Roads2HyCom
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DELIVERABLE 6.1-2 PART A

FEED-BACK AND FEED-FORWARD FROM WP4/5 AND DEMONSTRATION ACTIVITIES – TRANSPORT

REVIEW OF TECHNICAL, SOCIO-ECOMONIC AND SAFETY FINDINGS FROM FUEL CELL VEHICLE DEMONSTRATION ACTIVITIES

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The European Commission is supporting the Coordination Action "HyLights" and the Integrated Project "Roads2HyCom" in the field of Hydrogen and Fuel Cells. The two projects support the Commission in the monitoring and coordination of ongoing activities of the HFP, and provide input to the HFP for the planning and preparation of future research and demonstration activities within an integrated EU strategy.

The two projects are complementary and are working in close coordination. HyLights focuses on the preparation of the large scale demonstration for transport applications, while Roads2HyCom focuses on identifying opportunities for research activities relative to the needs of industrial stakeholders and Hydrogen Communities that could contribute to the early adoption of hydrogen as a universal energy vector.

Further information on the projects and their partners is available on the project web-sites www.roads2hy.com and www.hylights.org

REVIEW OF TECHNICAL, SOCIO-ECOMONIC AND SAFETY FINDINGS FROM FUEL CELL VEHICLE DEMONSTRATION ACTIVITIES

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Executive Summary

The overall objective of this report was to process current fuel cell vehicle demonstration activities regarding their technical, socio-economic and safety findings. For this purpose the major fuel cell passenger vehicle and bus demonstration projects in Europe, Japan and the USA were assessed.

The results of these projects are impressive. Each fleet application has successfully proven the technical reliability in demanding day-to-day conditions of both private and public transport. The lifetime and availability of the fuel cell fleets exceeded initial expectations and led to several prolongations of the demonstration activities. Further developments during the demonstration phase led to significant improvements of the vehicle reliability. These results underline that not “breakthrough inventions” but continuous evolutionary developments are required to commercialize fuel cell vehicles.

In general the availability of the refuelling infrastructure was high, although a couple of problems with the compressor technology, hydrogen contaminations and the refuelling interface itself were experienced. It is hard to find evidence of a broad scale or major financial or technical commitment by refuelling technology manufactures to develop new and more reliable refuelling technology, while making current technology more reliable. This is a gap in the global work program that must be filled if a hydrogen based transport energy system is to develop.

Fleet operators provided a very positive response regarding the daily-use of the vehicles, however there is still need for further education and training to achieve full customer acceptance. Range is still perceived as the most critical issue of fuel cell passenger vehicles but acceptable range can be achieved with the use of 70 MPa storage technology.

Strong vehicle safety records show no fundamental problems with fuel cell vehicles.

This report forms part of the Roads2HyCom Deliverable 6.1-2. A companion report containing a review of stationary fuel cell demonstration activity is also available to download from www.roads2hy.com (Document Reference R2H6033PU).

1. Introduction

Roads2HyCom (R2H) is a project to assess and monitor Hydrogen and Fuel Cell technologies for stationary and mobile energy application against current and future infrastructures, and the needs of communities which may be early adopters of the technology, in order to support the Commission and stakeholders in planning future activities. Further information about the project can be found on the project website www.roads2hy.com.

The objective of Work Task 6.1.2 is to process demonstration activities for transport and stationary applications in terms of technical, socio-economic and safety findings. This report presents a review of demonstration activities for transport applications. The results from processing stationary demonstration activities are covered in a separate report (R2H6033PU), which is also available to download from the project website www.roads2hy.com.

In regards to the transport sector, major demonstration projects in Europe, Japan and USA have been selected. Due to the fact that the amount of publicly available data for transport applications is very limited, the findings and lessons learned are more or less exclusively based on DaimlerChrysler's fuel cell demonstration experiences, being one of the major stakeholders in each of the assessed projects.

The findings of Work Task 6.1.2 will then be fed forward to WP4 and WP6.2 Collation of experiences with hydrogen demonstration projects, in order to identify gaps and to build up the methodology.

2. Profile Fuel Cell Projects

The following major fuel cell demonstration projects in Europe, Japan und US have been investigated: Clean Energy Partnership (CEP), Controlled Hydrogen Fleet and Infrastructure Demonstration and Validation Project, Japan Hydrogen & Fuel Cell Demonstration Project (JHFC), Singapore Initiative in Energy Technology, Zero Regio, Clean Urban Transport for Europe (CUTE) and HyFleet: CUTE.

2.1 Clean Energy Partnership (CEP)

Duration: 01-Oct-2002 – 31-Dec-2007

Venue: Berlin (GERMANY)

Scope: 17 vehicles (10 FCV's of DaimlerChrysler) and 2 fuelling stations

Partners: Aral, BMW, Berliner Verkehrsbetriebe (BVG), DaimlerChrysler, Ford, GM/Opel, Hydro, Linde, TOTAL, Vattenfall Europe and Volkswagen

Description:

The overall goal is to tap the technological potential of hydrogen as an energy carrier for transport applications, conducting tests with a view to suitability for routine use and system capability.

The Berlin hydrogen demonstration project consists of the hydrogen infrastructure of two hydrogen filling stations, the vehicle fleet, a hydrogen information centre and a service station for hydrogen vehicles. CEP is working with a total of three different hydrogen production methods as well as two different hydrogen propulsion systems.

In 2004 CEP started with the operation of a fully integrated hydrogen filling station at the Berlin Messedamm. At the Aral station gaseous hydrogen is produced on site via electrolysis and stored in compressed form, while super-cooled liquid hydrogen is delivered by truck and stored in a cryogenic tank. The hydrogen is used by vehicles with modified internal combustion engines and by fuel cell vehicles.

In March 2006 TOTAL has opened the second CEP hydrogen filling station in Berlin-Spandau. The hydrogen station has been integrated into a new conventional filling station and supplies gaseous und liquid hydrogen for buses and cars.

2.2 Controlled Hydrogen Fleet and Infrastructure Demonstration and Validation Project

Duration: 2003 –2009

Venue: California, Michigan, Florida (USA)

Figures: 59 vehicles (30 FCV's of DaimlerChrysler) and 9 refueling stations

Partners: Chevron, Hyundai-Kia, UTC Fuel Cells, DaimlerChrysler, BP, Ford, General Motors, Shell

Description:

Initiated in 2003, DOE's Controlled Hydrogen Fleet and Infrastructure Demonstration and Validation Project is the largest project of its type in the world. The scope of the project is to validate fuel cell vehicles and the supporting refuelling infrastructure in parallel under real-world conditions. Some objectives of the project include identifying the current status of the technologies and their evolution during the project, assessing progress toward technology readiness, and providing feedback to hydrogen research and development activities. The project covers multiple geographic locations and climates and a variety of sources of hydrogen, including renewables.

2.3 Japan Hydrogen & Fuel Cell Demonstration Project (JHFC)

Duration: March 2003 – March 2005 (JHFC-1)
March 2005 – March 2010 (JHFC-2)

Venue: Tokyo, Nagoya (JAPAN)

Scope: 59 vehicles (7 FCV's of DaimlerChrysler) and 12 fuelling stations

Partners: Toyota Motor Corporation, Nissan Motor Co. Ltd, Honda Motor Co. Ltd., DaimlerChrysler Japan Ltd., General Motors Asia Pacific Japan Ltd., Hino Motors Ltd., Mitsubishi Motors Corporation, Suzuki Motor Corporation, Nippon Oil Corporation, Cosmo Oil Co. Ltd., Showa Shell Sekiyu K.K., Iwatani International Corporation, Tokyo Gas Co. Ltd., Nippon Sanso Corporation, Japan Air Gases Ltd., Nippon Steel Corporation, Kurita Water Industries Ltd., Sinanen Co. Ltd., Itochu Enex. Co. Ltd., Idemitsu Kosan Co. Ltd., Babcock-Hitachi K.K., Tsurumi Soda Co. Ltd., Toho Gas Co. Ltd.

Description:

The Japan Hydrogen and Fuel Cell Demonstration project consists of a Fuel Cell Demonstration Program and a Demonstration Study of Hydrogen Fuelling Facilities for FCVs. Both studies are among the polymer electrolyte fuel cell (PEFC) research projects subsidized by the Ministry of Economy, Trade and Industry (METI).

Goals:

- Determination of energy saving effects (CO_2 emissions reduction and efficiency) achieved by FCVs and hydrogen stations
- Determination of environmental (non-CO_2) load reduction effects achieved by FCVs and hydrogen stations
- Data acquisition for preparing specifications, regulations and standards concerning the safety of FCVs and hydrogen stations
- Activities for familiarizing the general public with FCVs and hydrogen station
- Solving of problems involved in the dissemination of FCVs and hydrogen stations
- Efficient recovery of hydrogen from by-product gases, and development and verification of an efficient liquefaction technique

2.4 Singapore Initiative in Energy Technology (SINERGY)

Duration:	30-May-2001 – 29-Feb-2008
Venue:	Singapore (SINGAPORE)
Scope:	6 FCV's of DaimlerChrysler and 2 fuelling station
Partners:	BP, DaimlerChrysler, EDB

Description:

The Singapore Initiative in Energy Technology or SINERGY was launched on 30 May 2001. It is a program of the Economic Development Board (EDB) of Singapore to encourage investment by companies in alternative energy technologies. It provides a framework by which companies together with the government work hand-in-hand in developing solutions and testing of clean alternative energy and renewable energy technologies. It is a way to create opportunities for industry partnerships in innovative projects.

