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Fuel cell buses in the Stockholm CUTE project—First experiences from a climate perspective

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Abstract

This paper aims to share the first experiences and results from the operation of fuel cell buses in Stockholm within the Clean Urban Transport for Europe (CUTE) project. The project encompasses implementation and evaluation of both a hydrogen fuel infrastructure and fuel cell vehicles in nine participating European cities. In total, 27 fuel cell buses, 3 in each city, are in revenue service for a period of 2 years.

The availability of the fuel cell buses has been better than expected, about 85% and initially high fuel consumption has been reduced to approximately 2.2 kg H_2/10 km corresponding to 7.5 l diesel equivalents/10 km. Although no major breakdowns have occurred so far, a few cold climate-related issues did arise during the winter months in Stockholm.

Keywords: Fuel cell bus; Climate conditions; Evaluation; Auxiliary systems

1. Introduction

Public transit buses are widely viewed as one of the most viable strategies for commercialising fuel cells for vehicles and transitioning to a hydrogen economy. Some of the advantages with the use of transit buses as fuel cell platforms are that they have well-defined duty cycles, centralised fuel and maintenance infrastructure. Buses also allow more space for propulsion system and fuel storage packaging than for example passenger cars. They also have high utilisation rate. Furthermore as buses are highly visible in the community, fuel cell technology is provided a good showcase for the public. Therefore, governments in Europe, North and South Americas and Asia are supporting a number of fuel cell bus demonstration projects, 65 fuel cell buses were in operation in year 2003 [1].

2. The CUTE project

The project Clean Urban Transport for Europe (CUTE) is a demonstration and test of 27 fuel cell buses in public transit operation in nine participating cities. These cities are Madrid and Barcelona (Spain), Porto (Portugal), Luxembourg, London (UK), Amsterdam (the Netherlands), Hamburg and Stuttgart (Germany) and Stockholm (Sweden) (see Fig. 1).

The CUTE project is the world's first large demonstration project in terms of number of vehicles, partners and cities involved. It is also unique in that it includes development, implementation, operation and evaluation of fuel infrastructure and operation and evaluation of fleets of vehicles in revenue service in all the participating cities. The project is financially supported by the European Commission, the member cities and their local partners. The goal is to demonstrate the feasibility of the fuel cell technology in transportation applications and to collect the lessons learned from the project to form a basis for decision-makers in industry and administra-

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Fig. 1. Map of the CUTE project partner cities and the sister projects ECTOS in Reyjavik, Iceland and STEP in Perth, Western Australia [6].

tions in future urban transportation projects and investments. Another aspect of the CUTE project is that of educating the public about the fuel cell technology. An increased awareness of fuel safety and environmental benefit is critical to fuel cell bus success.

The CUTE project started in November 2001 and will continue through April 2006. During the first phase of the project, and prior to the arrival of the fuel cell buses, novel fuel infrastructures including hydrogen production, distribution and refuelling stations were developed and implemented in each city. The fuel infrastructure in each city is adapted to the local conditions, e.g., hydrogen production mode, budget situation, safety regulations. In addition, especially designed work shops for service of the fuel cell buses were built in each city. During the second project phase, the evaluation phase, each city tests its three fuel cell buses during a period of 2 years. All buses were delivered during 2003 and hence the fuel cell bus tests will continue until the end of year 2005. Data and experiences from both the fuel infrastructure and the bus operation are collected continuously. The gathered data is to be analysed with respect to the parameters such as hydrogen production performance, maintenance and safety, life cycle analysis, dissemination and fuel cell bus operation, bus performance and maintenance. Most of the various analyses are performed in a number of work packages within the CUTE project.

The coordinator of the project is DaimlerChrysler. The company is also per its subsidiary EvoBus the fuel cell bus provider of the CUTE project and of CUTE's sister projects, the Ecological City Transport System (ECTOS) project in Reykjavik (Iceland) [2] and the Sustainable Transport Energy Program (STEP) project in Perth (Australia) [3]. Another sister project, also with DaimlerChrysler fuel cell buses, is upcoming in Beijing (China) buses in the near-term future. More information on the CUTE project can be found in [4,5].

This paper focuses mainly on the results and experiences from the operation of the fuel cell buses in Stockholm during the first months of operation.

