unsustainability of the automobile. The car is the dominant form of maintaining personal mobility. Its benefits are powerful: it is a door-to-door transportation system, the means to gaining access to life necessities and employment, and a source of pleasure and social status. So are its disadvantages, including local air pollution, greenhouse gas emissions, road congestion, noise, mortality and morbidity from accidents, and loss of open space to roads, parking lots and urban sprawl. Many people are aware of the disadvantages but see no comparable substitutes to the automobile. The dilemma of an automobile owner is similar to that of a herd owner described in the classic case of a 'tragedy of the commons'[1] [1].

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[1] The metaphor is a community sharing a pasture. For an individual it is advantageous to increase his cattle stock. For the collective this means eventually overgrazing the field.

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The anticipated worsening of the negative effects of car dependency keeps this issue on the public agenda. In the USA, the discussion of urban sprawl is intense [2]. Local air pollution has prompted the State of California to develop the zero-emission vehicles (ZEV) policy [3] while on the national scale the Environmental Protection Agency (EPA) is introducing the long-delayed regulations of SUVs [4]. Europe is also seeking tighter controls of toxic emissions from cars. The greenhouse gas problematic is high on the European agenda as well as in many states, municipalities, and civil institutions in the US. In the rapidly developing countries, the problems of urban mobility are also drawing increasing attention. In New Delhi a recent court order requires that taxis and buses switch from gasoline and diesel fuel to the cleaner liquid natural gas fuel (LNG) [5]. Cities such as Curitiba and Bogota are carrying out daring experiments with alternative mobility systems [6]. Brazil has had its gasohol (alcohol from biomass for car propulsion) program for many years [7].

These efforts, however, pale *vis-à-vis* the projected growth in population, affluence, and people's appetites for the type of personal mobility car can provide. This is clearly evident in China, where car ownership is steeply rising, from 1.6 million in 1990 to 10 million in 2000, to 80–90 million anticipated in 2020. In July 2003 over 1.07 million cars were sold in China, compared to 1.06 million in the entire year of 2002, an increase of 98% [8]. Although in absolute numbers this is still low, compared to the US, the relative increase is staggering. Road accidents in China are growing as well. In the first 10 months of 2003 there were 90,000 fatal car-related accidents, with 400,000 wounded. Bicycles are being banned from car-congested large cities. The total level of carbon dioxide emissions in China is already second to the US, and will continue to rise steeply [9].

While the developed world is in no position to criticize the developing world for their desires to match them in affluence and mobility, the ecological consequences of these parallel trends will be disastrous. In that context, some developed countries have acknowledged bearing a responsibility for finding alternative ways to satisfy these needs and wants. During the 1990s, the Dutch program Sustainable Technological Development argued that increasing population growth and increasing production and consumption could only be met in a sustainable way by developing so-called 'factor 20 solutions'', meaning a 20-fold reduction in the intensity of consumption of energy and materials per capita by 2050 [10,11]. For greenhouse gas emission, especially CO_2, reductions of 75–85% per unit of need fulfillment are now generally accepted as necessary in the long term (see, for instance, [12]).

Such ambitious goals will require a mix of radical solutions. One of those is significant technological change in the automobile design. The car industry has demonstrated that dramatic reductions in tailpipe emissions are possible: since the passage of the US Clean Air Act of 1970 individual automobile emissions have declined by a factor of between 8 and 20, depending on the type [13]. The hydrogen fuel cell is considered by many to be the next major technological breakthrough in car design [14]. We discuss its promise and limitations in the next section.

But technological change in car design, however successful, is unlikely to suffice to counteract the current social trends in consumption. Fundamental rethinking of the entire system of personal mobility is also necessary [15]. The most radical solution would be a reduction of the transportation needs by either redesigning the infrastructure and land use to reduce the distances to work, shopping, recreation, and so on, or by increasing the reliance on tele-commuting, tele-shopping, e-conferencing, e-tourism and e-fun. A less radical and probably more realistic solution would be to shift to other modes of mobility: walking, cycling, using other types of vehicles, and public transportation. A third approach would centre on mobility services. These might include car-sharing (which unfortunately results in a relatively small reduction of the environmental burden), and creative chain mobility services, like joint transportation to and from work organized by employers as a way of increasing productivity [16–18].

The development of these solutions presents a great challenge to society, the governance system, and the market place, owing to the entrenchment of the car–petroleum system. The resilience of this system is enormous, not only for economic and infrastructural reasons, but also because of the resistance by the vested interest of powerful societal actors, such as car and gasoline manufacturers, filling stations, dealers and repair shops, and of the scientific and technological infrastructure that endorses the present situation. Moreover, the cultural symbolism of a car, and the social resistance to change in life-styles and daily routines, are equally strong [19,20].

Governments, while having a limited impact on fundamental lifestyle choices, can be change agents in other ways. As discussed earlier, governments can, and do, regulate air quality, fuel type, emissions of pollutants from automobiles, and to some extent car use through availability of parking and roads. They can facilitate fundamental technological innovation through regulations, incentives and subsidies. They also have considerable power to affect systemic socio-technical change by providing leadership, facilitating emergence of a widely shared vision of the future, by forming crucial networks among the key societal actors, and by creating platforms for interactions and learning. Examples of these types of efforts have been accumulating, like the Dutch transition management explained in the paragraph below. In California ZEV regulations facilitated the R&D expenditures by car and fuel manufacturers in alternatives propulsion systems. Switzerland has become a primary example of replacement of personal automobile with an efficient public transport [21].