The mobility partner of the SINERGY-Project is DaimlerChrysler, providing a total of 6 F-Cell vehicles, whereas BP as the infrastructure partner implements two hydrogen filling stations.

2.5 Zero Regio

Duration:	Nov-2004 – Nov-2009
Venue:	Frankfurt (Germany) and Lombardia (Italia)
Scope:	8 vehicles (5 FCV's of DaimlerChrysler) and 2 fuelling stations
Partners:	Infraserv GmbH & Co., Linde Gas & Engineering AG, DaimlerChrysler AG, Fraport AG, TÜV Hessen GmbH, Agip Deutchland GmbH, Lund University, Roskilde University, Saviko Consultants Ltd., European Commission, Eni S.p.a., Regione Lombardia, Sapio, Comune di Mantova, Universita commerciale Luigi Bocconi, Centro Ricerche Fiat

Description:

Zero Regio is an integrated project funded by the European Commission in the 6th framework programme.

The project consists of construction and demonstration of hydrogen infrastructure in two European regions for supplying fuel cell passenger cars. The project aims at developing and demonstrating zero emission road transport systems in normal daily use for the European cities. Total execution period for this important EU project is 5 years.

At the industry park Hoechst a large hydrogen source (30 Mm3/y) is available as a bi-product of a chemical plant. This has been used for thermal conversion so far. This source will be connected via a 2 km long transport line to a public service station for supplying hydrogen, similar to gasoline and Diesel. The service station will supply liquid hydrogen at -253°C as well as compressed hydrogen gas. For gas refuelling a 350 bar and a 700 bar dispenser will be employed. Five DaimlerChrysler "F-Cell" fuel cell vehicles will be demonstrated at the Frankfurt Airport.

In Lombardia hydrogen will be available from a central production facility as well as from an 'On-Site' reformer facility developed within the project. The reformer will produce hydrogen from natural gas at the service station. A dispenser unit for hydrogen gas at 300 bar will be built and integrated in the public multi-fuel service station to be built within the project. Three fuel cell vehicles from Fiat will be tested at the site.

The demonstration phase (3 years) of the project will be accompanied by an evaluation of the data acquired during the fleet tests with respect to energy efficiency, environmental impact and socio-economic aspects.

2.6 Clean Urban Transport for Europe (CUTE)

Duration: Nov-2001 – May-2006

Venue: Amsterdam, Barcelona, Hamburg, London, Luxembourg, Madrid, Porto, Stockholm, Stuttgart

Scope: 27 Citaro Fuel Cell Buses

Partners: European Commission, City Partners, Industrial Partners, Academic and Consulting Partners, Associated Projects.

Description:

The **C**lean **U**rban **T**ransport for **E**urope (CUTE) was a European Union project which saw the development and testing of 27 Citaro fuel cell buses - three in each of nine cities in Europe. The aim of the project was to demonstrate the feasibility of an innovative, clean urban public transport system. Different hydrogen production and refuelling infrastructures were established in each of the cities. The project saw practical applications of renewable energy sources to the transport system.

The project greatly improved public acceptance of the H_2 fuel cell transport system, and contributed to the development of a more secure energy supply for the EU. It has also contributed to strengthening the competitiveness of EU industry, leading to the creation of new jobs and, in the future, greatly contributing to the Kyoto commitments of the Member States.

In parallel 3 buses were demonstrated for two years in the EC funded project ECTOS in Reykjavik, Iceland.

2.7 Hydrogen for Clean Urban Transport in Europe (HyFLEET:CUTE)

Duration: 2006 – 2009

Venue: Amsterdam, Barcelona, Beijing, Berlin, Hamburg, London, Luxembourg, Madrid, Perth, Reykjavik

Scope: 47 Hydrogen powered buses

Partners: European Commission, City Partners, Industrial Partners, Academic and Consulting Partners, Associated Projects.

Description:

HyFLEET:CUTE sees the operation of 47 Hydrogen powered buses in regular public transport service in 10 cities on three continents. The project brings together 31 partners from industry, Government, academic and consulting organisations. Some of the worlds' leading automotive and technology development companies, major energy companies, policy developers and transport operators are collaborating to lead Europe into the development of the Twenty second Century hydrogen-based transport system of the future.

HyFLEET:CUTE has been established under and is financially supported by the European Commission's 6th Framework Research Programme. The European Union's Energy Policy aims at enhancing energy security through further diversification of energy sources diversifying and security energy sources while reducing CO_2 and other emissions harmful to the environment and human health. Hydrogen is a key element in this future strategy for road transport.

3. Results & Lessons Learned

More than 200 hydrogen fuel cell vehicles are currently running on public roads mainly in Europe, Japan and USA. The majority of them is in regular fleet operation and has accumulated a vast amount of mileage and operating hours.

3.1 Fuel Cell Passenger Vehicle Projects

DaimlerChrysler launched its Global F-Cell Program by introducing the first F-Cell vehicles in Japan by end of 2003 within the scope of the JHFC-Program. Throughout 2004 the remaining F-Cells and two Sprinters were delivered to the U.S. (DoE-Program), Europe (CEP) and Singapore (SINERGY).

Technical data from the vehicle and the fuel cell system are recorded with an onboard fleet data acquisition system (FDA) while the vehicles are in operation providing the basis for an in-depth analysis of the vehicle performance. This experience is a valuable input for the development of successive fuel cell vehicles.

3.1.1 Distance travelled / operating hours

By end of February 2007, all 60 F-Cell vehicles had travelled a distance of more than 1.2 million kilometres and had been operated for more than 34,000 hours. The total aggregate kilometres driven and hours operated successfully demonstrate the durability and reliability in demanding day-to-day conditions of private transport. In January 2007 the first F-Cell vehicle achieved more than 100,000 kilometres and 2000 hours without showing significant performance losses. In the meantime several vehicles have accumulated more than 1,000 hours of operation without showing any major degradation effects of the fuel cell stack.

3.1.2 Availability

The overall availability is defined as the amount of time when the F-Cell vehicle was fully operational as a percentage. The availability was surprisingly high, with a worldwide average of 85.5% (see Figure 1).

The highest availability has been experienced in Singapore, where the climate might have a positive impact on the durability, whereas in Germany the lowest availability of 84% has been experienced.

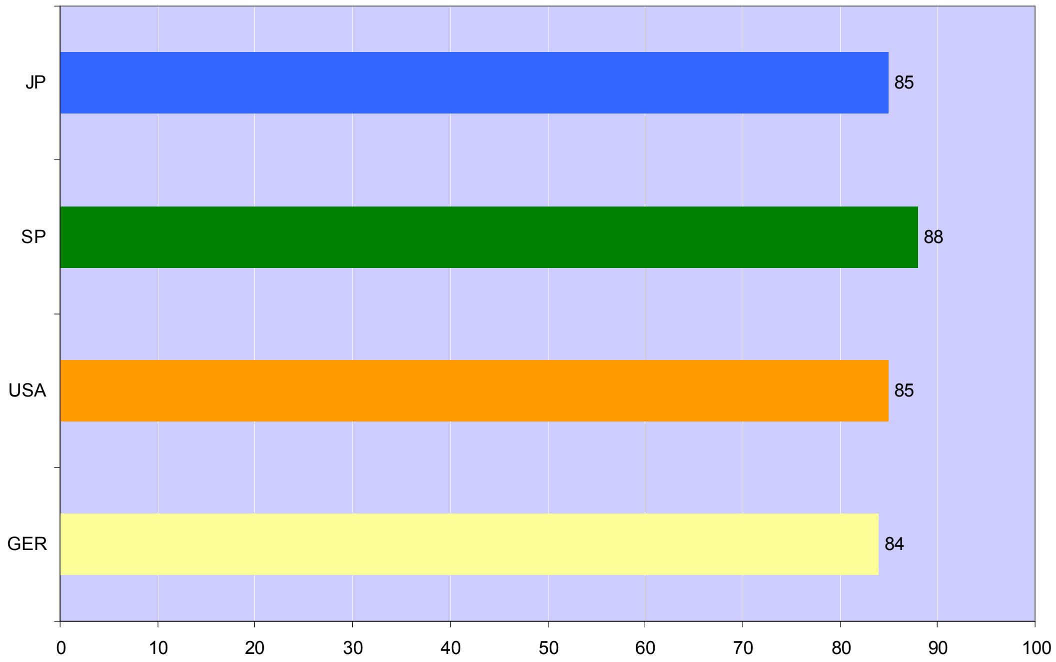

Figure 1: Worldwide F-Cell Vehicle Availability

3.1.3 Failure frequency

The failure frequency describes the number of failures per 1000 km of vehicle operation. During the first year of DaimlerChrysler's Global F-Cell Program in 2004 an average of 3.3 failures per 1000 km of operation was experienced. In 2005 the failure frequencies has been constantly lowered to an average value of 1.3 failures and in 2006 an average frequency of 0.9 failures per 1000 km has been achieved. Currently 0.25 failures per 1000 km are experienced, which means that on average every 4000 km only one single failure occurs. The main influence for this improvement was the continuous implementation of improved vehicle software (see Figure 2).