2.1. CUTE WP4 climate evaluation of bus performance

Stockholm has been assigned the analysis of the impact of climate on fuel cell bus performance in different climate regions. Stockholm has three main partners in this work package number 4 (WP4); Porto, Barcelona and London. The goal of WP 4 is to analyse the current performance and potential of the fuel cell propulsion system on a local climate basis. In the project, data of various sources is collected from mainly the specified partner cities. The information and data come from evaluation questionnaires and protocols for drivers and bus operator technical staff, and from GPS devices and on-board data logging system.

The CUTE project encompasses regions with widely varying local climate conditions due to region and season (see Fig. 2). The regions ranges from rather warm and humid areas of Porto, Portugal and Barcelona, Spain with the exception of Madrid, Spain, which is situated on a warm and dry high-altitude plateau to the highly humid but more moderate temperatures of London, UK and Stockholm, Sweden. The figures also include Reykjavik, Iceland, of the ECTOS project, which has about the same conditions in terms of average wind speed as London but has lower average temperature.

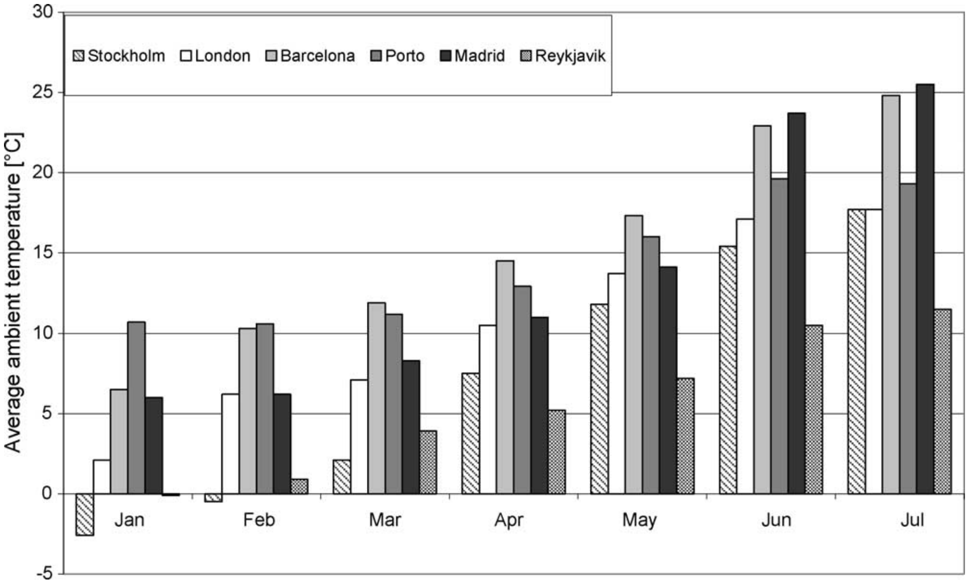

Fig. 2. The average ambient temperature of the time period January–July 2004, in selected cities within the CUTE and ECTOS (Reykjavik) projects.

3. The fuel cell bus— a description

The Mercedes-Benz Citaro fuel cell buses are equipped with a HY-205 P5-1 fuel cell engine developed by Ballard Power Systems, Canada. The fuel cell engine consists of a fuel cell system, based on Ballard's Mk9 generation fuel cell stacks, that supplies power to a central electric motor with a maximum power of 205 kW (see Fig. 3 and Table 1). The buses use compressed hydrogen as fuel, stored in Dynetek high-pressure cylinders mounted on the roof of the vehicle. The total hydrogen storage capacity is 40 kg at (15 °C, 350 bar) providing a bus operation range of about 200 km [4].

Table 1
Characteristics of the fuel cell buses in the Stockholm CUTE project according to the Swedish vehicle registration certificate [9]

Vehicle	Description
Dimensions ($L \times W \times H$) (m)	11.95 × 2.55 × 3.69
Gross weight (kg)	18,000
Curb weight (kg)	13,890
Maximum frontal axle load (kg)	7245
Maximum rear axle load (kg)	11,500
No. of passengers: maximum	57
No. of passengers: seated	32
Maximum speed (km h^{-1})	80 (limited)
Driveline	
Fuel cell system (kW)	>250 (2 stacks of 150 kW gross each)
Central electric motor (kW)	205
Hydrogen storage	
Total capacity (l)	1845 (9 cylinders)
Maximum pressure per cylinder (bar)	350

The figures may differ from those in other CUTE cities.