In another interesting shift, the Dutch government has adopted 'transition management' as a guiding principle of its National Environmental Policy Plan-4 (NEPP) [22]. *Transitions* are conceptualized as long-term, continuous processes in which a socio-technical system on a scale of the entire society changes fundamentally. They entail interconnected and mutually reinforcing changes in technology, economy, institutions, ecology, social norms, and belief systems. The concept of transition draws on the ideas of system dynamics and evolutionary economics. Extrapolating from historical cases, such as the transition from coal to gas heating in the Netherlands, the transition from sailing ship to steam ships in the US, and others, it presupposes that there is an initial state and a final state of societal steady state, and the shift may take as long as 50 years [23,24].

The underlying premise of the Dutch NEPP is that traditional policy instruments or technological innovation alone are insufficient for solving persistent sustainability problems like the greenhouse gas problem and the individual mobility challenge. Grin et al. [19] call the Dutch initiative a 'third generation environmental policy'', in which the government facilitates transition processes by setting long-term goals, and bringing the stakeholders together.

One of the problems with transition *management* is that it is not at all clear if there will be a stable final state, and what it will look like. We simply do not know if the car will continue its dominant position on the long term, or if one of the other solutions (other modes, new services, e-solutions, infrastructural changes) will become dominant. We also do not know if future solutions for individual personal mobility will contain the present oversized cars, or maybe small electric vehicles for use in mobility systems. One way to overcome these cognitive and analytical barriers includes visioning exercises aimed at creating a shared goal among stakeholders, followed by so-called 'backcasting', in which a future vision is translated into strategies and actions aimed at bridging the present with the future states. A related approach consists of constructing socio-technical scenarios that describe possible final states and different likely pathways for reaching them [25–31]. Small-scale experimentation with new technologies and services in a social context has been proposed as possible first steps in developing such strategies and actions [32,33].

The common thread in the above approaches is that they facilitate higher order learning: a new and radically different way of seeing the problem of individual mobility and of the roles of various stakeholders in finding a solution. In this paper we consider these approaches and their possible contribution to learning. The paper starts with a discussion of the widely considered technological solution to mobility—the hydrogen fuel cell car—concluding that this is possibly not a viable alternative. We then take a more systematic look at conceptualizing higher order learning as it relates to mobility, and at using visioning, backcasting, scenario building, and experimentation. Finally, we illustrate the deployment of these methods in an ongoing case study in the Boston Metropolitan area.

2. Hydrogen fuel cells in cars: promises and problems

For the last 10 years, hydrogen has been applauded as the fuel of the future. The advantages of fuel cells for car transportation lie in their high efficiency, low maintenance requirements, owing to the absence of moving parts, and the zero-emissions potential, which makes them especially suited for city traffic. In recent years, the enthusiasm for cars powered by hydrogen fuel cells has reached a hype proportion in some sectors, with visions of a 'hydrogen economy' [14,34], 'hydrogen future' (President Bush's 2003 State of the Union address) and 'hydrogen highways' (California Governor's public statement in February 2004).

But the obstacles to pursuing these visions are daunting. Although fuel cells have undergone a tremendous miniaturization, increase in efficiency and reliability, and cost reduction, they are still very expensive relative to the traditional internal combustion engine. More importantly, the question of generating hydrogen has not been solved. While hydrogen is abundantly available on the planet, making it available as fuel is energy intensive. There are generally two routes to generating hydrogen: electrolysis (using electricity) and chemical reforming. To be environmentally sustainable, the electricity necessary for electrolysis would have to be generated from renewable sources (green electricity). With a few notable exceptions, such as Iceland, which possesses abundant geothermal and hydro-energy and has actually built the first commercial hydrogen fuel station in Reykjavik [35], green electricity is in short supply. One analysis [36] argues that for at least the next 30 years there will not be enough renewable energy available to produce hydrogen sustainably. Furthermore, vehicle on-board storage of pure hydrogen, although possible under high pressure, is still inconvenient because of its low energy density and the need for large volumes.

The reforming method uses various carbon-based starting materials to generate hydrogen, either on-board or in central locations. The most promising feedstocks for making hydrogen this way are: gasoline, methanol, and natural gas. Here, one of the major drawbacks is that this approach generates 'leftover' carbon dioxide, which must be disposed in an environmentally acceptable way. So far, no consensus has emerged with regard to the feedstock of choice or the on-board versus distribution network alternatives [37]. Daimler (Daimler Chrysler after the merger) has been a strong proponent of methanol, while General Motors and Toyota, and later PSA, Renault, and Nissan set their preferences on gasoline. All car manufacturers have been simultaneously experimenting with using hydrogen as a fuel. BMW has made the strongest commitment to hydrogen as the fuel of choice, but has been using it for an internal combustion engine, not a fuel cell.

Without a consensus around the fuel question, both petroleum companies and most governments are reluctant to invest in infrastructure, preferring instead the 'wait-and-see' attitude. This of course creates a 'chicken-and-egg' dilemma.

