

Annual Report 2009 of the CCEM Project

Transition to Hydrogen Based Transportation: Challenges and Opportunities

1. Final Report (for printed report)

Research questions

For an assessment of the opportunities provided by the introduction of hydrogen as a transportation fuel, the following aspects have been considered:

- The life cycle impact of the full fuel cycle for hydrogen is compared both to conventional and to other alternative fuels.
- With a view to atmospheric chemistry, changes in the hydrogen emissions due to transport are analyzed.
- The optimum design of a vehicle depends strongly on both the desired performance / utility and on the available fuels. A methodology for an unbiased assessment of vehicle design options is developed.
- Introduction of hydrogen requires profound changes of the transportation system and its use by society. The associated dynamics of innovation diffusion into markets is studied, considering barriers, opportunities, and feedbacks.
- Global economy strives at maximizing intergenerational welfare. Energy-economic models consider resource scarcity and climate protection goals as important drivers promoting changes in the transportation system.

Comparison of alternative and conventional fuels by life cycle analysis

The life cycle impact of biofuels and hydrogen as an energy carrier was compared to conventional fuels. With a view to transportation, results are conveniently expressed in terms of grams of CO_{2,eq} per kilometre. Even for advanced passenger vehicles with a consumption equivalent to 3 litres of Diesel or 4 litres of gasoline, emissions are dominated by fuel combustion during the use phase (Fig. 1). If methane from biomass (SNG) is substituted for natural gas, a large reduction is achieved. For fuel cell vehicles propelled by hydrogen produced from fossil fuels, the prevailing emission contribution comes from the fuel chain, with pronounced differences depending on the source (coal gasification versus steam methane reforming). The ecological advantages of hydrogen are reaped if the latter is produced from renewables. While water electrolysis using hydro-electricity (if additional quantities are available in the energy system at large) gives rise to lowest overall emissions, the solar thermal dissociation of water in a two-step process represents an attractive alternative that does not require renewable electricity upfront.

Hydrogen in the atmosphere

Hydrogen may act as an indirect greenhouse gas, by changing the concentration of the important OH radical in the atmosphere, and thereby increasing the residence time of the greenhouse gas methane. Concerns on these effects have been

formulated in the context of an energy economy that would largely rely on hydrogen. In order to address them, the present inventory of hydrogen emissions has to be compared with scenarios for the future.

The start-up phase under cold start conditions often makes a dominant contribution to overall H₂ emissions, as do fuel-rich conditions. Emissions over a driving cycle are much smaller for diesel cars than for those with gasoline-fuelled engines, whereas motorcycles and scooters emit significantly higher quantities (Fig. 2).

Comparison with the few available test results from fuel cell vehicles shows that future road emissions will be dominated by 2-wheelers and fuel cell vehicles, and efforts invested to control them. However, these would be typically lower than the losses associated with the production, transportation, distribution, and storage of hydrogen.

Estimations from the literature of loss rates from various production, distribution, storage, and end-use systems have been critically reviewed. The lower range of loss rates quoted by industrial sources appears to be more realistic. Combining these reasonable assumptions with potential shares of hydrogen in a global energy system at the end of the 21st century, it is expected that H₂ emissions from energy-based H₂ use should remain within the realm of current estimates of total anthropogenic H₂ release into the atmosphere.

Multi-criteria assessment of alternative drivetrains

The introduction of alternative concepts such as fuel cell vehicles provides an opportunity to re-design the vehicle in its entirety, rather than making incremental improvements starting from existing models. This is the context of the heuristic vehicle design performed in this study. Groups of user-defined technology options (e.g. size-class of vehicle, fuel type, and chemical energy converter), exogenous variables (such as fuel prices) and endogenous technology options (e.g. materials used, tank size, rated power of the chemical energy converter, hybrid architecture, and battery capacity) are defined while respecting existing relationships between the design choices and physical principles. Output from the powertrain simulation and life-cycle models are criteria of interest to drivers, manufacturers, and regulators such as fuel consumption, greenhouse gas and pollutant emissions, total cost of ownership, range, acceleration capability, and safety.

An analysis of the effect of vehicle weight reduction on cost, safety, and environmental impact of the North American heavy-duty fleet confirms that a reduction in the average vehicle weight of the heavy duty fleet is accompanied by a net reduction of the overall societal cost of mobility.

Detailed technical modeling of the powertrain options (primary converter, hybrid architectures, optimal control) have been performed for given driver requirements. Results are shown in the form of trade-off curves (Fig. 3). This example, chosen from a large set, illustrates that the required technical performance (here expressed as top speed) has a pronounced influence on the CO₂ emissions.. Hybrid vehicles are able to achieve better performance with lower CO₂ emissions, mitigating this important trade-off. For the hydrogen fuel cell vehicles, the use of hydrogen produced by solar

electricity (using photovoltaic electrolysis) is clearly the superior option. Electric vehicles perform well due to their high efficiency, even if the current US electricity mix is assumed.

Preliminary stakeholder profiles have been used to generate multi-criteria decision analysis results, allowing for different weighting of economy, ecology, and performance criteria according to personal preference. The results show that the "optimum" vehicle strongly depends on stakeholder priority for some technologies (e.g. chemical energy converter and fuel), while others are preferred by most stakeholders (e.g. lightweighting technology).. While petrol / diesel hybrids continue to prevail for high payload and range requirements, fuel cell vehicles emerge as a superior option for typical passenger car applications, and purely electric vehicles find their optimum application where low range and performance is tolerated.

System dynamic analysis of market penetration

A system dynamics model for vehicle substitution in the European fleet was developed to map the concepts of technology diffusion and substitution, including the innovative characteristics of a behavioural norm developing within a society, that influences the inherent and perceived attractiveness of alternative propulsion modes.

The expected technical development, including technology diffusion, is taken as the baseline. For the European car stock, it is analyzed what policy packages, what levels of stimulation, and which features of inherent attractiveness are necessary to reach defined European emission reduction targets. Figure 4 illustrates that fiscal incentives alone are not very effective unless the inherent attractiveness of alternative propulsion technologies (such as hybrids, natural gas cars) is raised. But it is only with the introduction of a "near-zero emission" vehicle (here represented by a fuel cell vehicle running on renewable hydrogen) that the goal of halving passenger transport emissions by 2050 could be reached.

Supposing that the emission challenges can not be met by incumbent technologies, it is interesting to analyze which type of transformation would be expected to occur within the car manufacturing industry. Whereas the possibility of a disruptive transformation is taken into account, in which a newcomer conquers the market with a new technology, it is considered more likely that with industry realizing the need to achieve stringent emission targets, the incumbents would carry the necessary, fairly radical innovation in an endogenous transformation.

Hydrogen in the energy system – energy economic modeling

Scenarios for the evolution of the world energy system have been developed to analyze the conditions under which alternative fuels and vehicle drivetrains may be competitive, accounting for resource and climate constraints. Economic energy-systems analysis of these scenarios was carried out using the European Hydrogen MARKAL model, the Global Multi-regional MARKAL model, and the Swiss MARKAL model. It was found that the use of both hydrogen and biofuels in transportation can contribute to achieving climate stabilization targets on a global level. Biofuels, and hybrid cars employing these fuels, are found to be competitive under moderate

climate policy targets stabilizing atmospheric carbon dioxide (CO₂) concentration at 650 parts per million volume (ppmv) (see Fig. 5). One key factor for the deployment of biofuels is the global availability of biomass and its cost. The contribution of biofuels to transportation is reduced with more stringent climate policy targets, with biomass utilized in these cases for the decarbonisation of other sectors of the energy system, such as heat or electricity production. Hydrogen is competitive under the most stringent climate policy targets, such as 450 ppmv CO₂ (see again Fig. 5). Subsequent analysis of conditions under which battery electric vehicles could play a larger role, indicates that substantial reductions in battery costs are likely to be needed. In agreement with the global studies, the enforcement of ambitious climate targets in Switzerland will necessitate profound changes in the vehicle fleet.

Outlook

Further evaluation is proceeding to interpret the trade-offs among vehicle design options for various stakeholder groups. Completion of the actors' model will consolidate conclusions on company innovation strategies. Besides peer-reviewed publications, the results of the project will be published as a book, expected to appear in the second half of 2010.