Typically, pure hydrogen-powered fuel cells exhibit high-energy conversion efficiency at full load operation. Furthermore, in contrast to a diesel engine, the fuel cell shows high efficiency at idle and part load operation. Since the vehicle propulsion power demand of urban vehicles is usually at 10–20% of the maximum load, fuel cell buses should be well-suited for revenue service, economising on fuel in all the "stop-and-go" situations that normally are encountered in urban traffic. Hence, the fuel consumption in diesel equivalents of a fuel cell bus is expected to be 30% lower than that of a standard diesel bus of similar size [7,8]. It is important to point out, however, that the buses in the CUTE project are small series vehicles and low fuel consumption was not the main goal of the vehicle design. Instead, reliability and robustness, maintainability and cost were the major design objectives of the fuel cell buses in order to learn as much as possible about the behaviour of fuel cells under real life conditions. As a consequence, the fuel cell version of the Citaro is over 2000 kg heavier than the diesel version [9]. Also, the fuel cell engine (including hydrogen storage) and the electric driveline are basically the only new components in an otherwise standard diesel platform. Furthermore, this design uses a single, central, electric motor that powers both a conventional automatic gearbox from ZF and the bus accessories that normally are powered by a diesel engine. The bus accessories, the air compressor in the fuel cell system and some pumps for the fuel cell engine are driven mechanically by an especially constructed gear case on the rear end side of the electric motor. The alternators and the air conditioning (A/C) compressor are belt-driven with the gear case with a consequent slightly higher efficiency loss than the other accessories. The fact that most components in the bus are powered through mechanical power rather than electric power leads to inherent efficiency losses and does not really reflect the