One manifestation of the uncertainty and confusion about the future of a fuel cell propelled car is the number of analyses and scenarios that have been produced in recent years and the inconsistency of the results. In 2000 a group at MIT led by Weiss [38] produced an influential report on the comparative environmental assessment of fuel cell cars. The report concluded that: ''vehicles with hybrid propulsion systems using either an internal combustion engine (ICE) or fuel cells are the most efficient and lowest emitting technologies assessed. In general, ICE hybrids appear to have advantages over fuel cell hybrids with respect to life cycle GHG emissions, energy efficiency, and vehicles costs, but the differences are within the uncertainties of our results and depend on the source of fuel energy: ''… If automobile systems with drastically lower GHG emissions are required in the very long run future (perhaps 30–50 years or more) hydrogen and electrical energy are the only identified option for 'fuels', but only if both are produced from non-fossil fuels of primary energy (such as nuclear or solar) or from fossil primary energy with carbon sequestration.''

The 2003 update of the MIT report concludes: ''there is no current basis for preferring either fuel cell or ICE hybrid power plants for mid-sized automobiles over the next 20 years or so. Hybrid vehicles are superior to their non-hybrid counterparts and their advantages are greater for ICE than for FC designs. Hybrids can reduce both life-cycle energy use and greenhouse gas emissions to about 37 to 47% of current comparable vehicles and to about 52 to 65% of what might be expected in 2020 as a result of normal evolution of conventional technology'' [39].

In contrast, a parallel study by General Motors [40] reports that hybrid hydrogen fuel cell vehicles give a 47% reduction of greenhouse gas emissions relative to the present vehicle. This is consistent with GM's current interest in developing fuel cell vehicles for the market, albeit with a petrol infrastructure and with petrol reforming under the hood.

In order to explain the different outcomes, Feng et al. [41] made a comparative analysis of four life-cycle analyses including those of GM and MIT (prepared for Ford). They clearly show that the differences can be largely explained by the choice of methodology, time frames, vehicles sizes, and assumptions about the baseline. Taking all into account, they calculate that in all studies the hybrid hydrogen fuel cell car has the largest advantages in fuel efficiency and thus in GHG emissions, ranging from 92% MPG equivalent gains in the Weiss/MIT study, 138% in the GM study, to 173% in one of the other studies. It needs to be taken into account that, according to An Feng, ''MIT results imply greater gains from 2010 to 2020 for conventional drive train technology than for fuel cell vehicle (FCV)''. However, An Feng does not discuss how much of the fuel efficiency increase comes from hybridization and how much from the fuel cell component.

Ogden et al. [42] developed an ''optimistic scenario'' under a number of assumptions: among others ''aggressive ZEV (zero emission vehicle) mandates (50%)'', a quickly developing infrastructure, and continuation of falling prices with cumulative FCV production. The authors conclude that even under the most favorable conditions FCV will not make a major contribution to the green house emissions problem before 2025, and possibly later.

The scenarios developed by Eyre and others for the UK [36] build on three groups of assumptions about: the demand, technology, and energy systems. On the demand side, baseline, world markets (a high demand scenario), and global sustainability (a low demand scenario) are considered. Five different technological trajectories are considered, including: rapid progress (hybrids and fuel cells), biomass (methanol), and a combination of the two; and four energy systems are considered, including: business as usual (BAU), high renewables, electrolytic hydrogen, and high biofuels. The authors conclude that using renewable energy directly for electrical power generation for the grid yields a larger reduction in CO_2 emissions than producing hydrogen for use in transport; at least till 2030. Only in cases where there is excess capacity of renewable energy (like on Iceland), or when there is an additional effective market demand for renewable energy, or when there is potential for the production of renewable hydrogen off-grid, there may be a net carbon benefit. Vehicle innovation (hybrid and hydrogen fuel cells) leads to significant reductions in greenhouse gases (GHG) in 2050, and more are achieved by combination with renewables or with biomass hydrogen. The most promising scenarios however in terms of reduction of GHG emissions in 2050 are made in the high biomass scenarios.

In sum, no clear environmental winner emerges from the various designs of a hydrogen-powered car. Different assessments produce widely different results. Furthermore, the environmental gains of hydrogen fuel cell vehicles are widely disputed, especially relative to internal combustion-electric engine (ICE) hybrid vehicles. It appears that the environmental gains of going from a conventional vehicle to ICE hybrid vehicle are much larger than the gain of going from hybrid ICE to hybrid fuel cell vehicle. This might suggest that focusing on the popularization of ICE hybrid vehicles may be more effective than investing into hydrogen fuel cells.

Hence, perhaps a re-framing of the significance of hydrogen is in order: rather than perceiving it as the fuel of the future car and a solution for the problems of the automobile, we should see hydrogen as a medium for transporting and storing energy, which has been generated elsewhere (preferably by renewable resources). One of its uses might be as fuel for automobiles. Others may include distributed stationary electricity generation or as a replacement of batteries for such appliances as mobile phones and laptop computers. With this new perspective on hydrogen, we may be able to re-frame the debate as well and to ask: what is the most sustainable and cost-effective way to store and transport energy, and to make it available for fuelling cars and buses? In the end, hydrogen may not the solution. Electric or bio-fuel solutions, for instance, may be more cost-effective and sustainable.