Figures for the Annual Report

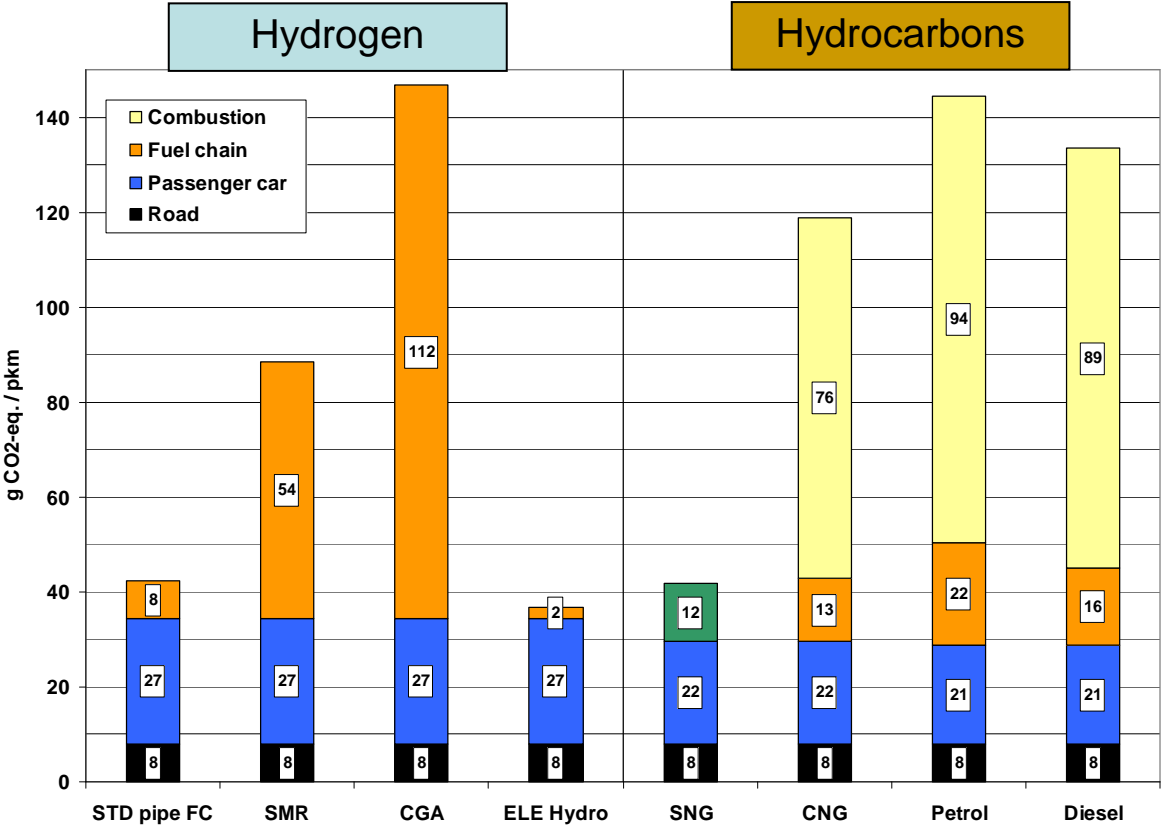


Fig. 1
 GHG emissions in grams of CO_{2,eq} per passenger kilometre (including fuel chain, operational emissions and construction, maintenance, and disposal of car and road infrastructure; average load of 1.59 passengers per average car of the year 20xx) showing contributions of life cycle stages. Abbreviations: STD pipe FC = Solar Thermal Dissociation (two-step ZnO/Zn water-splitting cycle) + H₂ pipeline transport from Spain to Switzerland + use in Fuel Cell; SMR = Steam Methane Reforming; CGA = Advanced Coal Gasification; ELE Hydro = Electrolysis using Hydropower; SNG = Synthetic Natural Gas; CNG = Compressed Natural Gas.

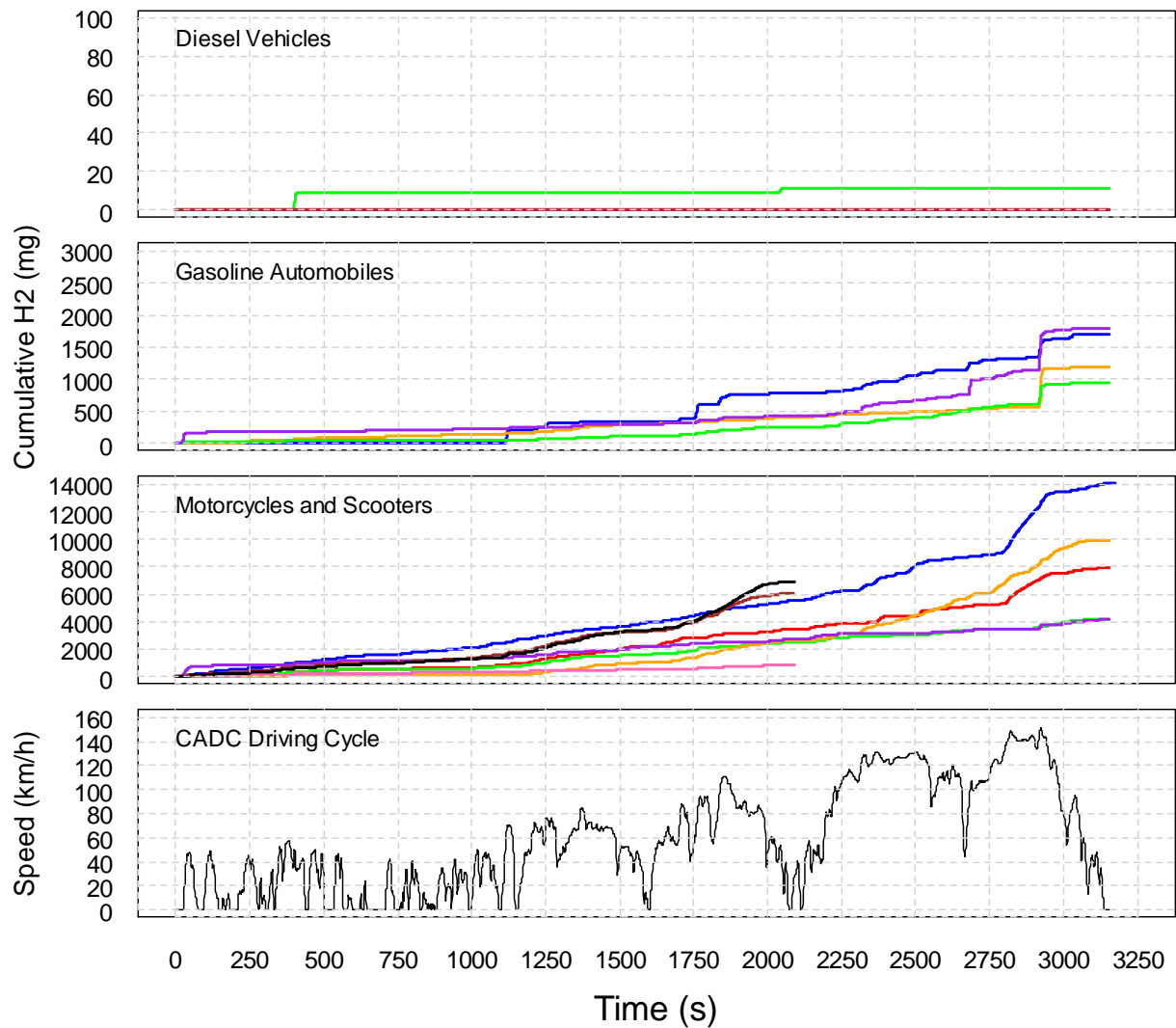


Fig. 2. Cumulative H₂ emissions (in mg) for the diesel vehicles, gasoline automobiles, natural gas vehicles, and 2-wheelers. All vehicles were operated under cycle Common Artemis Driving Cycle (CADC). Different colours represent different vehicles in the same vehicle class. Note the difference of scales for H₂ on the y-axis. Evident are the very low emissions from the diesel vehicles and the high emissions from the 2-wheelers and natural gas vehicles. The 3 shorter curves for the motorcycles and scooters represent the scooters, whose displacements and top speeds prevented them from conducting the motorway cycle of the cycle.