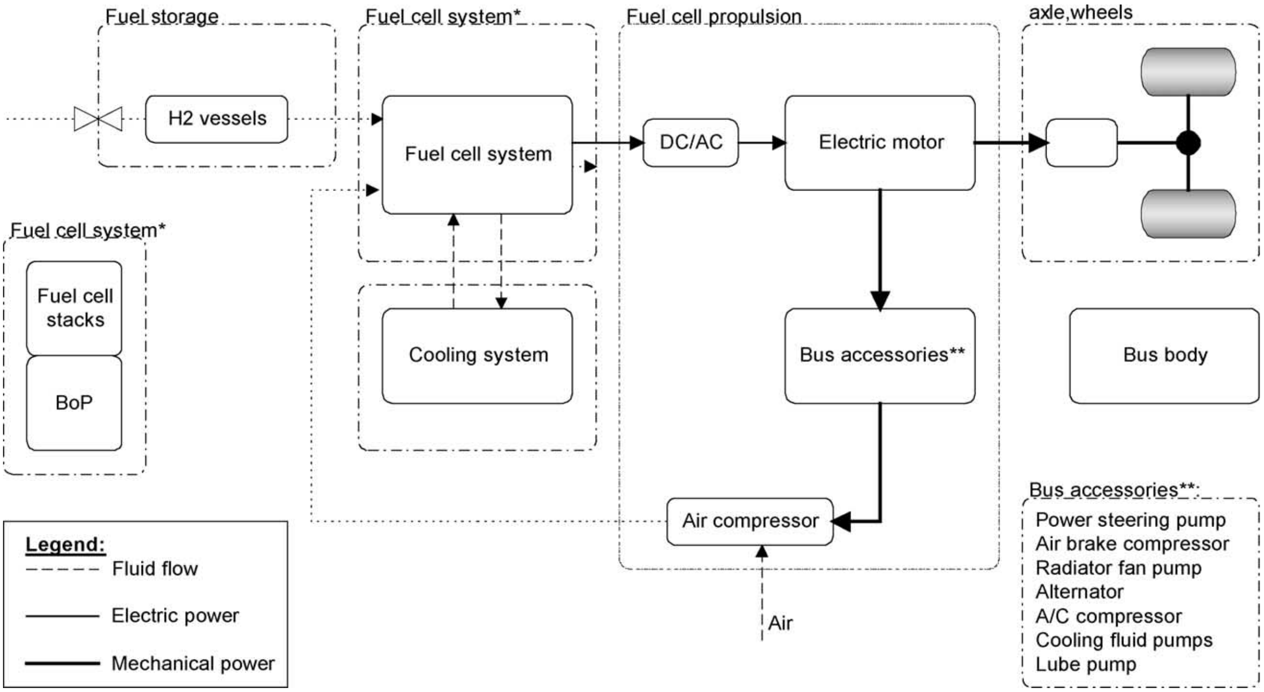

Fig. 3. Schematic overview of the electric driveline of the Mercedes-Benz Citaro fuel cell buses in the CUTE project, based on [4]. (BoP, balance of plant components).

full potential of an electric driveline using fuel cells and/or batteries.

4. Stockholm

The Stockholm CUTE project involves eight partners. These partners are Stockholm Public Transport (SL), the project co-ordinator City of Stockholm, the bus operator Busslink, the energy and gas distributor Fortum and the WP 4 group at the Royal Institute of Technology (KTH). Financial support is given by the European Commission, the Swedish Energy Agency, the Swedish Agency for Innovation Systems (VINNOVA) and the air compressor supplier Opcon AB.

4.1. Hydrogen infrastructure

Hydrogen is produced and stored on-site on the same location as the refuelling station and the bus workshop, at a bus depot on the island of Södermalm in central Stockholm. The hydrogen is produced from electrolysis of water, using electricity produced by certified green power (hydropower and wind power). The electrolyser, provided by Stuart Energy Systems, Canada, has a designed capacity of 60 N m^3 H_2/h with a power consumption of about 4.8 kW. Fortum is responsible for the entire hydrogen refuelling station in Stockholm.

The major events in the process for the different hydrogen facility applications, e.g., workshop, hydrogen storage, hydrogen production and refuelling station, are displayed in Fig. 4 [10]. The process for permits was rather long, 18 months, in total. This was mainly due to lack of already existing hydrogen regulations on permit application procedures, a common problem also experienced by many other CUTE cities. Hence, a unifying European legislation on hydrogen facilities and hydrogen vehicles, would be beneficial. Instead, and again like many other CUTE cities, regulations for natural gas were used and somewhat adapted to the new fuel. Another complicating factor specific for Stockholm was that the hydrogen production and storage facilities and refuelling station were located on land owned by the City of Stockholm, rented by the bus operator. Negotiations with the parties lead to changes of the building plan of that area and a time-limited permit to use the land was granted. With the lessons learned in this particular case, the next time a hydrogen project is to be launched in Stockholm, or elsewhere in Sweden, at least the permit procedure will be known and likely to be significantly less costly and time consuming.

5. Tests

Tests have been performed in Stockholm in order to obtain fuel consumption and bus auxiliary system data of different bus power train systems including Mercedes-Benz Citaro fuel cell and diesel buses during different local climate conditions. So far, the tests have been performed in two periods, in July and September 2004, for two reasons. Firstly, the buses were first used on a demonstration route with few passengers. Once the buses started to operate on a regular bus route, in the end of August, the passenger load has increased considerably. Hence, both routes need to be tested in more details in order