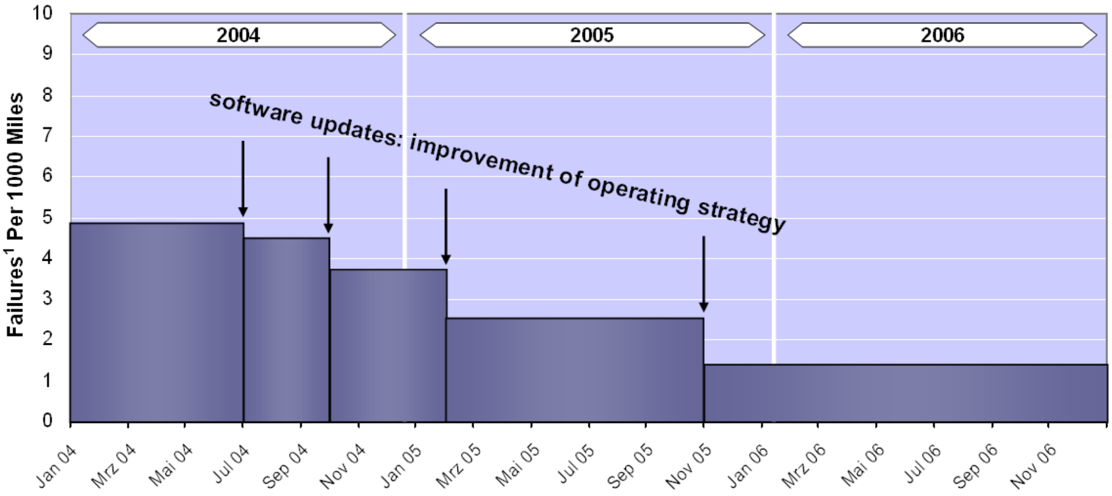

Figure 2: Software updates of the F-Cell

[1] The failure types can be divided into three groups: "Minor issues", such as an empty windshield wiper tank reflected by 26%, "Quit on road", for example due to a sensor failure reflected by 28%, and "Limited operation", which means a fuel cell power reduction, caused for example by too hot system operation or a low cell occurrence reflected by 46%.

3.1.4 Climate conditions

Furthermore the FDA records the ambient climate conditions (temperature, humidity, ambient pressure). The records of the "F-Cell" fleet show a wide range of environmental temperature during vehicle operation (Figure 3).

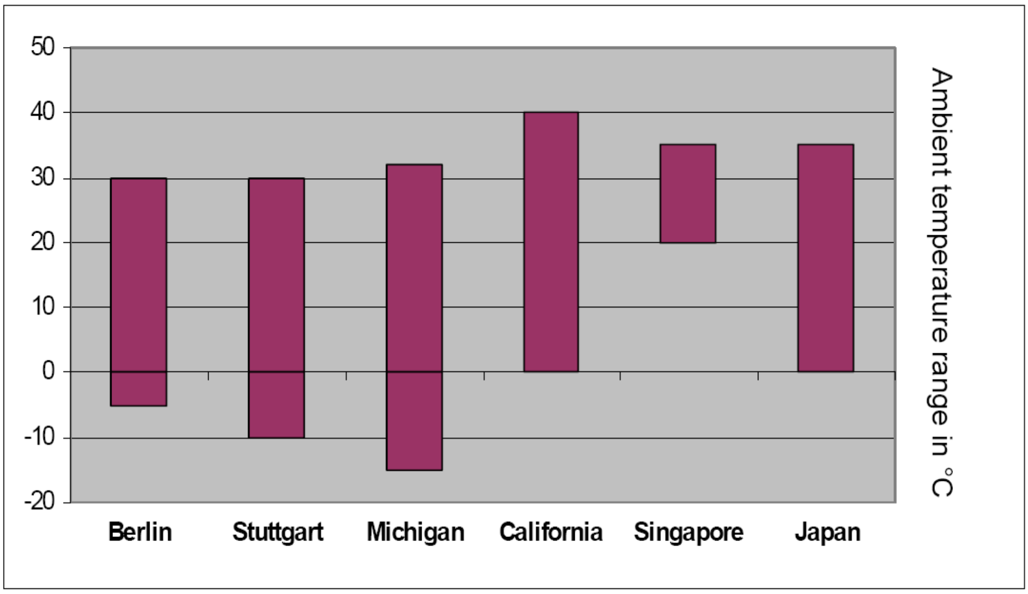

Figure 3: Ambient temperature ranges during F-Cell operation

Especially interesting is the analysis of the part of the fleet which is operated in subzero temperatures to monitor the performance of the "F-Cells". Other extremes are marked with the operation of the "F-Cell" in Singapore with maximum temperatures up to 36°C and a relative humidity of up to 90% or in California with maximum temperatures of up to 40°C. Up to now there is no indication for correlation between climate conditions and vehicle availability and lifetime.

Additionally "F-Cell" vehicles are in operation in different geographical regions and under different driving patterns. These patterns range from municipal operation to inter-urban driving behaviour, from reserved to aggressive driving, from speedy to rather slow operation and from flat to mountainous areas.

3.1.5 Fuel consumption

The comparison of fuel economy between a fuel cell powered F-Cell vehicle and a comparable diesel powered A-Class vehicle underlines the TTW-efficiency advantage of the fuel cell power train. The F-Cell has a 33% better fuel economy, measured in the New European Driving Cycle (NEDC), than the comparable diesel powered A-Class (see Table 1).

Table 1: Fuel Economy of F-Cell vehicle and comparable diesel powered A-Class vehicle in the New European Driving Cycle

Vehicle	Fuel Consumption New European Driving Cycle (NEDC)
F-Cell, A-Class 65kW	128 MJ / 100 km or 3,6l Diesel equivalent / 100km
A-160 CDI, A-Class 55kW	172 MJ / 100 km or 4,8l Diesel equivalent / 100km

The following figure shows the average fuel economy and average vehicle speed of the F-Cell vehicle during real fleet operation in Singapore. There are two vehicles, FC-31 and FC-45, which are quite close (3.8-4.0 l DE/100km) to the fuel economy measured in the driving cycle whereas three F-Cells have an up to 66% worse fuel economy (5.9-6.0 l DE/100km). The reason for this is quite obvious when you look at the average vehicle speed of those F-Cells. Those three F-Cells have been operated at an average speed between 26-28 km/h whereas the other two F-Cell vehicles reached average speeds between 40-42 km/h. These low average speeds were caused by frequent stop-start situations.

The average speed of a vehicle reflects very well the traffic conditions, mode of applications and of course the individual driving pattern of the operator which is, not surprisingly, similar with conventional combustion engines. In mega cities like Tokyo with average speeds of 15-20 km/h it is common that 50% of the journey time the vehicle is idling. Hence the fuel consumption in such cities can be easily reduced by implementing a start-stop function into the vehicle, which is of course not limited to Fuel-Cell vehicles only.

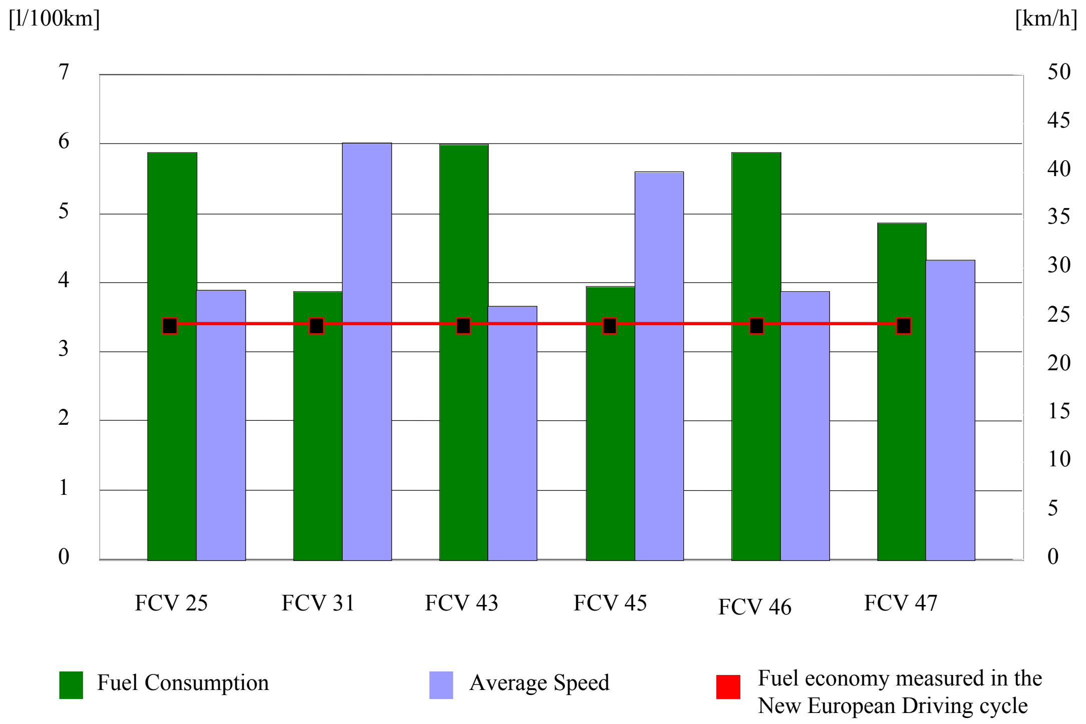

Figure 4: Fuel Economy and Average Vehicle Speed of the F-Cell in Litre Diesel Equivalent / 100km during real operation in Singapore.