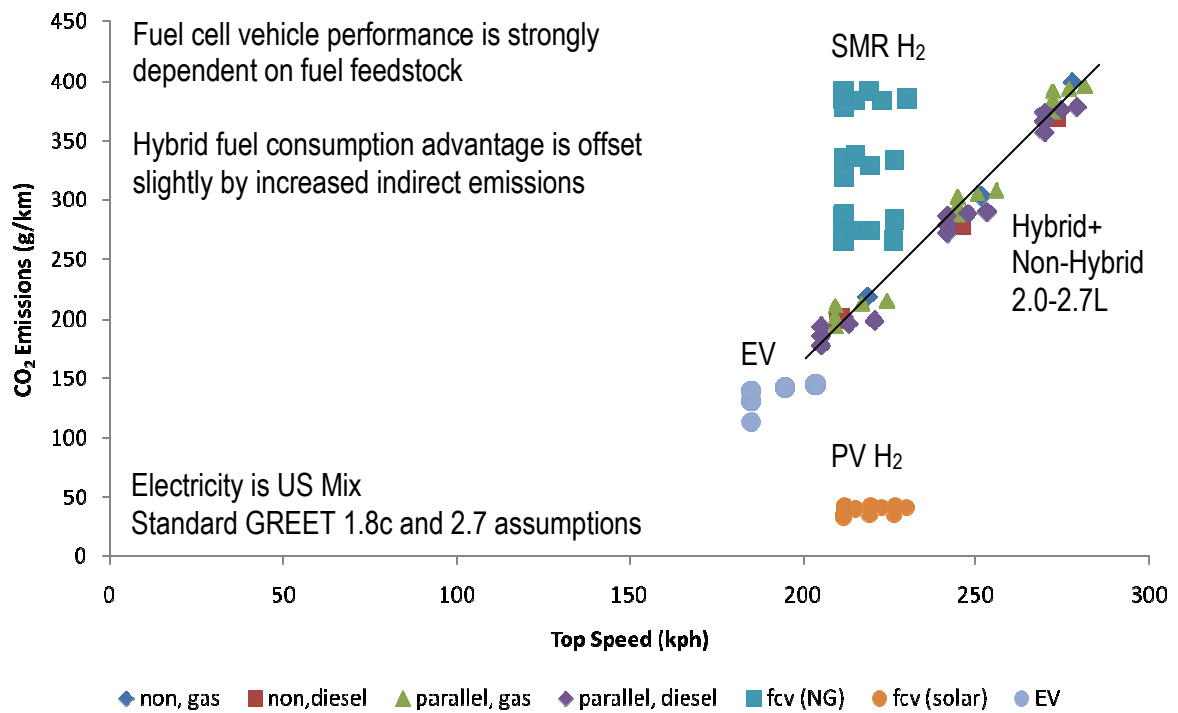


Fig. 3

Trade-off curves resulting from heuristic vehicle design.

As an example, life cycle CO₂ emissions are plotted against performance, expressed by top speed. Hybrids emit less for small battery sizes. Fuel cell vehicle performance is strongly dependent on fuel feedstock (SMR: steam methane reforming; PV: electrolysis using photovoltaic electricity). For the electric vehicles (EV), the US electricity mix is assumed.

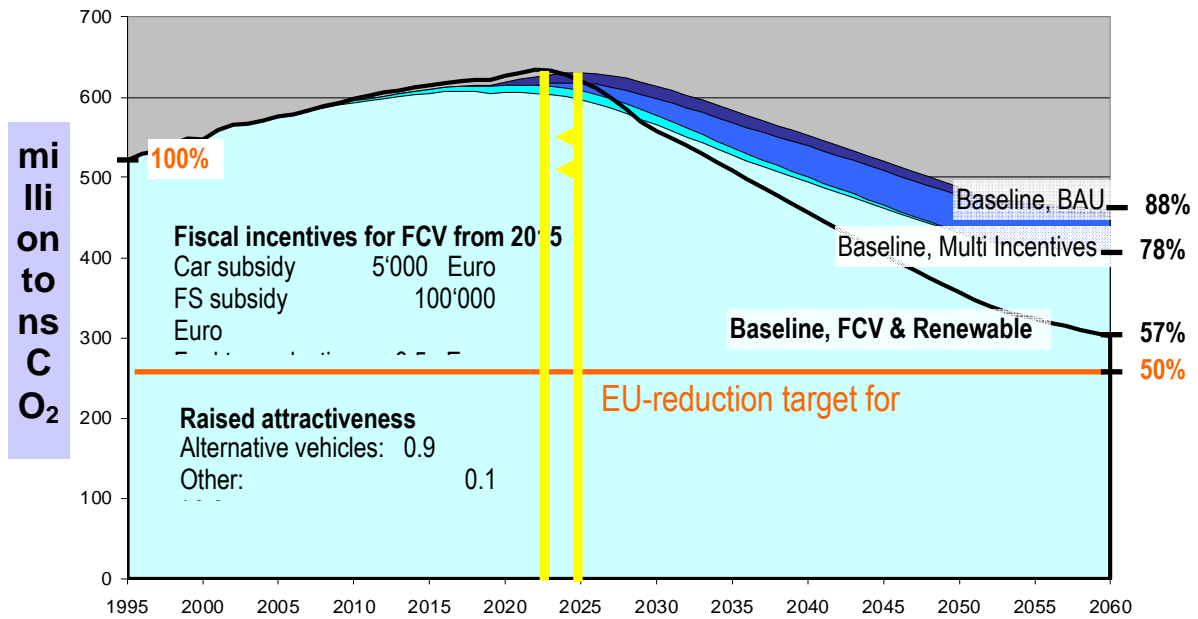


Fig. 4

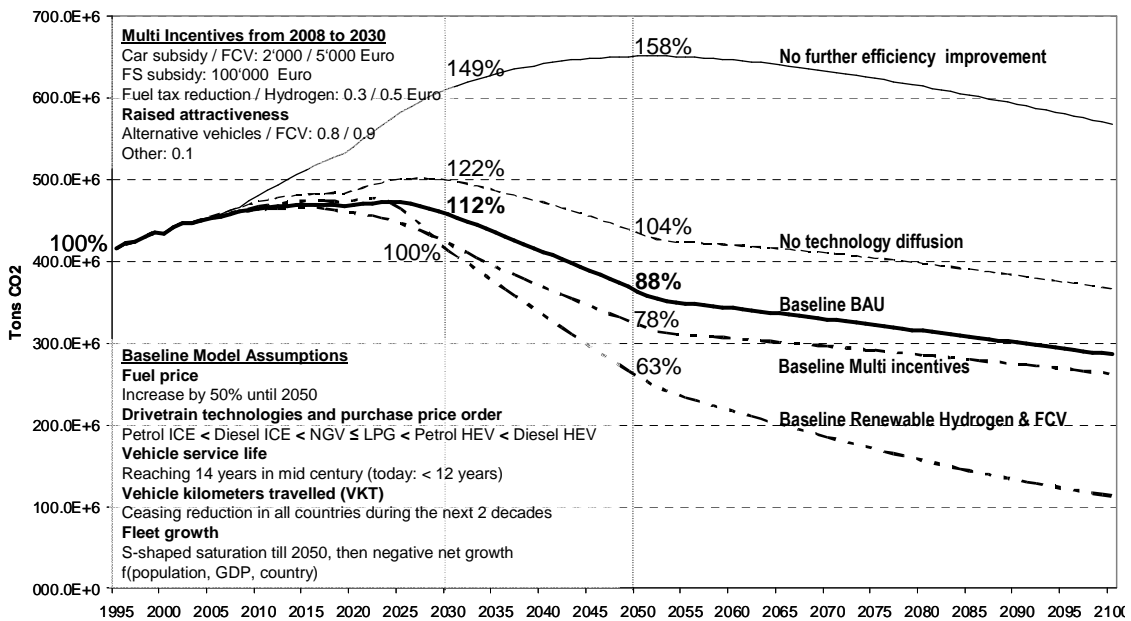


Fig. 4 (alternative):

Comparison of CO₂-emissions savings a) from further emphasis on reducing fuel consumption of conventional drivetrains, b) from alternative technology diffusion (e.g. Hybrids, NGV) c) from Multi incentive policy packages and d) from near zero emission vehicles (e.g. renewable H₂ FCVs).

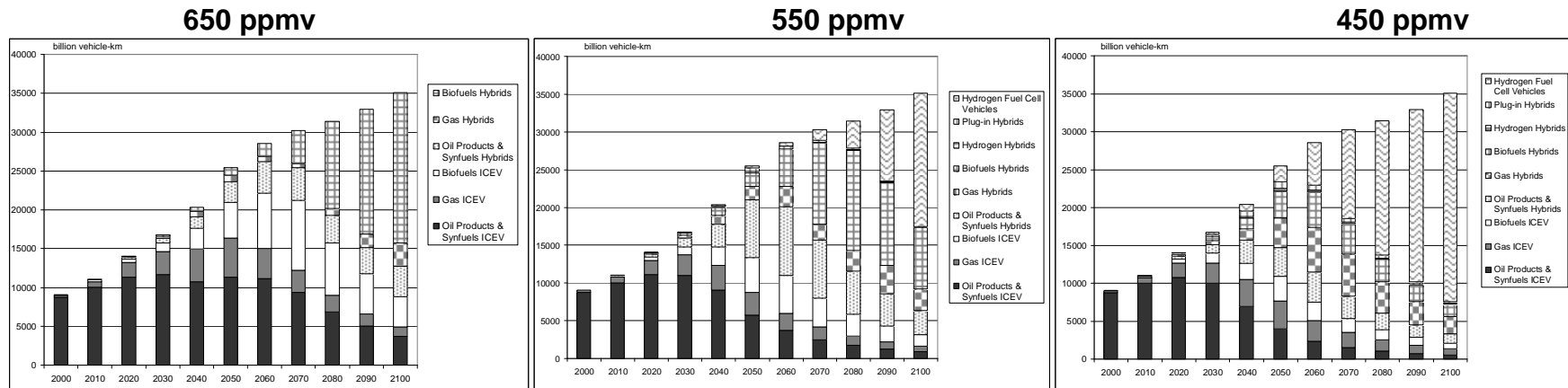


Fig. 5
 Development of personal transport across scenarios different climate change mitigation scenarios
 (from left: 650 ppmv, 550 ppmv, 450 ppmv)

2. Task: Life cycle analysis of hydrogen and biofuels production and use

Remo Felder, Anton Meier, Solar Technology Laboratory, ETH Zurich and PSI

2.1 Status of Task

- This task has been completed in 2007 with the thesis of Remo Felder. A publication summarizing the crucial results appeared in 2008 (see list).