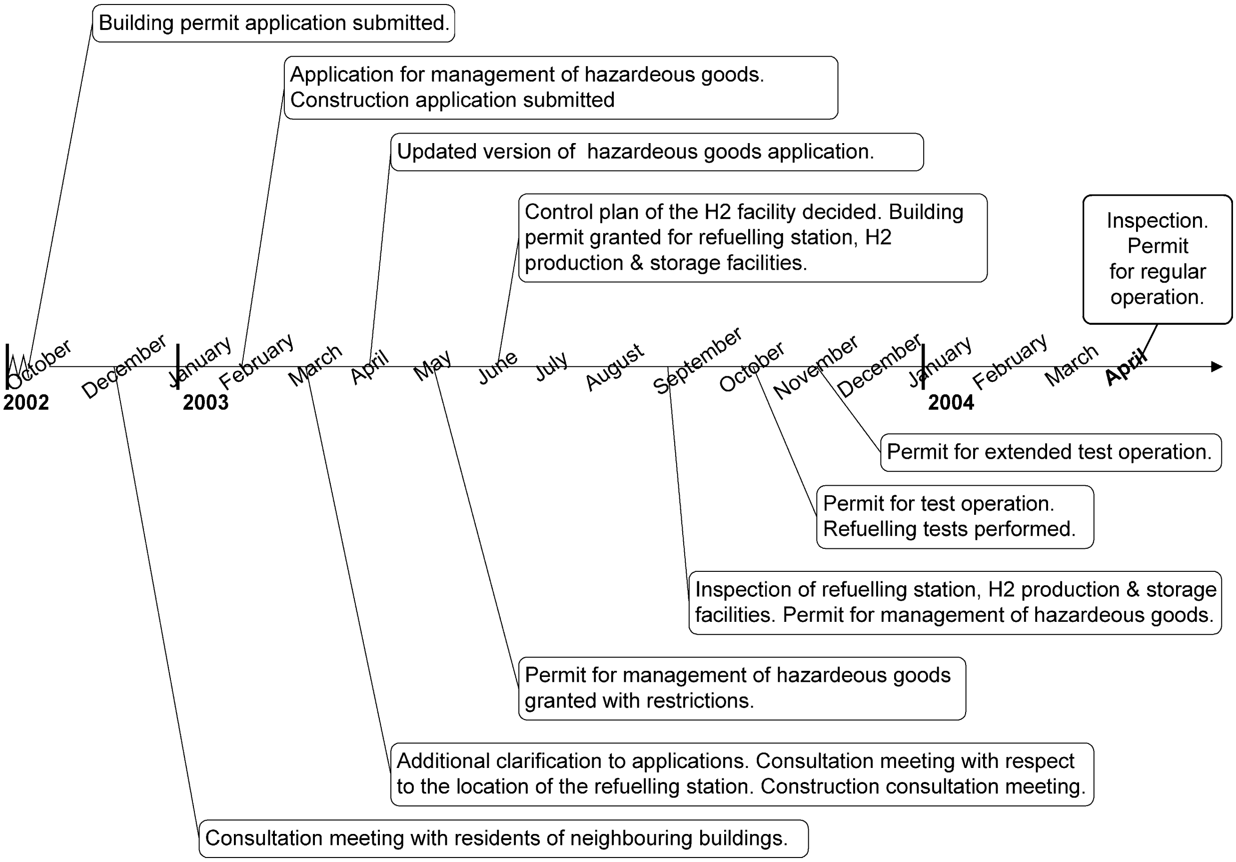

Fig. 4. The permit procedure in the Stockholm CUTE project, based on [10].

to explain fuel consumption and other performance numbers. Secondly, seasonal changes may have an impact on the performance. Therefore, tests will also be performed during the winter months in Stockholm and in other cities as well.

There are two aspects of the tests, a fuel consumption comparison between fuel cell and diesel buses and a more specific analysis of the fuel consumption and other fuel cell system parameters of fuel cell buses on a second by second basis in a logged duty cycle.

5.1. Data acquisition

In order to define the power requirements of the fuel cell buses, the duty cycle profile data, e.g., parameters such as speed and altitude versus time, was to be collected. For measurements of speed and altitude of the buses, Global Positioning Systems (GPS), Garmin GPSmap 76CS, were purchased. These GPS devices are equipped with built-in barometric altitude meter, monitoring the altitude by the measuring the ambient air pressure. The uncertainties in the measurements of altitude are estimated to be ±3 m. Antennas for the GPS devices were attached to the exterior of the buses, on the front end of the destination sign module, in order to facilitate and secure a good data acquisition. During the test periods, one appointed instructor was on-board the bus to help out and instruct the bus drivers, monitor and record GPS data and fill in test protocols. Detailed information of the fuel cell system and its auxiliary system is monitored and collected via proprietary data acquisition system on the fuel cell buses and was provided for the test periods by Ballard and DaimlerChrysler.

Weather data for Stockholm was provided by the Swedish Meterological and Hydrological Institute (SMHI). The distribution of minimum and maximum temperatures in Stockholm during the first months of bus operation is shown in Fig. 5. It should be noted that subzero temperatures still occurred in April.