3.1.6 Safety incidents

Strong vehicle safety record shows no fundamental safety problems with the vehicles. There have been minor incidents e.g. false alarms of a hydrogen sensor, which were reasoned by a shifting sensor signal.

3.1.7 Customer Acceptance

Among the customers of “F-Cell” vehicles DaimlerChrysler has performed surveys on customer acceptance and perception. The purpose of these activities was to:

- Understand driver’s perception, attitudes and usage of fuel cell vehicles
- Investigate potential consumer market risks and chances for fuel cell vehicles
- Develop proposals to assist the design of pilot projects and related communication activities

Interviews were conducted with “F-Cell” partner organizations in the United States, Germany and Singapore consisting of governmental organizations, and profit and non-profit entities. Participants from different levels within the organization and with different amounts of alternative fuel requirements (from none to significant) were mixed.

In general the feedback was very positive. Respondents told the “F-Cell” was easy to use and they did not require much time to learn how to operate the vehicle. Both vehicle and refuelling experiences were positively assessed (see Figure 5 to Figure 8).

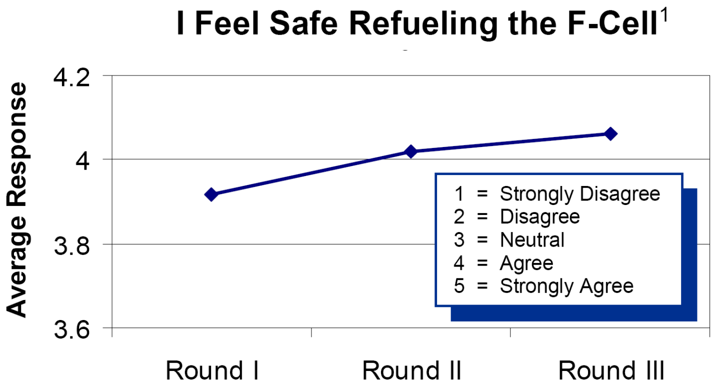

Figure 5: Customer acceptance and perception study results; 1US only, DoE funded

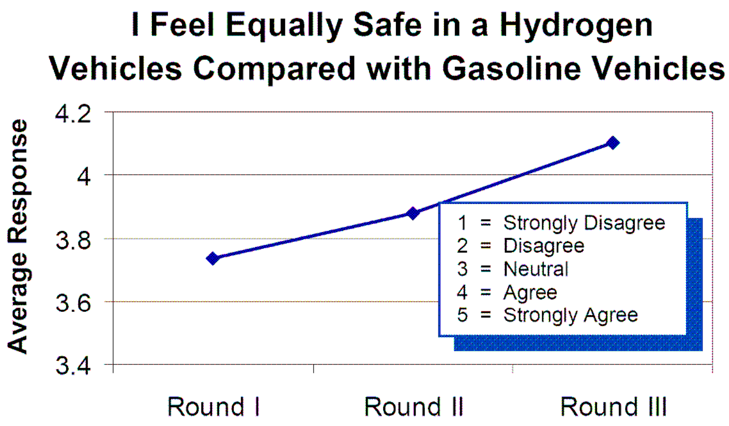

Figure 6: Customer acceptance and perception study results

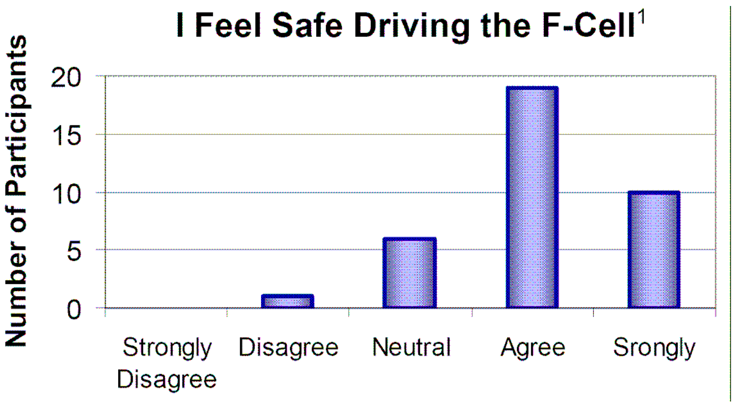

Figure 7: Customer acceptance and perception study results; 1US only, DoE funded

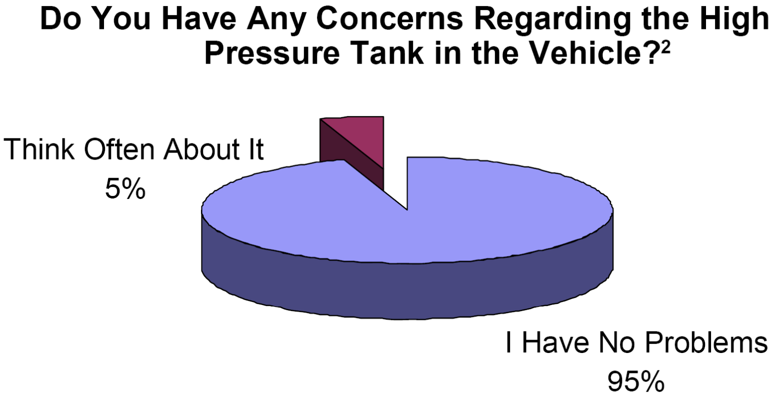

Figure 8: Customer acceptance and perception study results; 2Germany only; EU funded

The limited network of hydrogen fuelling stations available today placed constraints on participants. It has to be noted that the participants that took part in the survey were not representatives for the general public. Respondents indicated they would be willing to drive approximately nine miles to find a hydrogen fuelling station. The limited range of the “F-Cell” (180 km) is a crucial point for the acceptance of the technology. The average desirable range mentioned by the survey participants for a fuel cell vehicle is approximately 320 km. Deploying 70 MPa hydrogen storage technology in the next generation of DC’s fuel cell fleet vehicle will increase the range to approximately 400 km.

The acceptance of fuel cell technology among the respondents increased strongly with the degree of information provided and with experience.

Thus the market introduction of fuel cell vehicles has to be supported by an effective process of communication. A comprehensive education programme should be implemented to gain public acceptance in addition to provide the society with necessary information about the technology, its advantages and safety measures.

3.1.8 Infrastructure

The hydrogen infrastructures of the chosen demonstration projects comprise a wide range of hydrogen supply pathways and technologies for on-site production and external delivery, hydrogen conditioning, storage and dispensing.

In general the availability of the refuelling infrastructure was quite high, however there have been quite a few problems with the compressor technology, hydrogen contaminations and the refuelling interface.

In regards to safety the data indicate a strong infrastructure safety record, but station robustness to external forces and false alarms could be improved.

The main issues in regards to customer acceptance are the very long refuelling times of more than 3 minutes to refuel a F-Cell vehicle (1.8kg H2) as well as the large tolerance of the filling level (see Figure 9 and Figure 10). As you can see in Figure 10 below none of the stations lie within the corridor of 95-100% state of charge (SOC).