3. Task: Hydrogen in the atmosphere

Steven W. Bond, Stefan Reimann, Martin K. Vollmer, Brigitte Buchmann, Empa, Dübendorf

3.1 Scope of Activities

- Assessment of today's atmospheric fossil-fuel vehicle-related H₂ budget
 - Verification of resulting emissions with real-world driving cycles on the dynamometer test stand at Empa
 - Validation with tunnel and road side measurements
 - Data analysis of continuous measurements at Jungfrauoch for European source evaluation
- Evaluation of future emissions of H₂ related to mobility
Hydrogen emissions from the following mobile sources have been assessed at the chassis dynamometer test stand in Empa's Laboratory for Internal Combustion Engines:
 - Gasoline vehicles
 - Diesel vehicles
 - Gasoline-hybrid vehicles
 - Natural gas vehicles
- The following technologies will be measured based on availability:
 - Hydrogen fuel cell vehicle

3.2 Status of Project

The PhD work of Steven W. Bond is progressing according to plan. In order to assess present and future emissions of H₂ from road transport, emission measurements from the following engine types have been performed to date: gasoline, diesel, natural gas, and gasoline-hybrid. A fuel cell vehicle was measured in 2007; however, this vehicle was a 'prototype'. Emission measurements from a 'road-ready' fuel-cell vehicle would, therefore, likely be more representative of observed H₂ in a real-world traffic context. The exhaust measurements in 2009 comprised natural gas and a small number of gasoline-hybrid vehicles.

For 2010, it is planned that the analyzed vehicle exhaust data be published in the form of peer-reviewed journal articles. A book chapter on 'Anthropogenic H₂ Emissions to the Atmosphere' is also currently in preparation, and will include

aspects from both vehicle exhaust H₂ emissions and the assessment of H₂ leakage/losses from other anthropogenic sources. These publications will provide a comprehensive overview of H₂ emissions from various important anthropogenic sources. The results of these measurements can be included in both life cycle analyses (LCA) of new technologies for transportation and global chemical transport models (CTM) for the assessment of the effects of these new technologies onto the atmosphere.

Hydrogen emissions from industrial and residential heating systems have been tested to assess the importance of the stationary sources versus emissions from transportation.

Ongoing continuous measurements of ambient H₂ have been performed with a RGA-3 instrument at the high-Alpine station of Jungfrauoch since 2005. These data are being evaluated for trends and European source regions in connection with the mobile and stationary source measurements. These activities are also part of the EU project EuroHydros (<http://www.meteor.uni-frankfurt.de/eurohydros>), which aims at a better understanding of the atmospheric H₂ budget, including sources and sinks in Europe. As the main aim of this project is to report the actual status of hydrogen emissions in view of a potential future hydrogen-based economy, it has a strong link with CCEM-CH activities. The details of these measurements will be subject to a forthcoming publication.

Together with the University of Utrecht (Institute for Marine and Atmospheric Research) — one of the few laboratories for measurements of hydrogen isotopes — isotopes from gasoline-driven cars have been collected, analyzed, and investigated. These measurements are important to use the isotopic signal of H₂ in the atmosphere to constrain the global budget. A publication covering these measurements is forthcoming.

3.3 Main Results

Preliminary results indicate that H₂ emissions from the measured motorcycle/scooters were about a factor of 5 higher than those from the measured gasoline automobiles, and about a factor of 1.8 higher than those from natural gas vehicles. H₂ emissions from diesel vehicles were negligible, undetectable in many instances. H₂ emissions from current technology vehicles were found to be dependent on several factors, including vehicle and fuel type, engine and catalyst temperature at start-up, engine state (e.g. engine speed, which is influenced by vehicle speed and acceleration), and the lambda setting/control. Figure 2 displays cumulative H₂ emissions (in mg) of motorcycles and scooters (2-wheelers), along with diesel, gasoline, and natural gas vehicles from this study. Different colours in each panel represent different vehicles from each vehicle class.

As a follow-up to our preliminary assessment of H₂/CO ratios from gasoline-powered automobiles in 2008, further detailed analysis indicates that rather than being constant under all conditions, H₂/CO ratios are rather more constant under fuel-rich conditions not subject to chemical complexities of a three-way catalytic converter (TWC). H₂/CO ratios are typically higher when the TWC is functioning optimally (due to efficient CO removal and consequent H₂ production through the water-gas shift reaction), and lower and more predictable under fuel-rich conditions more representative of measurements without a catalytic converter. These findings

regarding the lower H₂/CO ratios are in line with the findings in the literature, and especially the results from road-side and tunnel measurements in Switzerland performed by Empa (Steinbacher et al., 2007; Vollmer et al., 2007) — studies that would have been subject to vehicles with less efficient exhaust after-treatment systems. A comprehensive qualitative and quantitative overview from current gasoline and diesel vehicles is forthcoming.

To evaluate the effect of a large-scale hydrogen economy, estimations from the literature of loss rates from various production, distribution, storage, and end-use systems have been evaluated. Generally speaking, citations of loss rates from industrial sources tend to focus more on the lower range, which may indeed be based on more realistic and reliable information from those involved in the industry. Quotes from other sources, such as from modelling studies, for example, tend to include upper end loss rates based on “worse-case” scenarios for a future hydrogen economy. Loss rates associated with a large-scale H₂ economy must be approached with caution, as they can, at this stage, only be put forward under hypothetical considerations. Preliminary results of anthropogenic H₂ emissions combining vehicle exhaust measurements and leakage to the atmosphere from various production, distribution, storage, and other end-use systems suggest that such emissions have in fact decreased with time and that future emissions should remain within the realm of past projections. These results are to be discussed in the above-mentioned book chapter on anthropogenic H₂ emissions.

Continuous H₂ measurements from the high alpine observatory at Jungfraujoch, Switzerland have been processed for the years 2005-2009. Mean daily H₂ and CO measurements taken over the entire study period display distinct variations, suggesting specific seasonal patterns, and the offset of H₂ and CO peaks and troughs by approximately three months, which is directly related to the sources and sinks of each trace gas. Interestingly, despite the known positive correlation between H₂ and CO from measurements taken directly near the source, for example, no significant correlation between the two trace gases can be observed on a short time scale, and mean H₂ and CO diurnal cycles vary completely out of phase at Jungfraujoch. H₂ shows a maximum in the morning and a minimum in the mid-afternoon, whereas CO shows a minimum early in the morning and a maximum in the mid-afternoon. The details of these measurements will be subject to a forthcoming publication.

In a collaborative effort with Utrecht University, the H₂ stable isotope signature (hydrogen/deuterium) was characterized for gasoline engine exhaust under various operating conditions, before and after catalytic converter. The results show that the predicted δD-H₂ of -270‰ is indeed found in our laboratory tests. However, there is significant variation in δD-H₂ depending on pre- and post-catalytic converter sampling, and on the operating status and the temperature of the catalytic converter. The results support the findings of a latitudinal gradient in atmospheric δD-H₂ with the most depleted H₂ found in the latitudinal range where most vehicles are driven. The details of these measurements are subject to a forthcoming, already submitted publication.