6. Duty cycles

6.1. The demonstration route: the water route (“Vattenlinjen”)

The first 8 months of operation, January to mid-August 2004, were designated to evaluate whether the fuel cell buses were reliable enough to be used in normal public transit operation or not. Therefore, a demonstration route passing the City Hall (Stadshuset) in central Stockholm was established (see Fig. 6). The number of passengers on this route was unfortunately rather low, in average 10 passengers per loop.

The characteristics of the 5 km long demonstration route are displayed in Figs. 7 and 8. The fairly low maximum speed

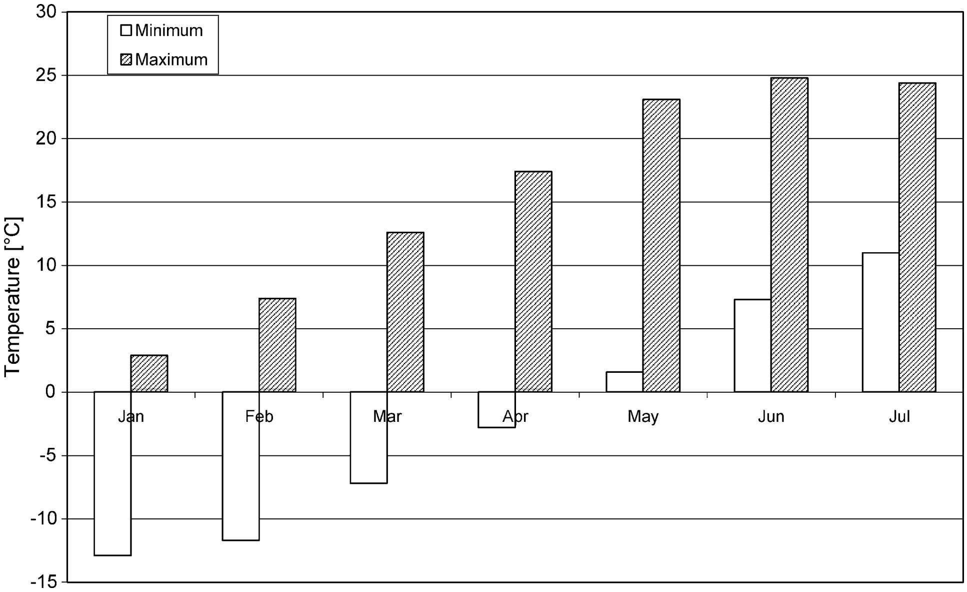

Fig. 5. The minimum and maximum temperatures in Stockholm during the time period January–July 2004.

Demonstration route "Vattenlinjen"	
Time [s]	1944
Distance [km]	5
Max. altitude [m]	11
Min. altitude [m]	-2
Max. speed [km/h]	39.2
Average speed [km/h]	9.3
Max. acceleration [m/s^2]	1.0
Max. deceleration [m/s^2]	-2.0
Idling time [s]	585
# of bus stops	12
# of bus stops per km	2.4

Fig. 6. Left: the demonstration route in central Stockholm that was used the first 8 months of operation of the CUTE fuel cell buses. Right: table with some of the characteristics of the demonstration route.

of 39 km h^{-1} and average speed of 9 km h^{-1} are normal numbers for inner city bus routes in Stockholm. The 12 bus stops and the duration at each stop (black marks) can also be seen in the figure. The idling time at each bus stop is displayed in Fig. 7; all other stops are caused by the traffic situation. The speed distribution diagram, Fig. 8, shows that the total idling time represents roughly 30% of the duty cycle time.