3. Beyond technological options and the imperative of societal learning

One would expect that the obvious long-term unsustainability of the present system, and government's desire to see progress in this area, would have mobilized the private sector to develop creative and profitable alternatives. At least in the USA, this has not happened. One possible reason is the enormity of overcoming the car culture in modern society, as well as the associated infrastructure. Another reason may be that the environmental and social costs of the current system are not fully internalized, which makes the alternatives not cost effective. Additionally, the systemic alternatives, such as dense housing development and mass transit, have poor reputation among consumers. Mass transit is viewed by many as slow, unreliable, inconvenient for modern lifestyles, uncomfortable, and expensive. There is much truth in these consumer perceptions, based on poor past performance of dense housing developments and mass transit. Likewise, alternative personal mobility technologies and services, human powered vehicles, car sharing, mobility services and others are perceived as less attractive or more expensive.

However, there are also many unrealized opportunities to minimize the negative aspects of dense housing and mass transit—from innovations in information technology, material science, and other technological fields, to the growing understanding of social systems that has accumulated within various professional communities of practice. For example, in a sustainable mobility system, individualized public–private mobility solutions could be designed that give the traveller much more satisfaction than being stuck in a traffic jam. A clever design of a collective mode of transport or of dense urban and suburban living arrangements could make the proximity of other people attractive rather than threatening. But that would require a fresh perspective, a more imaginative range of alternatives, new problem framings, different approaches to interpreting observations and analyzing options. In short, it would require *higher order learning*. In the next section, we discuss how different techniques and initiatives—visioning exercises, backcasting, scenario-building, and small-scale experimentation—can facilitate such learning.

The theoretical foundation for these approaches emerged in the 1970s, when theories of rational choice and bounded rationality were not able to explain fully personal, business, and government decision-making processes under high uncertainty and in rapidly changing external environments. As a reaction, theories of cognitive, organizational and policy learning emerged. Since a full account of these theories and their development goes beyond the scope of this paper, we drew on a selected set of theories that describe the processes leading to higher order learning on the level of an individual, a group and the society.

Higher order learning is a radical change in approaches to interpreting observations (interpretive frames) and to solving problems and advancing objectives. The term "higher order" denotes what in organizational sciences has been dubbed "double loop" [43,44] or "generative" learning [45], and in policy sciences as "conceptual" learning [46]. It entails changes in the assumptions, norms and interpretive frames which govern the decision-making process and actions of individuals, communities and organizations, or which underlie a policy discourse. Higher order/double loop/generative/conceptual learning contrasts with lower order/single loop/adaptive/technical learning, respectively, in which problems are corrected or policies altered without changes in problem definition, interpretive frames or in norms and values.

Learning occurs through a feedback-stimulus mechanism, when the existing, well-accepted, time-tested and trusted interpretive frames and competences receive feedback on their performance in solving a problem or advancing specific objectives. If, as a result of this feedback, it becomes apparent that the desired results are not forthcoming, these cognitive constructs become subject to reassessment and, if necessary, are replaced with new ones. A sense of urgency is an important facilitator of learning because it forces repeated trying (and failing) that is central to the learning process.

This broad concept of feedback-stimulus is consistent across a wide range of disciplinary writings about learning, from cognitive sciences to organizational sciences to policy sciences. In the context of organizations, the stimuli necessary for higher order learning come from threats to organizational survival and success, failures, disasters and other surprises [43–45,47]. Senge [45] additionally writes about using mental model building and structured interactions, scenario building, role playing, visioning, system thinking and other group techniques that generate feedback on the accepted assumptions and behaviors, as the means to stimulate higher order learning in organizations (see also the review by Easterby-Smith [48]).

Wenger [49] uses a "community of practice" as a unit of analysis in considering learning in various types of social organizations. In this author's framework, the feedback process that is central to learning takes place by way of interaction between the deep competency possessed by a community of practice and the experience it acquires by interacting with the outside world. These boundary processes produce learning. Several factors can enhance the learning at the boundaries: having something to interact about, such as a specific project or a problem to solve; ability to communicate in a common language; and the presence of individuals who serve as brokers of new ideas among different communities of practice.

In policy sciences, like in organizational and cognitive sciences, learning is attributed to the presence of feedback loops between the existing belief system and interpretive frames, and new experiences. While the organizational and cognitive sciences take an individual or a group as their unit of analysis, policy sciences center on the scale of the society, referring to these processes as social learning. Authors such as Lee [50] and Van Eijndhoven et al. [51] emphasize the role of new knowledge in providing the feedback, while Sabatier [52], Wildawski [53], Glasbergen [46] and Schön et al. [54] emphasize interactions among groups with different belief systems and interpretive frames as the means for learning. There is a widespread agreement that crises, a sense of urgency, and the availability of platforms for interaction are important facilitators of learning [54,55]. Paquet [56] advocates social experimentation as an effective inducer of the processes leading to learning.

For the purpose of discussing the learning, which is necessary for achieving major innovations in the current individual mobility system, these disparate bodies of knowledge can be distilled down to this: learning takes place when key actors representing a range of interpretive frames, problem definitions and core competences engage in intense interactions around an issue, a problem or an idea.

4. Learning through visioning, scenario building, backcasting, and small scale socio-technical experiments

In the last 10–15 years, many new approaches have been developed to induce learning for sustainable development and sustainability. Here we briefly mention visioning (often in creative processes), scenario building, backcasting, and small-scale socio-technical experiments.