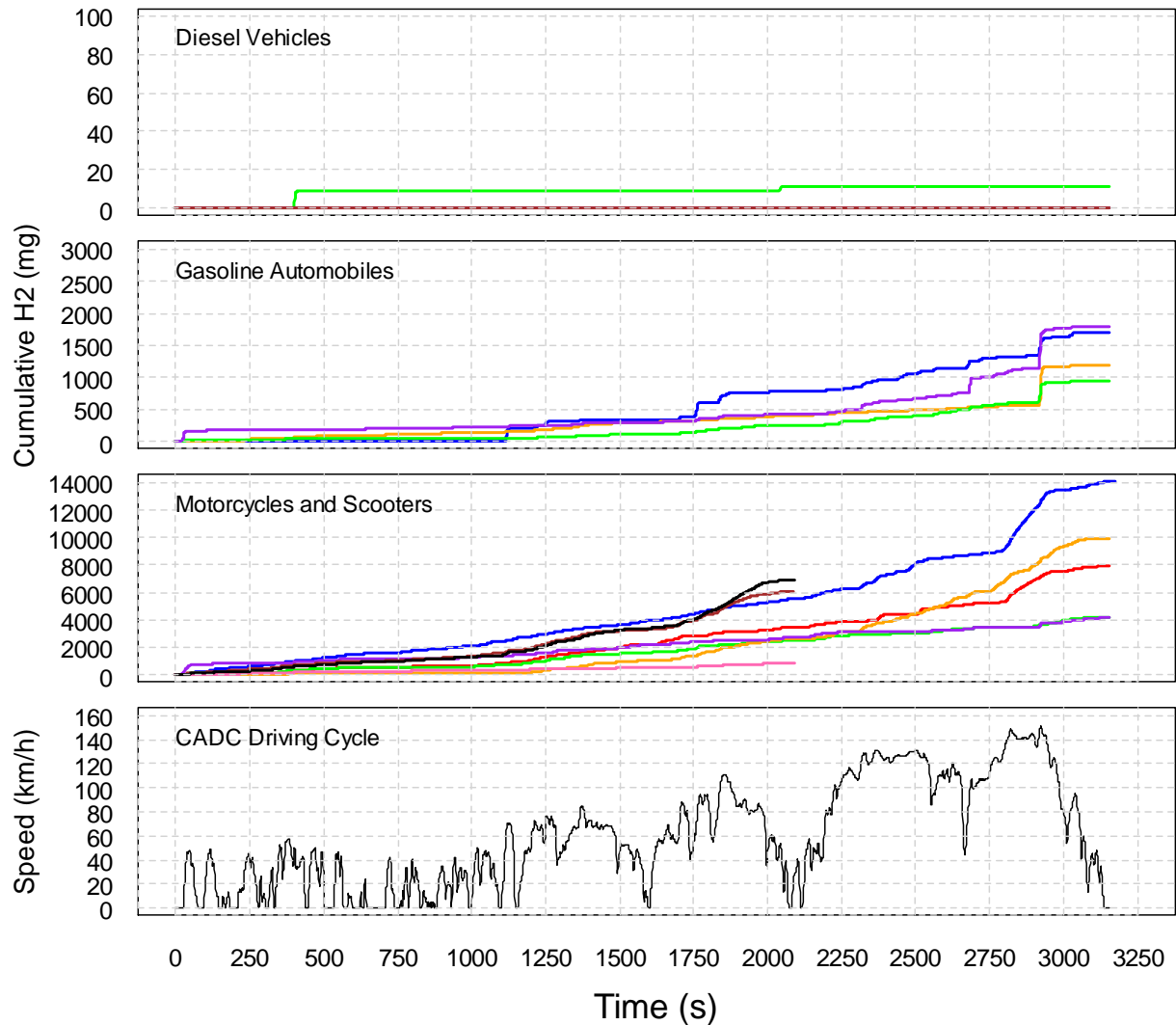


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4. Task: Heuristic vehicle design

Warren Schenler, Erik Wilhelm, Paul Scherrer Institut

4.1 Scope of Activities

Within the scope of this task a virtual vehicle fleet composed of various current and future technologies have been developed using the commercial vehicle simulation software CRUISE and MATLAB / Simulink. The tank-to-wheel information provided by the simulations is combined with LCA data from the ecoinvent and other relevant databases to provide a complete well-to-wheel description of each particular combination of design options. In order to combine the various vehicle characteristics in a self-consistent way, design heuristics from historical and standard practice are used to ‘train’ a vehicle design algorithm. This set of automatically generated virtual vehicles enables stakeholders to make an unbiased comparison of the relative merits of new and incumbent technology options according to their priorities. Multi-criteria decision analysis allows users to determine the impacts of different weightings of key criteria such as cost, performance, utility, environment and safety. A very large number of powertrain models have been generated in order to evaluate technology effects for a broad range of options. The design set has also been validated for key technology variations (including engine, control strategy, and hybridization).

4.2 Status of Project

The “Technical Characterization of Emerging Vehicle Technologies” task was furthered substantially during 2009. The definition of design rules from engineering practice and first principles has been completed, with over 60 distinct and validated heuristics which are used to ensure self-consistency in the generated design sets. These **heuristics** range from the trivial, such as matching appropriate fuels to chemical energy conversion devices, to the subtle, such as how battery systems must be sized to allow acceptable levels of energy to be recaptured during regeneration. The **automatic generation** takes an option set of 48 million potential distinct technology combinations and reduces them to 134 thousand coherent vehicle designs that form the virtual fleet to be simulated. Technical characteristics for engines, motors, batteries, fuels, and ultracapacitors have been gathered from many industry and academic sources to allow not only appropriate decisions to be made in the heuristic design method, but also in subsequent simulation tasks. A review of the **safety criteria** has been performed, and significant resources have been devoted to identifying the relationship between vehicle weight and occupant safety. A student project was initiated to simulate and characterize **ultracapacitor** technology for hybrid vehicles. Within the framework of this project, a motorized scooter was constructed to generate data for the vehicle models upon scale-up.

4.3 Main Results

Significant effort was directed towards solving the problem of optimal control in hybrid vehicle simulation. To ensure that each technology option is fairly compared with others it is crucial that optimal control be ensured for each powertrain configuration. This challenging constraint was met by applying **deterministic dynamic**

programming (DDP) techniques, which ensure global minimum energy consumption over specific driving cycles by controlling the power split between the chemical energy converter and electrical path. Once the powertrain architecture has been defined using the heuristic vehicle design algorithm, the DDP methods are used in tandem with vehicle dynamics modeling and life-cycle data to fully characterize the vehicle design according to the key stakeholder criteria. Six powertrain architectures have been developed that are able to cover the majority of hybridization options available to designers.

Initial well-to-wheels data has been gathered from two **life cycle** databases, GREET (Argonne National Laboratory, USA) and ecoinvent (Swiss Center for Life-cycle Inventories, Switzerland). The agreement of the databases for key metrics such as fuel cycle carbon emissions has been validated. The integration of life cycle inventories in the heuristic design set generator must be expanded to include data and scaling factors for a wider range of vehicle materials and constructions, and must be further validated to ensure applicability of the broad assumptions made in the LCA models.

A preliminary **multi-criteria decision analysis** (MCDA) using the weighted sum approach has been performed on a set of 1400 vehicle designs which were culled from the over one hundred thousand vehicle designs generated by the heuristic design algorithms. The results have been analyzed, with particular emphasis on the influence that stakeholder criteria has on the attractiveness of hydrogen technologies. Feedback was received from MIT and Ford project partners, which assisted in the refining of stakeholder preferences.

Top Two Stakeholder Preferences

Stakeholder		Engine	Hybridization	Body	Fuel	Displacement (L)	Electric Power (kW)	Fuel Cell Power (kW)	Battery Energy (Ah)
Street Racer	1	Otto	Parallel	Composite BIW	Gasoline	3.1	50	0	50
	2	Diesel	Parallel	Composite BIW	Diesel	3	50	0	50
Commuter	1	Otto	Parallel	Composite BIW	Gasoline	3.1	50	0	50
	2	Diesel	Parallel	Composite BIW	Diesel	3	50	0	50
Environmentalist	1	Diesel	Series	Al UniBIW	Diesel	0	110	0	80
	2	Diesel	Series	Al UniBIW	Diesel	0	110	0	80
Manufacturer	1	Fuel Cell	Series	Composite BIW	Hydrogen	0	110	40	80
	2	Fuel Cell	Series	Composite BIW	Hydrogen	0	110	50	80
Regulator	1	Diesel	Series	Composite BIW	Diesel	0	110	0	80
	2	Diesel	Series	Composite BIW	Diesel	0	110	0	80
Average	1	Fuel Cell	Series	Al UniBIW	Hydrogen	0	110	50	80
	2	Fuel Cell	Series	Composite BIW	Hydrogen	0	110	50	80

5. Task: Dynamics of transportation technology diffusion

S. Ulli-Beer, M. Bosshardt, M. Bouza; General Energy Department, PSI

5.1 Scope of Activities

The overall research task of this sub-project is to understand and model the fundamental processes of the diffusion and competition between different drive-train technologies e.g. of hybrid, natural gas and hydrogen fuel cell vehicles. It resulted in an innovative, well tested European Vehicle Substitution Model. The model is used for comparative policy analyses under different scenarios. Strategies are derived that help to meet CO₂-reduction goals (e.g. a 50% CO₂ reduction target within the EU).