7. Results

7.1. The demonstration route

For the demonstration cycle, the fuel consumption in July 2004 in the duty cycle shown in Figs. 7 and 8 was about 2.4 kg H_2/10 km, corresponding to 8 l diesel equivalents (DE)/10 km. The average fuel consumption of eight similar duty cycles for that specific day was slightly lower, 2.2 H_2/10 km, corresponding to 7.5 l DE/10 km (data for this day comes from on-board measurements). The fuel consumption figures were much higher in the beginning of the operation of the fuel cell buses in January 2004. At that time, there was an excessive fuel consumption of 3.8 kg H_2/10 km, corresponding to almost 13 l DE/10 km (data is based on calculations on total travelled distance and refuelled amount of hydrogen). The high fuel consumption figure is thought to be attributed to the drivers then not fully comfortable or trusting with the buses and the fuel cell bus concept. They tended to keep the buses idling for much longer time than needed and did not shut the engine off at scheduled breaks during a duty cycle shift fearing that the bus would not start if they did. Once they started to feel more comfortable with the new technique and more confident that the bus was not much different than a conventional diesel bus, the excess idling stopped and the practice of turning the engine off at scheduled breaks was reinstated, with the positive consequence of a significant drop in fuel consumption. To some extent, the initially very high fuel consumption was also due to the low temperatures of the months of January and February requiring longer start-up times, e.g., for heating the bus cabin.

In Fig. 9, the power distribution of the fuel cell bus over the demonstration route is shown. The power is divided be-

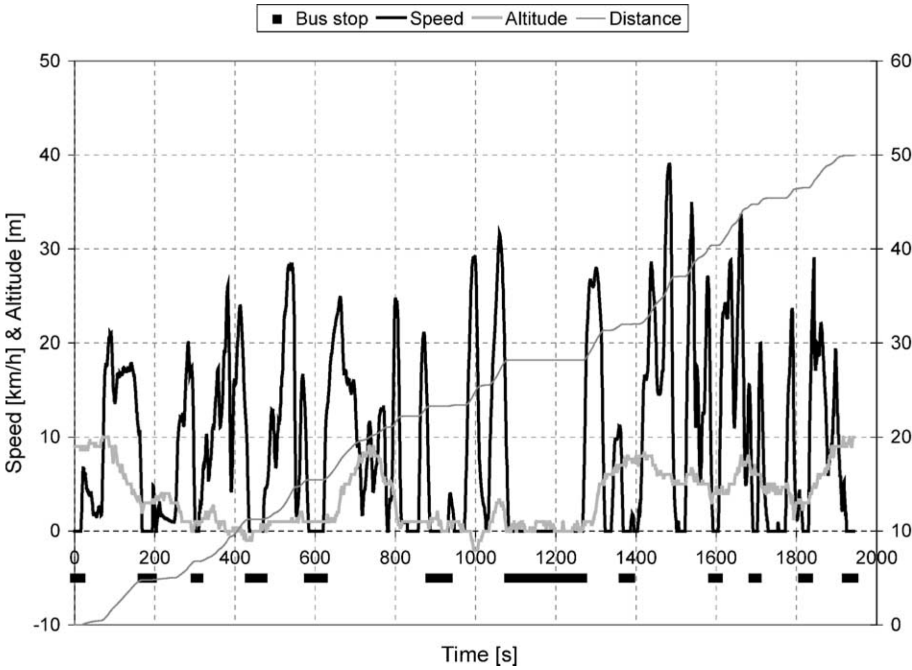

Fig. 7. The characteristics of a typical drive cycle on the demonstration route.

tween the hydrogen inlet power (based on the lower heating value (LHV) of hydrogen), fuel cell electric power output and the driveline motor power as well as the dump resistor power. The fuel cell power is generally within the interval of 20–40 kW with only a few outbursts of 100 kW or more at power demanding events such as accelerations. It can be noted that the dump resistor power is between 20 and 30 kW as much as 10% of the time. This implies that there is a big potential for improvements in the power control strategy.

As the fuel cell system is operated in a rather low power interval (see Fig. 9), the fuel cell stack efficiency is rather high, over 65% (based on LHV for hydrogen), for power outputs lower than 40 kW. Hence, it is the fuel cell propulsion system that reduces the overall fuel cell efficiency and that needs further improvements in the integration of system components. One way to comprehend the efficiencies of the different system components and the impact of these on the fuel consumption of the fuel cell buses is to use a Sankey diagram (see Fig. 10). The numbers in this figure are based