Drawing on several authors, Frans Berkhout [57] calls visions ''pseudo-facts that guide behavior'' [58], ''cognitive structures that orient behavior and define roles'' [59]), and ''metaphorical structures, consistent with underlying values'' [60]. He views ''technological visions'' (but it could be applied to all kind of visions) as ''mapping a 'possibility space'; a heuristic device for problem defining and problem solving; a stable frame for target setting and monitoring progress; a metaphor for building actor-networks; a narrative for focusing capital and other resources. (...) Every plan of action requires an image or a vision – so new visions are continually generated. (...) Visions come to be articulated and diffused for two reasons: Their intrinsic validity and attractiveness; the power of constitutive interests; visions with greater interpretive flexibility are more effectively diffused'' [57].

When used appropriately, visions are powerful devices that can orient and structure actions and behaviors. They have the power to inspire societal actors to investigate and test alternatives—from technology to behavior to culture and institutions. Shared visions may unify competing or warring interests by creating a shared framing of a situation. In the US, the Tellus Institute team has created a vision of the ''Great Transition'' as a metaphor to challenge ''policy reform'' as an inadequate approach to achieve sustainability, and to create an image of a sustainable possible future, with the aim to mobilize societal actors for changing culture and institutions [61]. In the Netherlands, the ''Transition Management'' group used a similar language, although the role of the future vision is less articulated [23].

Although visions do not offer a continuous progressive path from the present to the future, and require a creative ''jump'', they are not utopias. But neither should they be treated as blueprints for the future. Visioning has been widely used over the past two decades for building trend-following (possible) future scenarios. In scenario-analysis, the traditional way is to create ''alternative futures'' based on some form of trend-extrapolation, combined with dominant drivers. In this way ''possible'' futures are created as a space in which the ''real'' future will eventually develop. Shell [29] has, for instance, developed and used these types of scenarios for understanding better, and to be prepared for, possible factors that might affect the company's future. Trend-following scenarios are currently widely used by politicians and business community alike. By pointing out unwanted consequences of present developments (climate change, congestion) they pave the way for normative scenarios and visioning. These scenarios are themselves not normative, although of course all kinds of values are incorporated in them.

Another application of visioning is to create trend-breaching scenarios for *desirable* (in contrast to *possible*) futures. For instance, sustainability visions of the future might imply breaches of trend from the present developments. These breaches may be technological (radical innovations), but more often they are social and cultural (shifts in values from individualistic to communal, from increasing wealth to increasing well-being, from owning to sharing). In the SusHouse project [25,62], creativity workshops with stakeholders have been used to create the elements of normative future visions that depart markedly from presently dominant values in society. In a related approach, Berkhout et al. [63] developed socio-economic scenarios in relation to climate change and conceptualized them as ''learning machines'' meaning ''... the capacity to bind together the mental maps of diverse communities and to enable them to imagine alternative futures collaboratively''.

Backcasting is another tool for breaking through the creativity barrier and for facilitating higher order learning. It is a process whereby the construction of a future vision or normative scenario is followed by looking back from the future and then creating a strategy or action plan how to proceed from the present towards that desired future. Backcasting has been applied in the Netherlands as a promising participatory planning tool to identify and explore system-level innovations towards sustainability. It also aims at follow-up and implementation in public research, in companies and public interest groups, and in the government.

The origin of backcasting goes back to Amory Lovins, who proposed ''energy backcasting'' as an alternative planning technique for electricity supply and demand in the 1970s [64,65]. Lovins originally suggested that it would be beneficial to describe a desirable future (or a range of futures) and to assess how such a future could be achieved, instead of focusing only on likely futures. After having identified the strategic objective in a particular future, it would be possible to work backwards to determine what policy measures should be implemented to guide the energy industry in its transformation towards the future required energy industry.

Since the 1990s backcasting has also been applied in the Netherlands, first at the governmental program for Sustainable Technology Development (STD) from 1993 to 2001, and then in its EU funded spin-off, the research project, Strategies towards the Sustainable Household (SusHouse) from 1998 to 2000 [66]. Drawing on the Swedish experience, Vergragt and Jansen [67] proposed incorporating backcasting into the philosophy of the Sustainable Technology Development (STD) program. They described the basic idea [67, p. 136] as ''to create a robust picture of the future situation as a starting point, and start to think about which (technical and other) means are necessary to reach this state of affairs.'' In a later work Vergragt and Van der Wel [68] also emphasized implementation and planning for action, the idea reiterated by Hojer and Mattsson [69], and, like Dreborg [70] had done in Sweden, they pointed out the link between backcasting for technological development and the concept of constructive technology assessment.

One of the more ambitious applications of visioning and backcasting took the form of the so-called SusHouse Project. The aim of the project was to develop and test strategies for developing sustainable households in the future. This was a backcasting approach using stakeholder workshops, creativity methods, normative scenarios, scenario assessments and backcasting analysis [25,26,62,66,71]. Contrary to the Sustainable Technology Development Programme, the emphasis was less on the technology and more on achieving cultural and lifestyle changes contributing to sustainability. Creative problem solving (e.g. [72]), the importance of defining steps contributing to developing such a sustainable, desirable, and the importance of (conceptual) learning by stakeholders and involved researchers facilitating the process.