The diffusion / substitution model including preference changes in the decision function has been refined and calibrated in such a way that the development of historical market penetration of conventional drive-train technologies can be replicated (backcasting) for representative countries of the EU (finally all selected countries are separately calibrated including Germany, France, England, Italy, Spain, Poland, Sweden, and Switzerland). The model has been extensively tested including a variety of sensitivity analysis of critical and uncertain parameters.

The impact of nonlinear preference changes, and the competition between different drive-train technologies was analysed in detailed for country specific diffusion scenarios, highlighting the impact of the critical mass and the competition between different drive-train technologies on the diffusion process.

In collaboration with Christian Bodek from MIT, the System Dynamics model has been coupled with the Fleet-Model developed by Anup Bandivadekar (MIT): The coupling allowed simulating the impact on fuel consumption and CO₂-emission of different diffusion / substitution scenarios for EU-15 and EU-25. Actually, three different scenarios (Baseline, Growing Vehicle-Kilometer-Travelling, and Constant Fleet) combined with different policy experiments have been conducted for all representative EU countries, the EU-15 as well as the EU-25 case.

5.2 State of Project

The research for the European fleet dynamics modelling project has been completed in 2009. The PhD thesis of Mathias Bosshardt has been accepted by the ETHZ. The four planned peer-review articles are in the process of being submitted till End of 2009 or in 2010.

Manuel Bouza is continuing on this line of research. On October 1st 2008 he started his PhD research focusing on transformation patterns in the automobile industry. His System Dynamics simulation study investigates micro-processes of innovation in firms that influence industrial evolution at the macro-level. This research will be finished in 2011.

5.3 Main Results

The main results of the European fleet dynamics modeling project has also been abstracted in the activity report 2008. Here we would like to highlight some recommendations based on Bosshardt's modelling work. Subsequently some of Manuel Bouza's first conceptual results explaining different technology change patterns will be presented.

- Most effective policies are long term multi incentives creating favorable boundary conditions for near zero emission vehicles

Increasing the attractiveness of bridging alternative vehicle technologies and fuels (e.g. regulative measures, campaigns and marketing instruments such as labeling) may significantly reduce the promotion cost resulting from the required financial incentives. Support program should be designed as dynamical long term beneficial boundary conditions for clean and near zero emissions vehicles that need to be kept in place till near zero emission vehicles have gained enough dominance to replace the conventional petrol and diesel ICE. Also, real world experience has proven that voluntary agreements are not sufficient to supersede opposing market trends. Financial incentives also comprising fuel infrastructure investments need to be complemented with attractiveness raising incentives creating additional co-benefits and providing additional information on alternative technologies. This may not only help to change purchase behavior pattern but also voting behavior in favor of policy measures for near zero emission vehicles.

- Managing bottlenecks: rebound effects from infrastructure, improved fuel economy, early technological lock-in

First, infrastructure adjustment processes may create tradeoffs. Hybrid technologies support fuelling infrastructure and fuel availability of the conventional petrol and diesel ICE. This may slow down the market penetration of alternative fuels. Second, a bridging technology lock-in may delay the diffusion of near-zero-emission hydrogen FCVs, or near-zero-emission electric all-battery cars. Third, improved fuel economy may create a rebound effect if people tempt to drive longer distances or abstain from purchasing alternative technologies.

- Reaching critical CO₂-emission reduction targets

Game changing technologies with nearly zero emissions are required to meet critical climate change CO₂-emission reduction target for the light duty fleet.

Three determinants are critical for reaching the climate change critical CO₂-emission reduction targets. Near zero emission vehicles need to be introduced and promoted, today. The growth of the vehicle fleet as well as of the vehicle kilometers travelled need to be prevented. In pursuit of such transportation challenges, different policy domains and strategies need to be aligned that go beyond the technology considerations addressed in this work.

The fleet dynamics model would yield its highest benefit as a steadily improved and extended experimental modeling set up, corporately used by decision makers and scientists to test and refine long-term strategies, e.g. for the electrification of the light duty fleet in Switzerland. It complements least cost planning model approaches as well as engineering based technology assessment models.

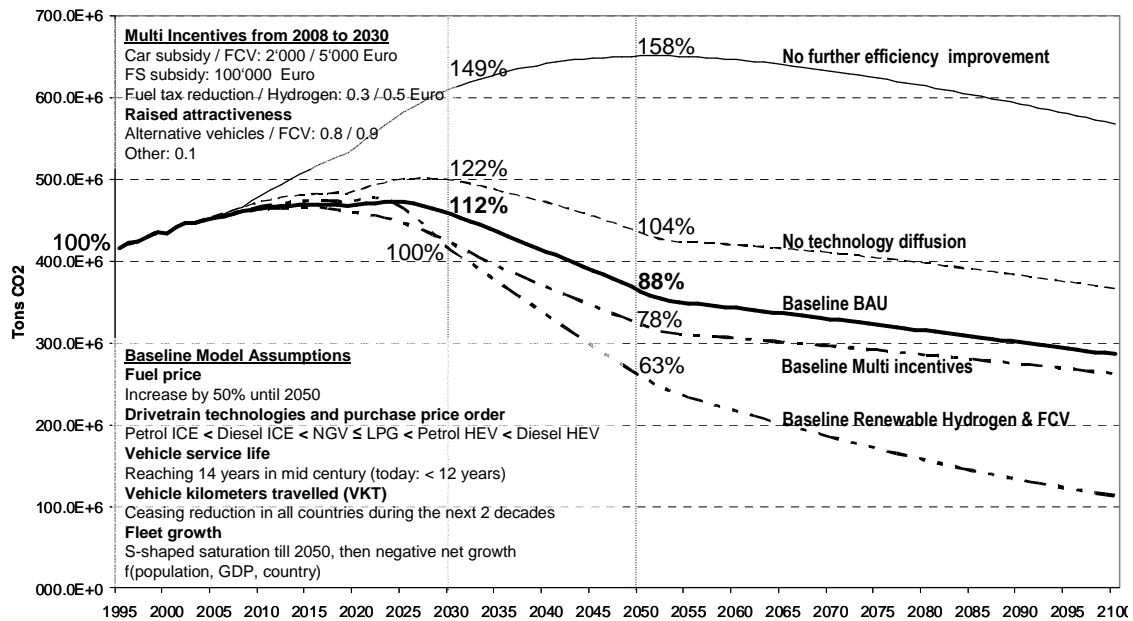
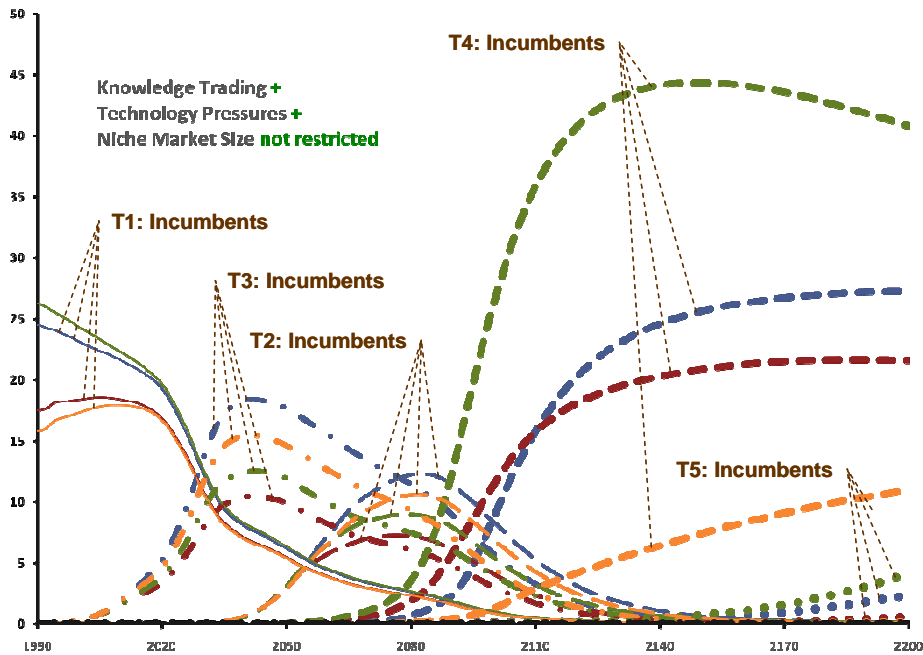


Figure 4: Comparison of CO₂-emissions savings a) from further emphasis on reducing fuel consumption of conventional drivetrains, b) from alternative technology diffusion (e.g. Hybrids, NGV) c) from Multi incentive policy packages and d) from near zero emission vehicles (e.g. renewable H₂ FCVs).