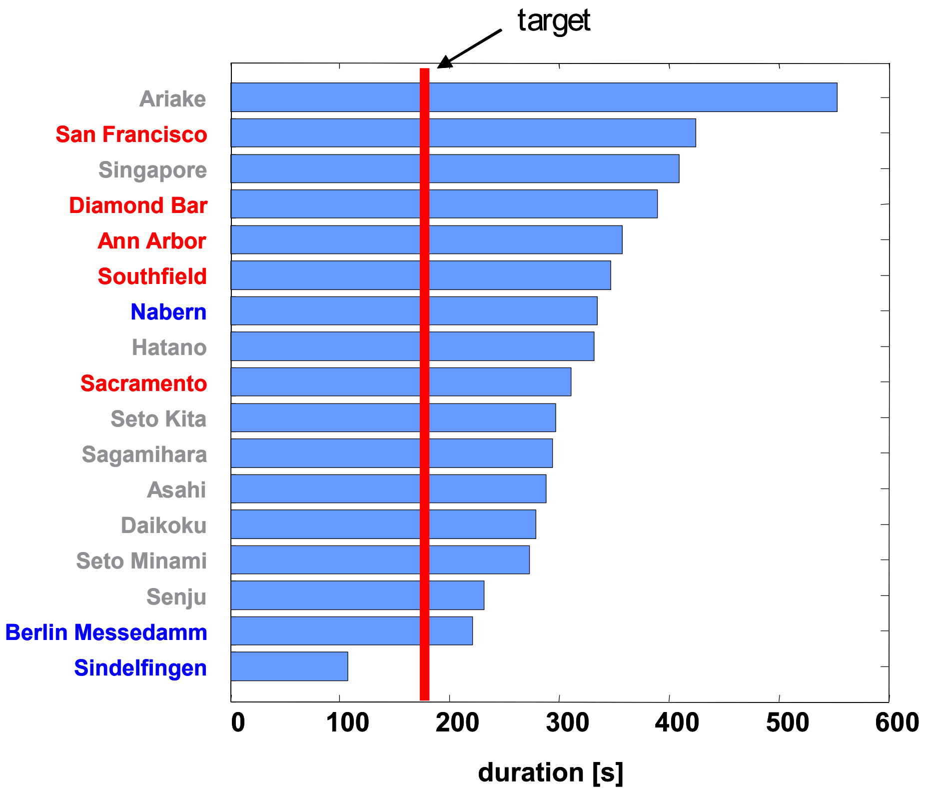

Figure 9: Duration of complete fillings at certain 35MPa refuelling stations

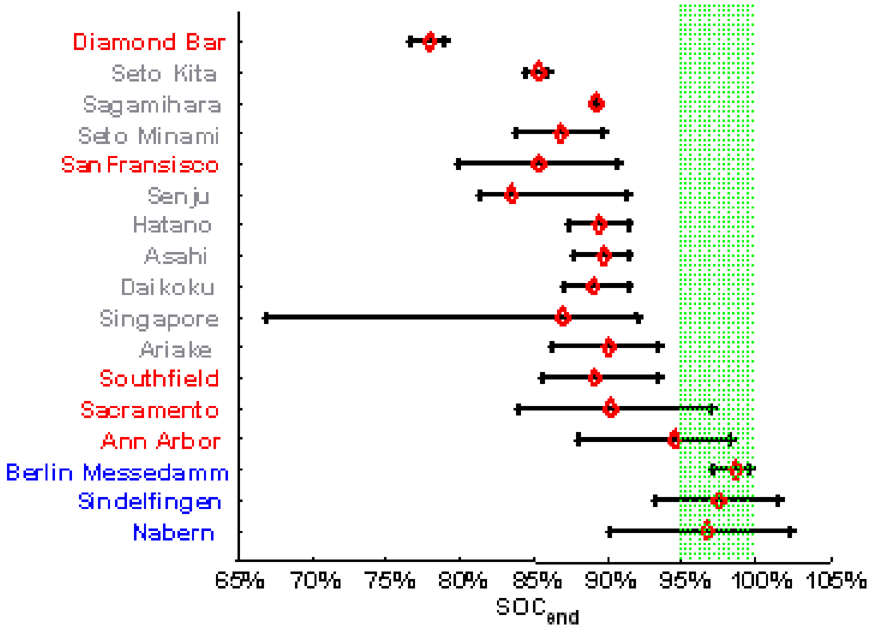

Figure 10: Range of filling levels at certain 35MPa refuelling stations

Due to the fact that the compression of the hydrogen gas in the vehicle during refuelling causes a temperature rise the fuelling station has to anticipate the heating effect to set the optimal filling parameters.

Without pre-cooling the refuelling time to achieve a 100% SOC rises dramatically with the ambient temperature, whereas with pre-cooling a 3min fill is achievable for ambient temperatures up to 40°C. Omitting pre-cooling may lead to fuelling times of up to 60min in worst case scenarios.

To enhance fuelling precision data communication between refuelling station and vehicle is necessary. This also prevents over fuelling and contributes to the overall safety.

In that respect hydrogen pre-cooling, especially for 70 MPa fuel cell vehicles, is essential to ensure fast refuelling times and acceptable filling levels.

Furthermore it has been experienced at some stations that a user-friendly act of filling is not given, e.g. due to the fact that protective clothes have to be worn during refuelling.

In some countries the regulations prevents the implementation of hydrogen dispensers into existing gasoline stations. However, these multi-fuel stations are very important for the build-up of an early hydrogen network in the start-up phase due to their cost effectiveness.

3.2 Fuel Cell Bus Projects [1]

DaimlerChrysler launched its Fuel Cell Bus Program in Europe in mid 2003 by introducing the first three Citaro F-Cell buses in Madrid, Spain. In the following months three buses were delivered to each of the public transport authorities in Amsterdam, Barcelona, Hamburg, London, Luxembourg, Madrid, Porto, Reykjavik, Stockholm and Stuttgart.

In addition to the European activities three Fuel Cell Buses were introduced in Perth, Australia in 2004 and another three buses in Beijing, China in 2005.

3.2.1 Distance travelled / operating hours

By end of February 2007, all 36 Citaro fuel cell buses (CUTE, ECTOS, STEP, China) had travelled a distance of more than 1.8 million kilometres and had been operated for more than 116,000 hours. The total aggregate kilometres driven and hours operated are an indication that the bus technology was successful both in terms of reliability and in terms of gathering data.

After the completion of two years of operation the CUTE buses had travelled a distance of almost 850,000 km operated for over 62,000 hours on European roads. Breaking down the mileage by month of operation, the CUTE buses completed an average of 35,800 per month in the nine CUTE partner cities.

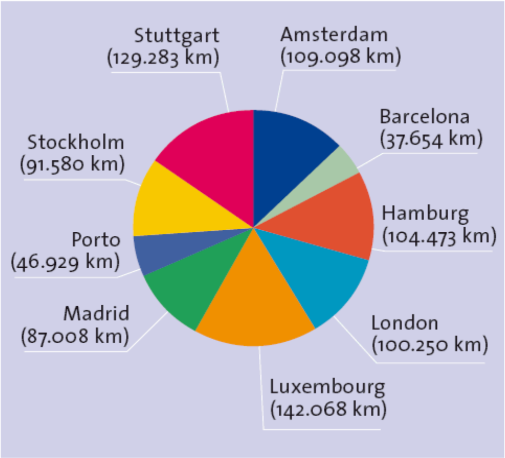

Figure 11: The total amount of kilometres driven in the nine CUTE cities [1]

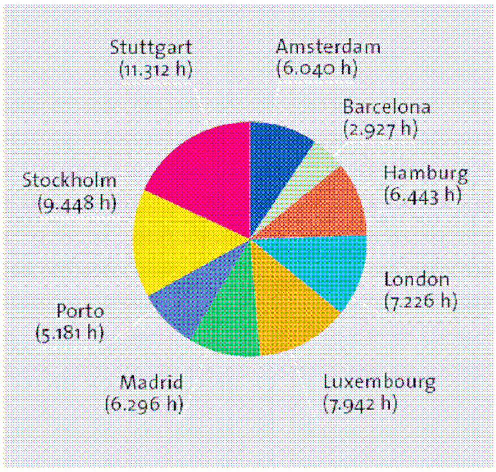

Figure 12: The operating hours in each CUT city [1]

3.2.2 Availability

The overall availability of the fuel cell buses was surprisingly high, with an average of almost 81.6% in all nine CUTE cities (see Figure 13). Barcelona had the lowest availability of around 60% mainly due to the contamination of the hydrogen vessels in the buses. Most of the contaminations were related to oil and carbon particles of the compressor. An extremely high availability was achieved in Stuttgart, where the three buses reached an availability of 99.6% from May 2004 onwards.

The definition used for availability was the number of downtime days per month as a proportion (%) of the total number of days in that month.

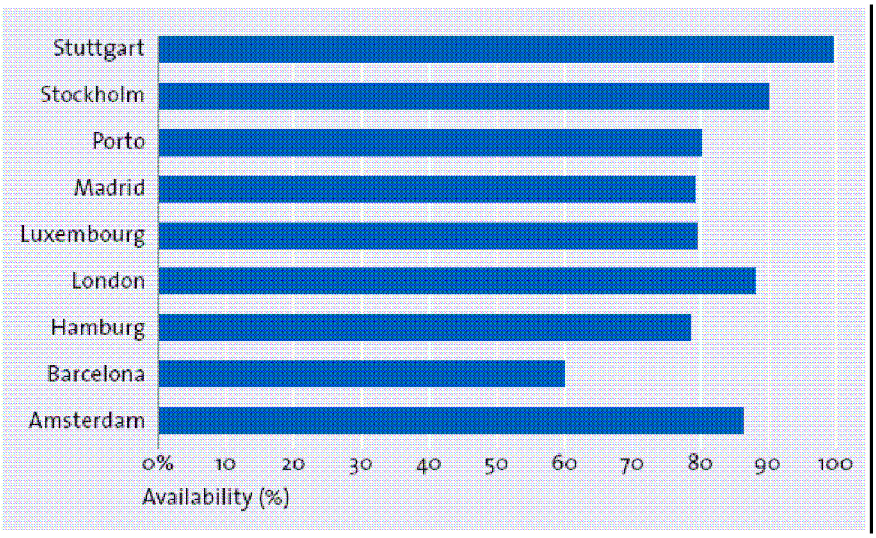

Figure 13: Availability of the buses in the nine CUTE cities. [1]

3.2.3 Reliability of components

The reliability of the key components such as the fuel cell stack module and the electric drive exceeded all expectations. The lifetime of the stack modules was much better than originally expected and modules achieved more than *4000 hours* without showing major degradation effects. The performance and availability was also high, however the fuel cell voltage monitoring board (CVM) was subject to numerous malfunctions and had to be improved.

In general there have been failures with “standard” mechanical components and high voltage components. Especially the latter case is one of the major risks for electric vehicles in regards to reliability and there further improvements are needed to make them suitable for automotive applications.