In another approach to facilitating higher order learning, Brown et al. [32,33] emphasized small-scale experimentation. These authors introduced the term *bounded socio-technical experiment* (BSTE) to denote a project exhibiting several characteristics: an attempt to introduce new technology or service on a scale bounded in space and time; a collective endeavor, carried out by a coalition of diverse actors, including business, government, technical experts, educational and research institutions, NGOs and others; a cognitive process in that at least some of the participants explicitly recognize the effort to be an *experiment*, in which learning by doing, trying out new strategies and new technological solutions, and continuous course correction, are standard features. In this context, the term ‘‘experiment’’ denotes a process of trying to accomplish something new, and assuming that the objectives will be achieved through recurrent trial and error, self-evaluation, problem solving, and mid-course correction. It is distinctly different from the concept of a controlled experiment, in which an intervention is applied to one group, and not to another, control, group.

A BSTE is driven by a long term and large-scale vision of advancing the society's sustainability agenda, though the vision needs not to be equally shared by its participants. Its goal is to try out innovative approaches for solving larger societal problems of unsustainable technologies and services. This latter characteristic distinguishes BSTE from, for example, solving a particular environmental problem in a community, or from a strictly market-driven introduction of a new mode of transportation.

Apart from creating an opportunity for testing a new technology before its readiness to face the market, BSTE allows for development of new social arrangements among actors, and to consider them as templates for other societal contexts. It is also a way to draw into the sustainability agenda actors who would otherwise not see a place for themselves in the types of projects in technological and system innovation that are often sponsored by powerful corporate, governmental, or NGO entities. A successful BSTE creates a functioning, socially-embedded new configuration of technology or service that then serves as a starting point for further innovation or for diffusion, or that can inform the policy making process (for instance, car sharing services [16–18]. An obvious indication of its success is when this new configuration diffuses beyond the experimental boundaries and is widely adopted. But even in the absence of a widespread adoption, the experiment's important legacy may be to induce learning among its participants and subsequent diffusion of the new ideas into the broader society: the participants serve as ‘idea brokers’ (to use Wenger's [49] terminology), who transmit ideas and knowledge into their own communities of practice. Learning occurs as a result of interactions and discourse between the new ideas brought in by BSTE participants and those that are already well established within an existing community of practice.

Several features make small-scale experiments effective learning systems. First, the participation by a heterogeneous set of actors who represent different organizations, communities of practice and institutional affiliations assures the presence of a range of interpretive frames and belief systems. Second, the vision of sustainability, which is the driving force for at least some participants, has the potential to provide a platform, an umbrella, for re-framing the clashing interpretive frames, should conflicts arise. Third, by evolving around a specific tangible ‘‘thing’’—the innovative product or service—the project provides a focus and a shared language. Other design features can be purposefully brought into the experiment in order to facilitate learning. These include: creating a sense of urgency; making deliberate efforts to encourage self-reflection and reassessment by and among the participants; and facilitating the emergence of a common language.

Our earlier empirical studies of experiments with alternative low-impact vehicles for individual mobility (Mitka, Sparrow and Gismo) showed the conditions under which learning took and did not take place and highlighted the mechanisms involved. In the case of the three-wheeled electrically assisted ‘‘bike plus’’ Mitka, some of the participants in these collaborative multi-stakeholder projects re-defined their companies' core business or their market strategies in relation to ecological impacts of individual mobility [32,33]. On the other hand, we argued that the market failure of the Sparrow and Gismo vehicles could have been possibly avoided, if learning processes were built into their marketing and design strategies [73].

Summarizing thus far, we argue that a combination of multi-stakeholder visioning, scenario development and analysis, backcasting, and small-scale socio-technical experiments may be the way to optimize higher order learning which is necessary to foster transitions to sustainable mobility systems. Unfortunately, the combination of these methods has not yet been attempted in a structured way. In the following section we describe an approach currently pursued by Tellus Institute, which includes visioning, backcasting and scenario development, but not yet small-scale socio-technical experimentation.

5. Application of visioning, backcasting, and scenario development for sustainable mobility in Boston metropolitan area

Many cities in the US and elsewhere aim to be sustainable. Often this means addressing specific local environmental, social, and/or economic problems, but rarely in an integrated way. To achieve true sustainability it is necessary to take the global dimension into account as well as the local. This means, for example, that climate change mitigation requires a long-term reduction of CO_2 emissions by 75–85%. Similarly, to achieve a truly sustainable and equitable footprint, American cities need comparable reductions in emissions, resource use, and waste generation.

In a project supported by the US EPA National Center for Environmental Research (2005–2007), Tellus Institute is developing scenarios aimed at reaching sustainability goals for the greater Boston area by 2050. They develop three sets of scenarios: (1) business as usual, without great surprises; (2) policy reform—with credible policy incentives for the short term); and (3) deep change—which, in addition to changes in technology and policy, assumes changes in behavior, lifestyles, and culture to address the deep shifts required to achieve a sustainable future that recognizes the Boston region's global responsibilities.

These scenarios comprise both a vision and a pathway for getting there. They have qualitative and quantitative elements. First, they develop narratives that describe these three alternative futures in terms of environmental, economic, and social drivers. From these narratives, indicators are derived representing the key issues of concern. The project is using a computer-based tool called *PoleStar* to develop the quantitative scenarios. The *PoleStar* system is a flexible and easy-to-use decision support tool for sustainability studies at the local, regional, national, or global levels. A broad range of issues and sectors are integrated in the scenarios including demographics, employment and income, economic activity, industry, land use, transportation, water quantity and quality, air quality, solid waste, energy production and use, agriculture, etc.