Manuel Bouza extends Bosshardt's work (demand side focus) and investigates the anticipated technological change in the automobile industry at a micro level including firms R&D investment and knowledge trading behavior (supply focus). His work contributes to the development of industry policies supporting an efficient transition towards a sustainable propulsion technology. Established industries develop and mature along continuous trajectories defined by the underlying technological paradigm relevant to serve the value network of the industry. Technological discontinuities and/or preference shifts at the higher levels of the value network may trigger a technological transformation in the industry. The factors discussed in the literature characterizing a technological change and its impact on the industry mainly are: 1. organizational inertia (path dependence) 2. pressures on the current socio-technical regime 3. maturity of the new technology and 4. knowledge trading and spillovers. In his conceptual work phase, Bouza describes three different industrial technological transformation processes, namely the Radical, Disruptive and Endogenous Transformations. The Radical and Disruptive Transformation processes have been previously described in the literature and he postulates a third transformation process, which he calls Endogenous Transformation. In an Endogenous Transformation, a new technology is developed in a joint effort by most organizations in the industry to substitute the old technology, which is no longer suitable to serve the value network of the future. Using industrial dynamics theory and data from qualitative interviews, he has developed a system dynamics model to further analyze the conditions under which a technological change in an industry follows one of the three mentioned transformation processes. Applying scenario analysis he finds that industry structures (e.g. market preferences and sizes), industry business practices (e.g. knowledge sharing) as well as overlying social and regulatory forces (e.g. technology pressures) significantly influence how the transformation will unfold.

Result 1: Endogenous Transformation



Result 2 : Disruptive Transformation

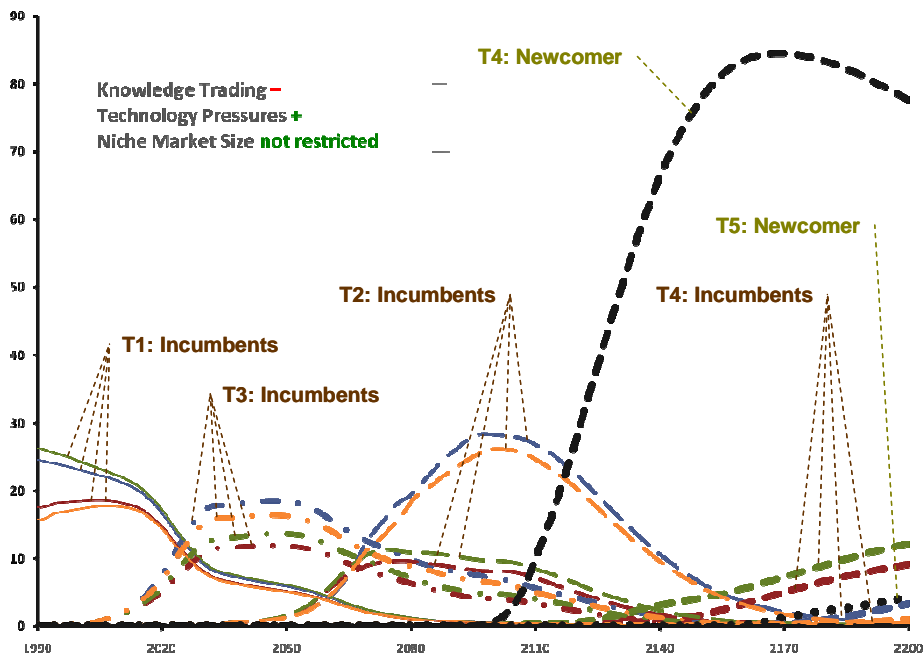


Figure 6: Illustrative conceptual scenarios of technology change highlighting the impact on market position of incumbents and newcomers. Knowledge trading and technology pressure leads to an endogenous technology change where incumbents keep their dominant market positions (Result 1). Without knowledge trading a disruptive technology change may occur where a newcomer may become the new market leader (Result 2).

6. Task: Energy-economic modelling of hydrogen-related issues

Hal Turton, Martin Densing, Socrates Kypreos, Timur Gül
Energy Economics Group. Laboratory for Energy Systems Analysis (LEA), PSI

6.1 Status of Project and Main Results

The sub-project “energy-economic modelling of hydrogen-related issues” was completed mid-2008, culminating in the PhD dissertation of Timur Gül (Gül 2008). Results of this work are published in the journal *Energy* (Gül *et al.* 2009), and it is expected that further results will soon be accepted for publication in *Energy Policy* (Gül *et al.* 2008). In addition, results of the analysis were presented at the 1st International Conference on Mobility and Energy in Vienna / Austria. In 2009, some of the work from the sub-project is being used as the basis of a chapter in the book *Transition to Hydrogen 2050: Roadmap to Clean Transportation* (Gül *et al.* 2010 (in Wokaun *et al.* 2010)). This work, together with other research in the Energy Economics Group (EEG) at PSI, has led to a new project collaboration with a major automobile manufacturing to analyse some further aspects of a transition to alternative technologies and fuels.

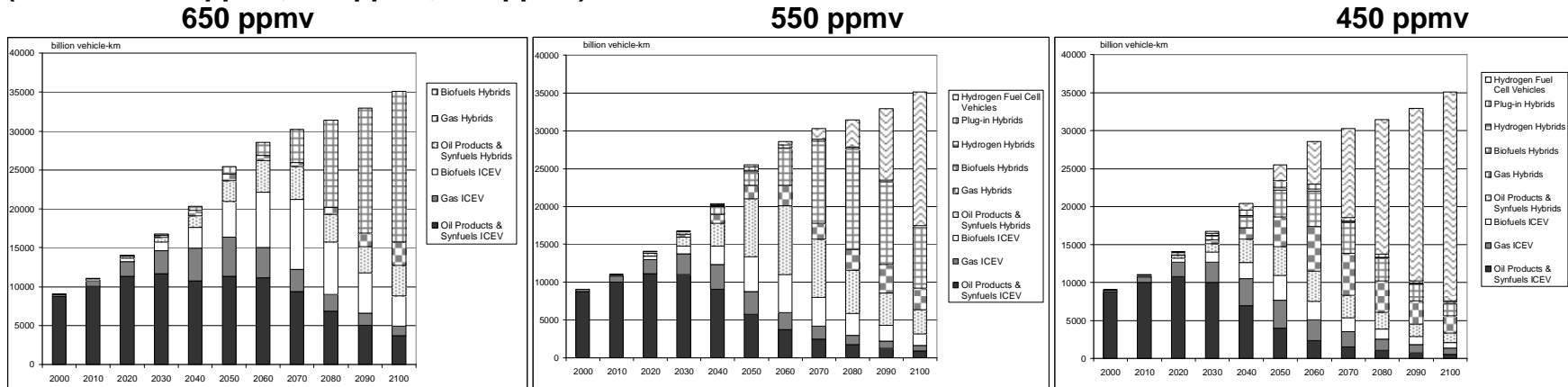
As a consequence of the end of the subproject in 2008, there are no major additional research findings to report for 2009. However, some supplementary analysis was conducted to explore the conditions under which battery electric vehicles could compete more vigorously with hydrogen fuel cell vehicles, and the results of this exercise indicate that battery costs would need to reach \$100/kWh or lower to make a substantial impact over the long term. Ongoing and future work of the group is expected to address this question more concretely.

6.2 Additional Activities

Although the sub-project “energy-economic modelling of hydrogen-related issues” was completed mid-2008, the EEG has continued some activities to support further analyses of the competitiveness of hydrogen against other fuel options, in particular electric vehicles and biofuels, in personal transport. This is being pursued through further development of the Global Multi-regional MARKAL model (GMM). GMM is a perfect foresight, bottom-up cost-optimization tool for assessing the competitiveness of energy technologies and the efficacy of policies. GMM incorporates a high level of technological detail with regard to hydrogen and biofuels production technologies as well as an elaborated hydrogen delivery infrastructure. In addition, the model includes detailed vehicle technologies options for a range of fuel options. Many of these features were developed as part of the sub-project that was finalized in 2008, and the activities in 2009 have focussed on maintenance and refinement of a number of features of the model, along with some ongoing additional analysis. Of particular note is work with GMM to delineate the car market into groups of consumers based on their willingness to accept vehicle options suitable for short-range travel only; introduction of shorter-range vehicle technologies; re-specification of some technology options based on new data; and inclusion of additional alternative fuel production technologies. It is hoped that this will provide additional insights about the conditions under which hydrogen is an attractive fuel for transportation, and a better assessment of alternatives in the transport sector.