3.2.4 Fuel consumption

An influence on fuel consumption due to climate was found when the temperature was below 0°C or above 18°C. This was primarily due to the need to heat or cool the cabin, e.g. in cold periods the energy used for heating the cabin area consumed up to 5 kg/100km fuel.

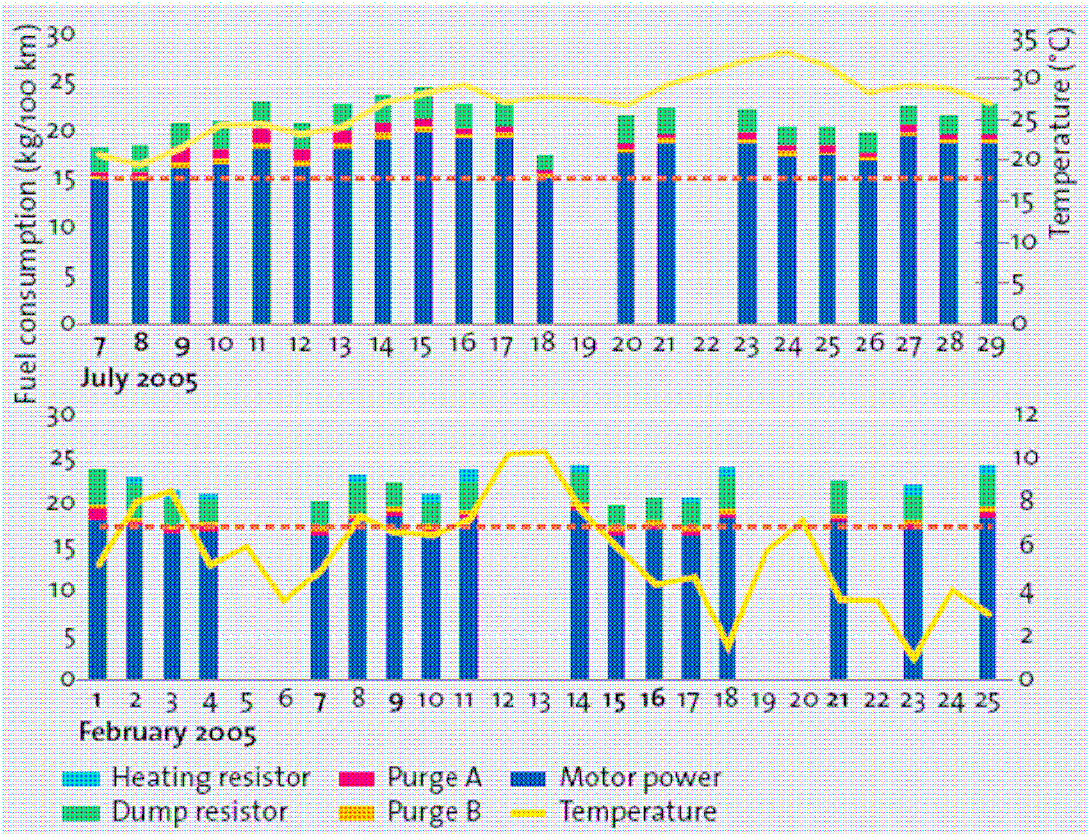

Figure 14: Power consumption charts for Madrid summer (above) and winter (below).

The red line represents a base consumption calculated from the dates marked. [1]

A challenging topography caused a further increase in fuel consumption. Driving downhill caused higher fuel consumption due to the significant consumption in the fuel cells during idling, compared with diesel vehicles that use virtually no energy going down hill.

However the CUTE buses were designed to meet reliability objectives and to test the fuel cell drive train and not be as efficient as possible. The buses therefore utilized as much of the existing mechanical Citaro bus components as possible. This design philosophy led to many of the fundamental efficiency potentials of a fuel cell drive train not being captured.

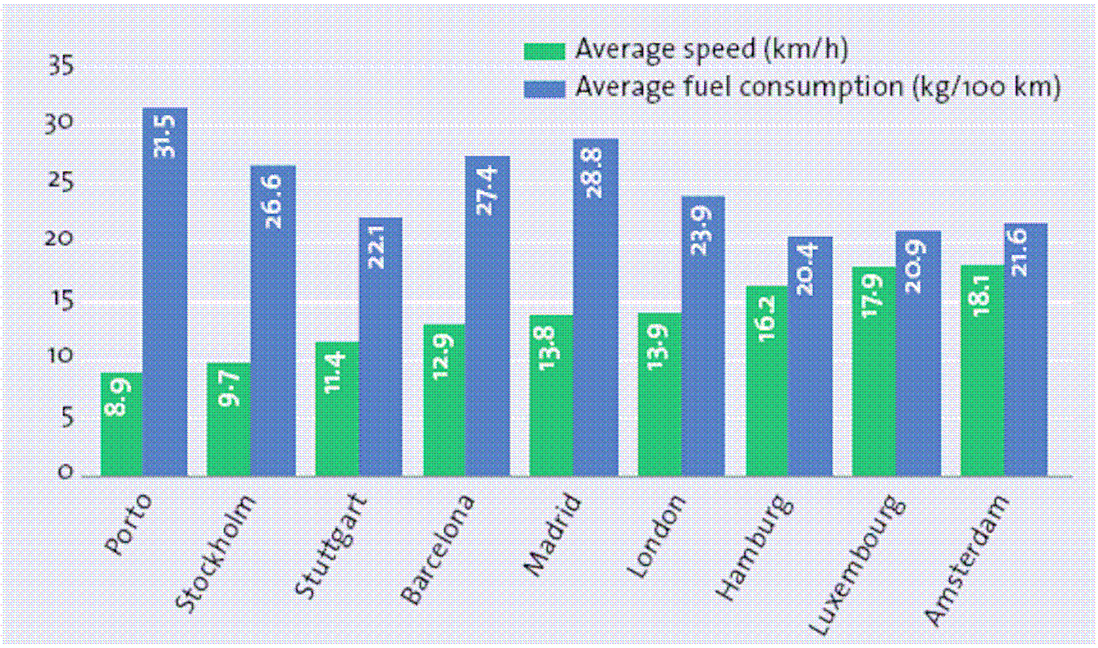

Figure 15: Average speed and fuel consumption for the nine CUTE cities. [1]

3.2.5 Safety incidents

The buses proved reliable and safe during operation under extreme European climate conditions, with daytime temperature conditions ranging from 39°C down to -16°C, and relative humidity ranging from 13% up to 100%.

3.2.6 Customer Acceptance

For a new technology to be successful it requires more then reliability for the concept to be commercial. A key requirement is to ensure that the drivers and the public are satisfied and safe using such a new technology.

Many of the participating partners were impressed by the durability of the fuel cell drive train and the availability of the fuel cell buses. The bus drivers were pleased with the performance of the buses and felt comfortable and safe to operate the buses. As a consequence, they became the main ambassadors for this new technology. All of this was important in forming the attitudes of the public towards the new technology.

The figure below shows the results of a driver survey, conducted by the City of Luxembourg, for the four cities Hamburg, London, Luxembourg and Stockholm. The analysis showed that most characteristics of the fuel cell buses were perceived as the same or better than regular buses. The only exception was that a majority of the drivers felt that a regular bus had better acceleration. This was mainly caused by the extra weight of the fuel cell bus. Two of the other performance parameters, speed and braking, was perceived as the same or better by most drivers.

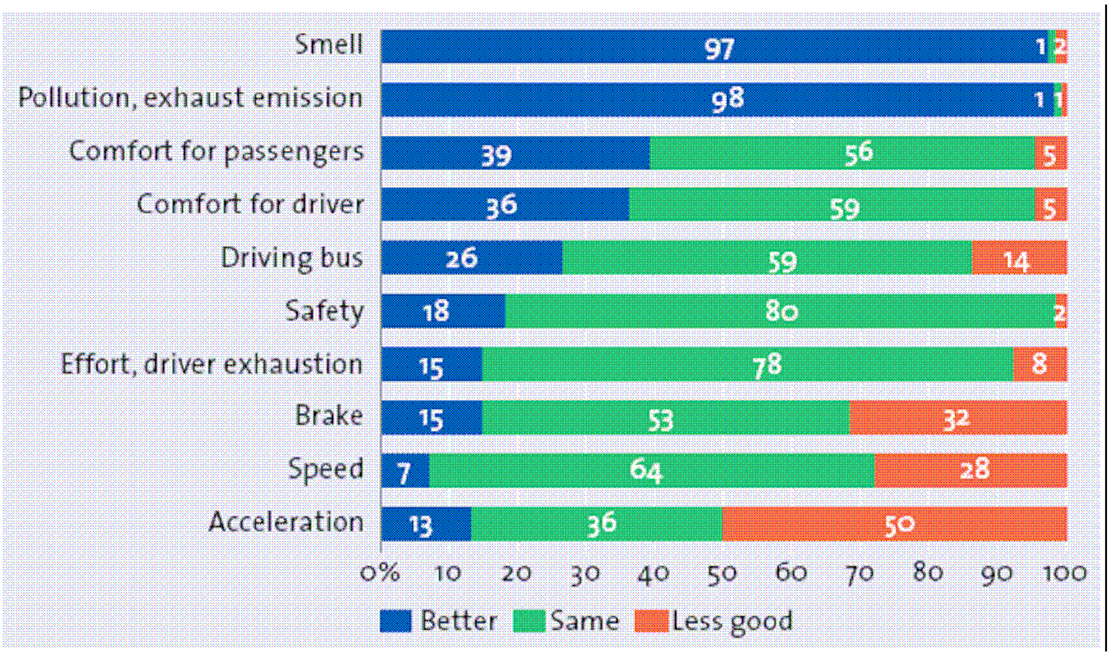

Figure 16: The drivers' opinions on some of the bus characteristics; Comfort, safety and performance: responses answers from the drivers in Hamburg, London, Luxembourg and Stockholm. [1]

3.2.7 Hydrogen infrastructure

The hydrogen infrastructures of the chosen demonstration sites comprise a wide range of hydrogen supply pathways and technologies for on-site production and external delivery, hydrogen conditioning, storage and dispensing.