Based on Tellus' past experience of developing long-range scenarios and reviews of other sustainability initiatives, they expect to find that under both the ''business as usual'' and ''policy reform'' scenarios, the region's activities are not sustainable from a global perspective. Such scenarios are likely to show resource depletion, environmental degradation, and failure to live within a fair CO_2 budget or ecological footprint. Thus, the ''deep change'' scenario will reflect a deeper commitment to meeting the region's global responsibilities and a preventative approach to environmental degradation and climate change. This will be constructed as a *backcast* from a desired future in 2050, identifying plausible development pathways for getting there, including the choices and actions for shaping a sustainable future. Apart from the ''push'' factors, exemplified by the threats of global warming and sea level rise, there will also be ''pull'' factors incorporated in the scenarios, which may make them attractive for future citizens, like more livable communities, the absence or minimization of sprawl, and an overall improved quality of life (as indicated by greater available leisure time, for instance).

The scenario development process includes stakeholder consultations and close coordination with an ongoing regional planning effort called MetroFuture, a project led by the Metropolitan Area Planning Council (MAPC), the Boston area's regional planning agency [74]. By linking the Tellus' scenario results with MetroFuture's broad stakeholder process, involving government, business, and civil society from around the region, other local and state policy initiatives, and grassroots citizens' efforts, they will receive broad consideration. In a first workshop in June 2005 with experts and civil society activists, it appeared that there is broad agreement about the future sustainability vision and the need for a deep change scenario. Although the details still need to be elaborated, the contours of a deep change sustainability vision became visible during this workshop.

As an example, in Box 1 we present the narrative for sustainable mobility for the Boston Metro area [75]. In this scenario, hydrogen fuel cell vehicles and the provision of hydrogen are embedded in a much wider transition to sustainable land-use planning and changed attitudes of consumers, as well as in institutional innovation. Thus, hydrogen fuel cells are not visualized as a technical fix, but as a part of a much broader portfolio of socio-technical solutions. This scenario is meant to catalyze and to endorse social movements that are working for a sustainability transition, but that are often working on parts of the solution (for instance bus rapid transit, bicycle paths, changing zoning regulations). It also seeks to influence and change policymaking on the city and state levels.

However, in order to be effective, the scenario should lead to backcasting and small-scale experimentation. Backcasting means in this context that, looking backward from this vision, pathways are developed how to get there, jointly with stakeholders. As first steps, and to facilitate higher order learning, small-scale socio-technical experiments should be set up in order to engage stakeholders in learning processes. Because of the infrastructure aspects, endorsement by local governments is a necessity. For instance, closing of parts of the inner city of Boston for internal combustion engines could spur the deployment of electric and fuel cell vehicles, and might as well generate new transportation services like (electric) bicycle rickshaws.

In this phase of the Boston scenarios project, both backcasting and socio-technical experimentation are not yet on the agenda. It is a challenge to make the transition from visioning and scenario building, which is often done in relatively small groups of like-minded innovative and creative individuals, to the much harder practices of backcasting and especially socio-technical experimentation. The latter often requires an inspired and inspiring ''process champion'' [76], resources, time, determination, as well as windows of opportunity in the political process.

6. Conclusions

The future of personal mobility system will likely consist of a mix of new technologies and changes in the present infrastructure, as well as new services and social arrangements. One type of technology that has received a great deal of attention over the past several years is the hydrogen fuel cell. In our view, the hydrogen fuel cell for automobile propulsion may play a role, but its place in the broader picture of sustainable mobility needs to be re-framed: from being a possible solution to the personal mobility problem to being a medium for transporting and storing energy that has been generated elsewhere (preferably by renewable resources).

Box 1. Vision for sustainable Greater Boston 2050 transportation and land use

In the year 2050, the Boston metropolitan region has become a leading cultural and economic capital, famous for its environmental leadership. New land-use and transport practices are the great hallmarks of this new beacon of sustainability. Consistent with the MA Climate Action Plan and the New England Governors and Eastern Canadian Premiers Climate Action Plan, a reduction of GHG emissions from transportation in the region have been reduced by up to 80% since 2000. The recently established coalition of local governments (or regional land use commission) developed and implemented a mix of policies aimed at rebuilding infrastructure, decreasing car use, and increasing public transit and other alternative modes of transportation, and stimulating citizens to live close to work, school, and recreation.

Brownfields, vacant lots and many parking lots in Boston and other inner/core communities have been redeveloped with mixed-use in-fill projects; development restrictions and/or fees are placed on undeveloped areas within the region; and mixed-use zoning is adopted throughout the region to encourage a mix of residences, offices and commercial activities within walkable/bikable distances from each other and from transit stations.

Citizens are predominantly living and working near public transportation hubs. Public transportation is attractive because of high speed and frequency, high comfort, and convenient payment. This has reversed the decline in transit use the region experienced in the first few years of the century. Public transportation use is now routinely encouraged by employers who offer free or reduced cost transit passes as a benefit, and a high fraction of offices and workplaces being situated near transportation hubs. Easy access to transit stations is provided by an extensive MBTA[2] car-sharing program, as well as pick-up shuttle services using electric vehicles, underground parking spaces near stations, and high quality provisions for bicycle storage.