Figure 5:

**Development of personal transport across scenarios different climate change mitigation scenarios
(from left: 650 ppmv, 550 ppmv, 450 ppmv)**



7. Publications

Publications 2009

Wilhelm, E., Schenler, W.W., (2009). Heuristics for the Design of Advanced Powertrains: Strategies for Manufacturers. Proceedings of the International Advanced Mobility Forum (IAMF), March 10-12th 2009, Geneva, Switzerland.

Wilhelm, E., Schenler, W.W. (2009) Heuristic Design of Advanced Drives: Analysis of Trade-offs in Powertrain Electrification. Electric Vehicle Symposium 23 (EVS 23), 13-16th May, 2009, Stavanger, Norway. Invited Proceedings: WEVA Journal, Special Edition

Gül T., Kypreos S., Turton H., and Barreto, L. (2009): An energy-economic scenario analysis of alternative fuels for transport using the Global Multi-regional MARKAL model. Energy 43, 1423-1437, doi:10.1016/j.energy.2009.04.010.

Gül T., Turton, H. (2009): Illustrating perspectives of energy and mobility. PSI Report 09-08. Paul Scherrer Institute, Switzerland.

Ulli-Beer, S., M. Bosshardt, P. Dietrich, A. Wokaun (2009a).
"What alternative drive-train technologies and policies are needed to meet a 50% CO2 reduction target?" In S. Das (Ed.), "Sustainable Mobility Applications for Engineering". SAE International, Detroit, Michigan, USA. ISBN: 978-0-7680-2154-7.

Ulli-Beer, S., M. Bosshardt, P. Dietrich, A. Wokaun (2009b).
"What alternative drive-train technologies and policies are needed to meet a 50% CO2 reduction target? The case of the EU-fleet" DN: 2009-01-0319.
SAE World Congress "Racing to Green Mobility". Sustainable GHG Emission. Detroit MI USA, April 2009.

Ulli-Beer S., F. Gassmann and A. Wokaun (2009 in press).
"Generic Structure to Simulate Acceptance Dynamics".
System Dynamics Review. Vol. zz, [p. xx \(bitte beim "Gut zum Druck" bei S. Ulli nachfragen\)](#)

Bouza, M. S. Ulli-Beer, P. Dietrich, A. Wokaun (2009)
"Comparison of possible transformation processes in the automobile industry".
Proceedings of the 9th Swiss Transportation Research Conference, September 9. – 11. 2009, Monte Verità, Ascona TI, [p. 26](#)

Bouza, M. S. Ulli-Beer, P. Dietrich, A. Wokaun (2009)
"Endogenous transformation in the automobile industry."
Proceedings of the 27th International Conference of the System Dynamics Society, July 26 - 30, 2009, Albuquerque, New Mexico, USA. [p. 11](#)

Ulli-Beer S., F. Gassmann and A. Wokaun (2010 in press).
"Generic Structure to Simulate Acceptance Dynamics".
System Dynamics Review. Vol. zz, [p. xx \(bitte beim "Gut zum Druck" bei S. Ulli nachfragen, ob schon bekannt\)](#)

Publications planned for 2010

Ulli-Beer S., B. Kasemir, S. Lienin, A. Wokaun (submitted): How can regions develop robust technology change strategies towards sustainable road transportation? A case analysis of the novatlantis pilot region Basel in Switzerland. Technovation.

Bosshardt M., Ulli-Beer S., Gassmann F. and Wokaun A. (submitted): Tipping point and technological lock-in: Effects from a social behavioural norm building process. Technological Forecasting and Social Change.

Wilhelm, E., Schenler, W.W., (2010 forthcoming). Climate Health and Passenger Safety: Trade-offs in Reducing Heavy Vehicle Weight. International Journal of Vehicle Design. IN PROGRESS-

Wilhelm, E., Schenler, W.W., (2010 forthcoming). Review of software tools for powertrain modeling. SAE International. IN PROGRESS-

Gül, T., Turton, H., Kypreos, S. Barreto, L. (2010): Long-term Scenarios of the Global Energy and Transport System
In Wilhelm, E., Wokaun, A. (eds.). Transition to Hydrogen 2050: Roadmap to Clean Transportation. Cambridge University Press, UK (approved by publisher).

Wilhelm, E., Wokaun, A. (eds.). Transition to Hydrogen 2050: Roadmap to Clean Transportation. Cambridge University Press, UK (approved by publisher).

Gül T., Kypreos S., Turton H., L. Barreto (submitted): A modelling analysis of cost-effective technology choices for reducing CO₂ emissions in European transport.

M.K. Vollmer et al. Molecular hydrogen (H₂) emissions and their isotopic signatures (H/D) from a motor vehicle: Implications on atmospheric H₂ (submitted).

S.W. Bond et al., H₂ emissions from current gasoline and diesel vehicles.

S.W. Bond et al., Atmospheric molecular hydrogen mixing ratios in the free troposphere derived from continuous observations at the high-Alpine site Jungfraujoch.

S.W. Bond et al., Potential atmospheric impacts from hydrogen losses to the atmosphere from various production, distribution, storage, and end-use systems.

S.W. Bond et al. Anthropogenic H₂ emissions to the atmosphere (book chapter).

8. Oral Presentations

Oral Presentations 2009

Bond, S. W., H₂ in the atmosphere – an integration from the exhaust pipe to a remote alpine site, 20 April 2009, Vienna, Austria.

Bond, S. W., Hydrogen in the Atmosphere – Direct and Remote H₂ Measurements – Recent Results from Empa, EuroHydros 3rd annual meeting, 3/4 June 2009, Helsinki, Finland.

Steinbacher, M., EuroHydros Workpackage 4 - Calibration, quality assurance and data management, EuroHydros 3rd annual meeting, 3/4 June 2009, Helsinki, Finland.

Vollmer, M.K., Santa's view on hydrogen: H₂ emissions from residential combustion systems, EuroHydros 3rd annual meeting, 3/4 June 2009, Helsinki, Finland.

Vollmer, M.K., Anthropogenic sources of atmospheric molecular hydrogen (H₂): Deliverable 2.4 of project, EuroHydros 3rd annual meeting, 3/4 June 2009, Helsinki, Finland.

Bond, S. W., Anthropogenic H₂ Emissions to the Atmosphere, 22/23 October 2009, MIT, Cambridge, MA, USA.

Wilhelm, E., Schenler, W., (2009). Heuristic Design of Hybrid Vehicles. Talk at the MIT-PSI Workshop "Before a Transition to Hydrogen Transportation", October 21-22, 2009; MIT Cambridge MA, USA
Wilhelm, E., (2009). Heuristic Design of Hybrid Vehicles. LEA Seminar, Paul Scherrer Institute, August 26th, 2009

Wilhelm, E. "Analysis of Technology Trade-offs using Heuristic Vehicle Design" NES PhD Day, June 16th, 2009, PSI, Villigen, Switzerland

Wilhelm, E., Schenler, W. "Losing Weight to Save Energy: How Advanced Materials Could Affect Tomorrow's Vehicle Fleet" EMPA PhD Symposium, November 19th, 2009, EMPA, Dübendorf, Switzerland

Ulli-Beer, S.; M. Bosshardt, P. Dietrich, A. Wokaun (2009)
"Wie können wir in ferner Zukunft wieder mit gutem Gewissen Auto fahren?" Talk.
Auto Basel, September 18. 2009, Basel

Ulli-Beer, S., M. Bosshardt, P. Dietrich, A. Wokaun (2009)
"How do country specific boundary conditions affect the diffusion of alternative drive train technologies in the EU?" Presentation at the International advanced mobility forum, March 10. – 12. 2009, PalExpo, Geneva

Ulli-Beer, S., Bosshardt, M., Dietrich, P., & Wokaun, A. 2009b.
"What alternative drive-train technologies and policies are needed to meet a 50% CO₂ reduction target? The case of the EU-fleet". Presentation at the SAE World Congress "Racing to Green Mobility". Sustainable GHG Emission. Detroit MI USA, April 2009.

M. Bouza, S. Ulli-Beer, A. Wokaun (2009).
Technological Transformation Patterns. Talk.
MIT-PSI Workshop AGS. October 21 – 22, 2009, MIT Boston, USA.

Bouza, M. S. Ulli-Beer, P. Dietrich, A. Wokaun (2009)
"Comparison of possible transformation processes in the automobile industry".
Talk at the 9th Swiss Transportation Research Conference, September 9. – 11. 2009, Monte Verità, Ascona TI

Gül T., Turton, H. (2009): Illustrating perspectives of energy and mobility. Presentation and Paper at the International Advanced Mobility Forum, 10-12 March 2009, Geneva, Switzerland.