The various hydrogen supply pathways made a tremendous contribution to the wealth of learning's from CUTE. Since the operating phase has been completed with great success, many challenges of the past look simple today. It was not apparent at the outset that the individual technical solutions would perform so well (see Figure 17).

	Hydrogen production path	Technology turn-key supplier	Compressor type	Compressor rated capacity in Nm³/h	Compressor manufacturer	Storage size in kg hydrogen	Refuelling type	Dispenser supplier	Max. filling time in min	Interval between 2 buses in min
Amsterdam	electrolysis	Hoek Loos	hydraulic	300	Linde	490	overflow + booster	Linde	15	0
Barcelona	electrolysis	Linde	hydraulic	300	Linde	170	overflow + booster	Linde	20	before 3rd bus: 60 (or slower refuelling of 3rd bus)
Hamburg	electrolysis	Norsk Hydro Electrolysers	diaphragm	62	Hofer	400	overflow	Brochier	< 10	0 [2]
London	external [1]	BOC	cryogenic pump	900	ACD Cryo	3,200	vapourisation of pressurised LH_2	Fueling Technologie Inc.	30	0
Luxembourg	external	Air Liquide	diaphragm	60	Burton Corblin	500	overflow	Air Liquide	10	0
Madrid	steam reformer + external	Air Liquide	diaphragm (two)	50 and 2,400	PDC Machines Inc.	360	booster	Air Liquide	10–15	0
Porto	external	Linde	hydraulic	300	Linde	172	overflow + booster	Linde	12–15	before 3rd bus: 20 (or slower refuelling of 3rd bus)
Stockholm	electrolysis	Hydrogenics Systems	1 membrane, 1 hydraulic	525	PDC and HydroPac	95	overflow + booster	Fueling Technologie Inc.	20–35	0 [3]
Stuttgart	steam reformer	Mahler IGS	hydraulic (two)	100 and 5,380	Idro Meccanica	282	overflow + booster	Brochier	< 15	0

[1] London: details for storage of liquid hydrogen given, as in operation from May 2005 in Hornchurch.
[2] Hamburg: up to 120 min when taking in maximum capacity.
[3] Stockholm: interval between second and third bus 8 hours due to limited storage size.

Figure 17: Characteristics of the CUTE filling stations

The critical components in terms of downtime have been identified below in Figure 18, Figure 19 and Figure 20. These quantitative findings are well in line with statements from the bus and station operators when consulted about their views on advances and issues arising from the trials. The user interface was given first priority in terms of safety. Operators were in general satisfied with the performance of the infrastructure installations. The level of their individual satisfaction reflects the availability of the particular local facility (see Figure 21 and Figure 22). Bus operators that had previous experiences with CNG-powered vehicles and refuelling installations pointed out that there were no fundamental differences between CNG and hydrogen infrastructures. Contingency arrangements for backup supply turned out to be vital.

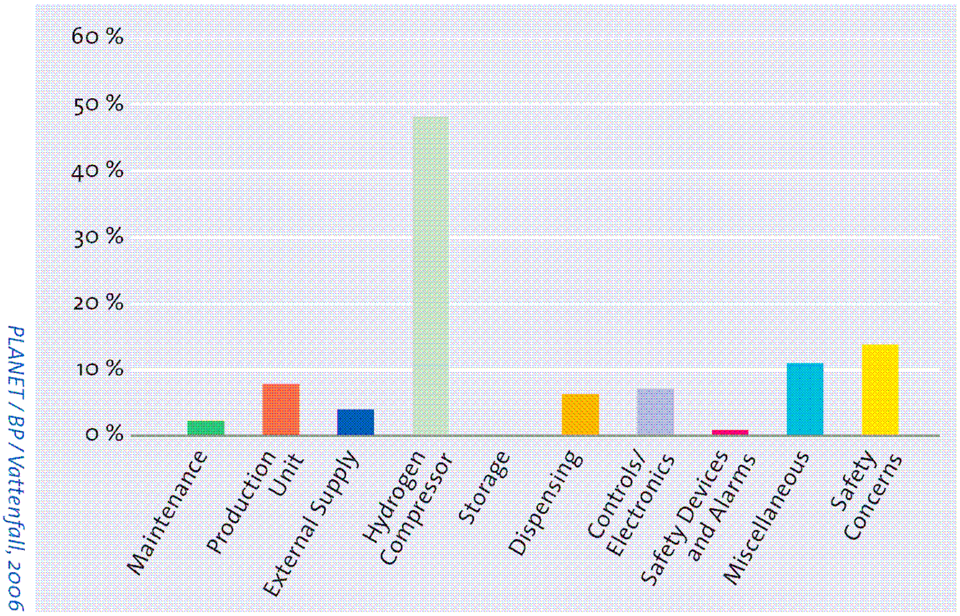

Figure 18: Causes for downtime of the station unit across all sites.

'Maintenance' represents scheduled maintenance;

'Safety Concerns' represents periods when the station was technically OK but taken out of service due to safety concerns;

All other categories represent failure and repair of the component and its auxiliaries.

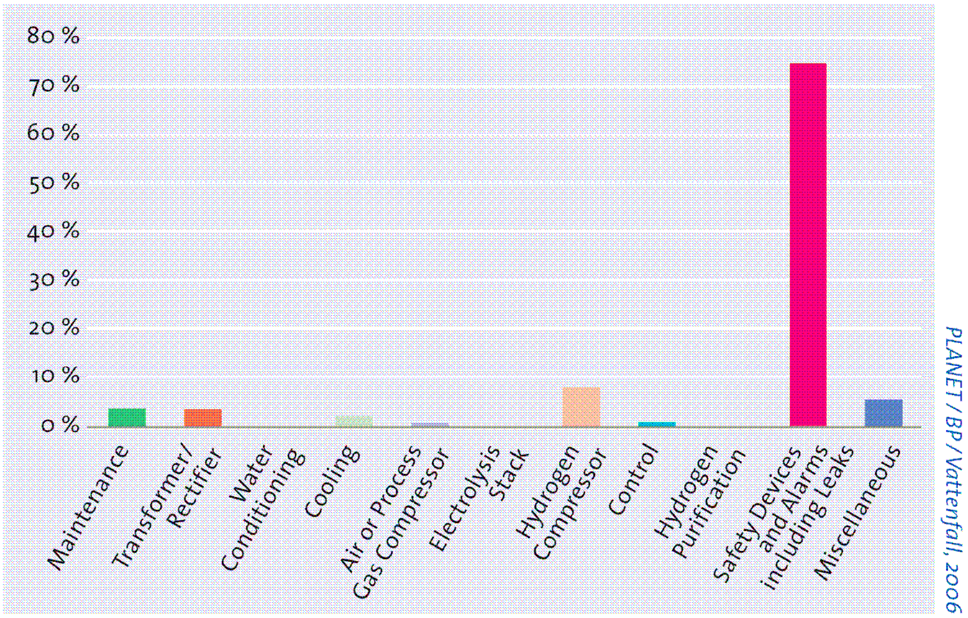

Figure 19: Causes for downtime of the production units based on water electrolysis.

'Maintenance' represents scheduled maintenance;

All other categories represent failure and repair of the component

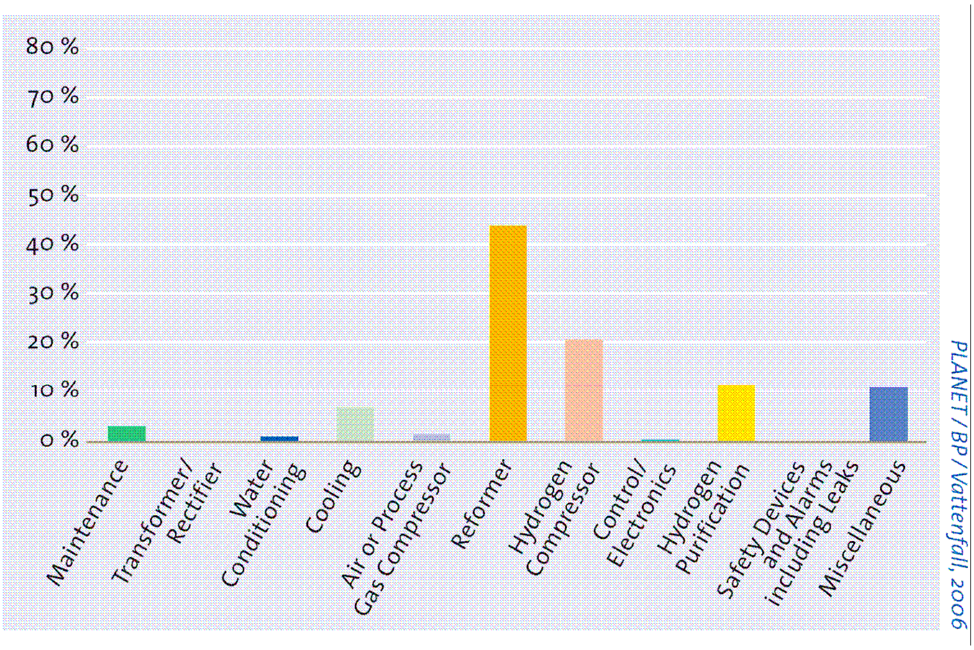

Figure 20: Causes for downtime of the production units based on steam methane reforming.