Individual car use has decreased as alternative public and private transportation options have become so convenient. Transit includes a number of modes: "bus rapid transit," rail, light rail, car-sharing, taxis, and ferry services. Walking, cycling, shared taxis, and high-speed transit have become easy, attractive, quick, comfortable, and less expensive than driving and parking, especially in Boston proper and the inner core communities. All public fleets and most private cars are hybrids or run on hydrogen that is produced from renewables or natural gas. Significant investments have been made in carbon sequestration projects within the region and outside it to reduce the net greenhouse gas emissions considerably. Electric and fuel cell bicycles are common to help overcome adverse wind and ascents; bicycle lanes are common on most major roads. New technologies such as three-wheel electric covered bicycles provide transportation for handicapped, elderly, and other individual users.

Major highways (93, 95, 90, 1) are redesigned from single-car use with lanes for bus-rapid transit (BRT) and high-occupancy vehicles, and for (electric) bicycles and scooters. One lane on either side is dedicated to BRT, and a second lane for passing BRT and high-occupancy cars only. Their use is stimulated by time and place dependant congestion pricing. Some transit nodal points are attractively situated close to highways in order to facilitate easy access.

A large part of downtown Boston is closed for individual cars except certain categories (high-occupancy, all-electric or hydrogen vehicles; electric multi-occupancy taxis). In this area public transit is free; bicycle facilities are readily available (lanes, storing, zip-car-like renting system); and the long-needed rail link between North and South Stations is in place. The traffic light system has been modernized to promote pedestrian and bicycle use and safety. In a significant part of the city private cars pay a London-type congestion fee according to size and type of propulsion, thus discouraging use of large vehicles (SUVs) and non-zero-emission cars.

The quality of schools near public transportation hubs is very high due to new financing schemes (de-linking from local property tax), including vehicle insurance programs based on fuel type, size of vehicle, and efficiency. High-quality recreation and sports facilities are situated close to schools, thus reducing need for transportation. Transportation needs are further reduced by extensive tele-commuting (at least 20%

[2] Metropolitan Bay Area Transportation.

Box 1 (*continued*)

on average) and increased tele-shopping (or ''e-shopping'') with alternative fueled vehicle fleets for goods delivery.

Boston is an attractive city for its citizens and for visitors because it combines urban features such as shops, cultural attractions, restaurants, schools, and museums, with green features including parks, rivers, and the coast, with excellent public transportation services. Moreover, land use and transportation policies have created a region that is without the nuisance, disruption, and impacts of reliance on private vehicles and large parking lots. Because of its public transportation infrastructure and mix of incentives, the Boston area offers a wide variety of services with high accessibility within short distances.

From an institutional perspective, public–private partnerships have realized innovative solutions by experimenting with new technologies. By including universities and technical institutes in research and development, new private high-tech enterprises developing innovative mobility solutions are thriving. Advanced information and communications technology (ICT) is widely used for road pricing, congestion pricing, fare payment, trip reservation, information and communication services, tele-working and tele-shopping, combining trips, and vehicles sharing. These organizations and businesses are an important component of a thriving regional economy.

Government has an important role to play in building a system of sustainable mobility, through regulatory policies, and strategic incentives and disincentives. But a transition from a car-centered personal mobility system toward a sustainable mobility system cannot be designed as a blueprint, owing to its complexity. Rather, a broad societal learning process is needed, with a focus on the system as a whole: its spatial characteristics, the infrastructural and technologic options, individual needs for mobility and access, cultural norms, and institutions, as well as their mutual interdependence.

Several bodies of disciplinary knowledge, including cognitive and social psychology, policy science, organizational science and sociology, have accumulated with regard to how learning occurs on the level of individuals, groups, organizations and the society. Based on this collective research, we know that learning takes place when key actors representing a range of interpretive frames, problem definitions and core competences engage in intense interactions around an issue, a problem, or an idea. Building on this knowledge, and drawing on the empirical experiences from the area of sustainability, we propose four approaches to facilitate societal learning toward a transition in the current mobility system. All entail intensely interactive multi-stakeholder processes.

Visioning—a heuristic device which maps a ''possibility space''—is one such approach. It can be powerful instrument for inspiring societal actors to investigate different problem definitions, test alternative strategies, and find shared areas of agreement. Scenario building and backcasting, especially when used as a follow-up to visioning exercises, are also promising multi-stakeholder approaches. Both aim at creating blueprints to bridge the present and the future; scenarios create ''alternative futures'' based on some form of trend-extrapolation and informed by an understanding of dominant drivers; in backcasting a future vision or normative scenario is followed by looking back in time and creating a strategy or action plan for proceeding from the present toward the desirable future. Scenario building and backcasting have been applied in the Netherlands as promising participatory planning tools for identifying and explore system-level innovations towards sustainability.

Experimentation on a small scale with new technologies and services is the fourth approach we advocate to facilitate societal learning. Such experiments should be designed with particular features in mind; we refer to the latter as bounded socio-technical experiments, BSTE.

The above multi-stakeholder approaches may be practiced at various levels, from local to national, with experimentation probably being best suited for a smaller scale. In parallel, regional, national policies and agreements are necessary to reinforce such smaller scale initiatives and to stimulate technological innovation.

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