'Maintenance' represents scheduled maintenance;

All other categories represent failure and repair of the component and its auxiliaries.

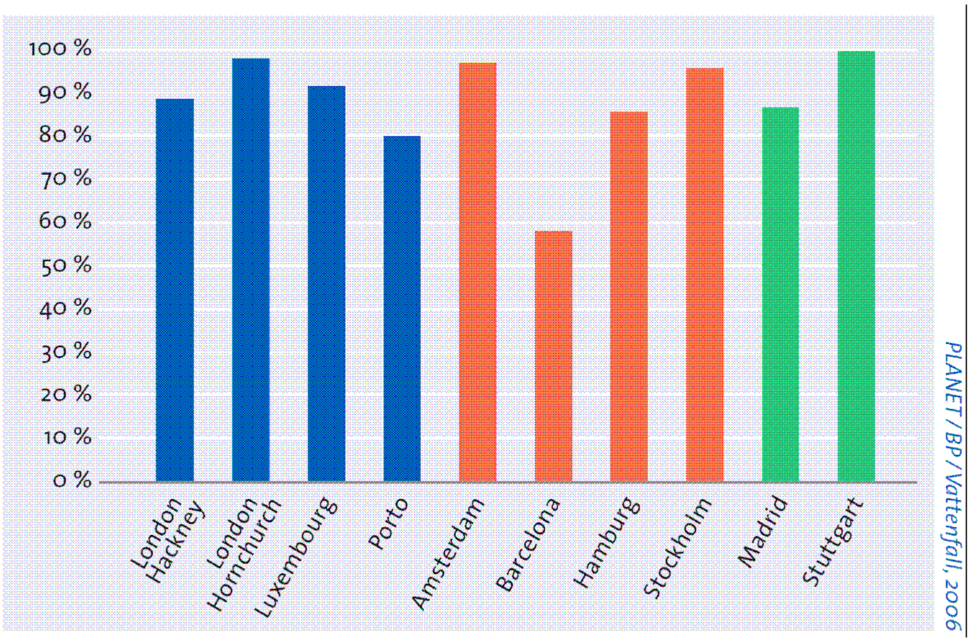

Figure 21: Average availabilities of the station units.

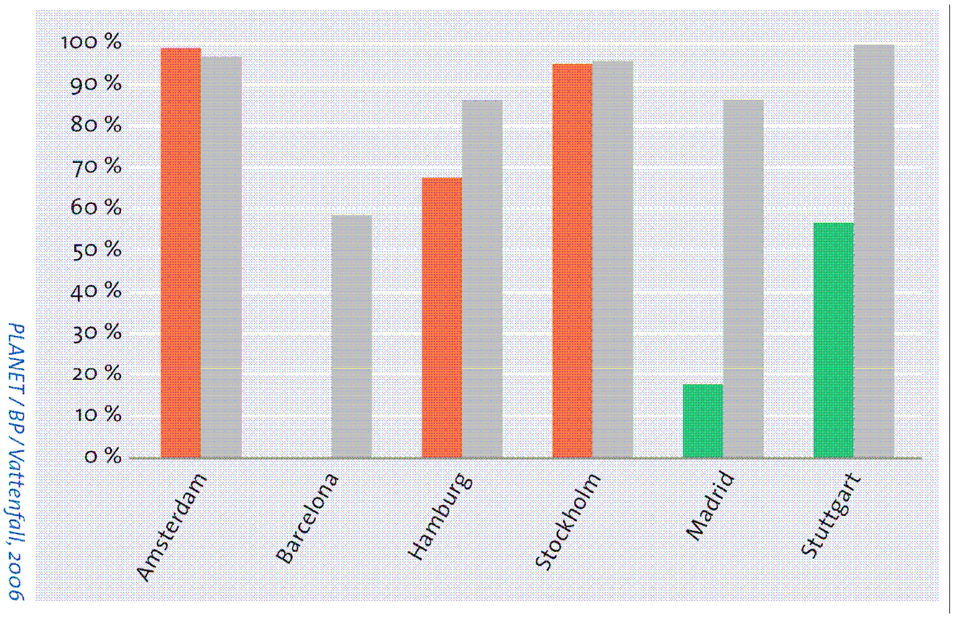

Figure 22: Comparison of average availabilities of the production units (coloured bars) and station units (grey bars).

There is no availability figure for the production unit in Barcelona due to incomplete data.

It will be of great importance to achieve a basic level of standardisation for hydrogen refuelling facilities. This will also enable turn-key suppliers to choose components from a range of manufacturers and, therefore, should help to reduce the investment cost and footprint, increase efficiency (resulting in lower operating cost) and advance overall performance.

On the organisational side, infrastructure suppliers and operators need to develop clear concepts of how to react rapidly to problems with the installations, especially in the crucial ramp up phases of operation. Accordingly, agreements with component manufacturers and local contractors need to be in place. This includes demands stemming from multi-site and multi-country projects, such as language and culture.

A coherent framework for data acquisition and evaluation across sites, and even between individual demonstration projects, are a prerequisite for success, and not only in transport related activities. Such a framework must be finalised before hardware is ordered. There must be one person at each site who is responsible for the capture of all data (most likely from several sources). These people should be trained in a joint workshop before the start of operation. The objectives of the data collection procedure must be transparent to them and misunderstandings regarding the meaning of individual indicators and their data bases must be avoided as much as possible. Again, diversities regarding vocational training background, language and culture must be considered.

The hydrogen infrastructures used in CUTE were adequate for supplying small fleets. Larger fleets will require the refuelling of numerous units concurrently, either with substantially reduced refuelling times far below 15 minutes and no waiting between two vehicles, or slow refuelling overnight.

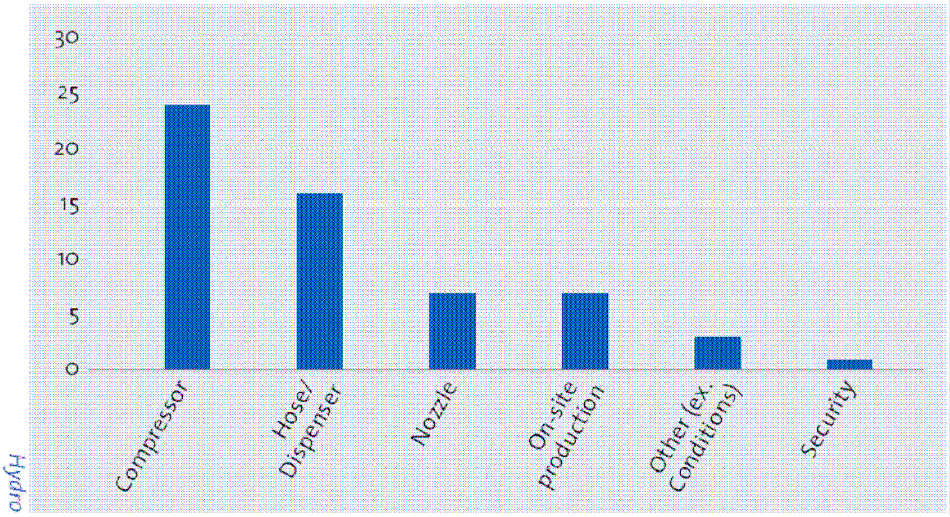

Figure 23: Nature Safety Incidents during Operational Phase of CUTE Project [1]

There are significant opportunities to improve production technologies in terms of reliability and efficiency.

Major constraints are impurities of the hydrogen even at extremely low levels which can harm the fuel cell performance. While fuel cell manufactures understandably would like the hydrogen purity to be increased, hydrogen providers and vehicle operators are certain that this would be a major impediment to the wide scale introduction of a hydrogen fuel cell transport energy system. The challenge here is to find a suitable compromise of reliable provision of hydrogen at the greater purity and to produce fuel cell systems that are much more tolerant of hydrogen impurities.

It is hard to find evidence of a broad scale or major financial or technical commitment by refuelling technology manufactures to develop new and more reliable refuelling technology, while making current technology more reliable. This is a gap in the global work program that must be filled if a hydrogen based transport energy system is to develop.

4. References

[1] CUTE Brochure and CD ”Detailed Summary of Achievements“