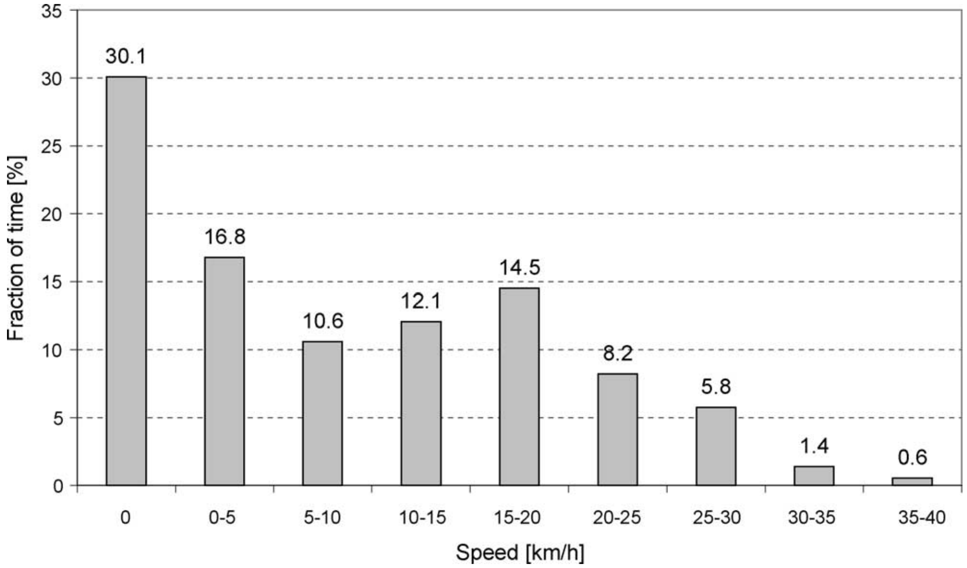

Fig. 8. Speed distribution diagram for a typical operation on the demonstration route, with the fraction of duty cycle time on the *y*-axis and different speed intervals on the *x*-axis.

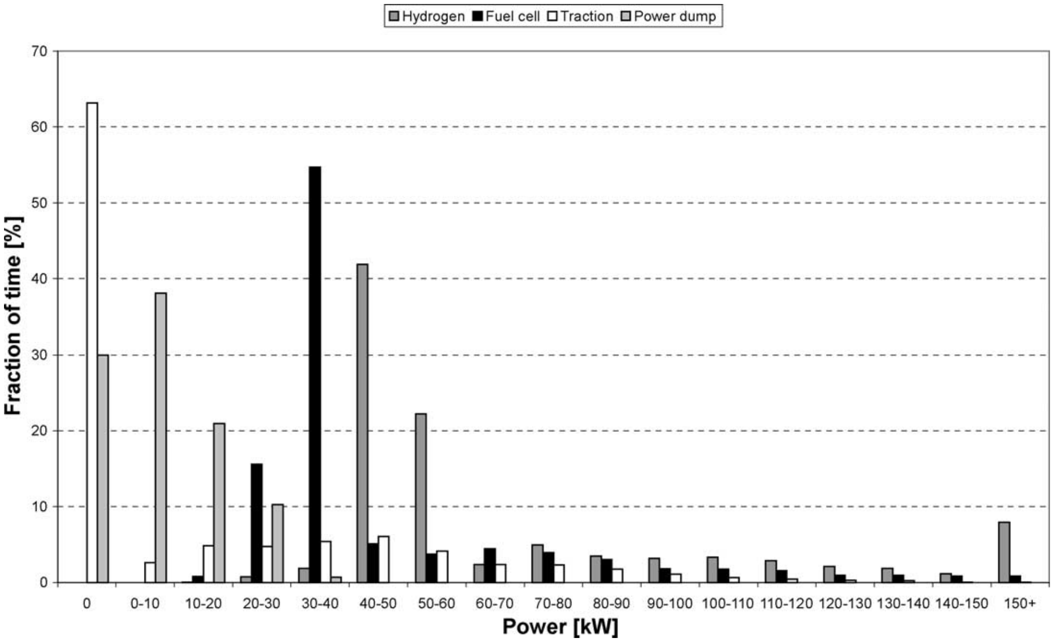

Fig. 9. The power distribution as fraction of the total duty cycle time for a typical operation on the demonstration route.

on LHV of hydrogen and average power consumption values over the demonstration route (please use Fig. 3 for reference). The fuel cell stacks produces electricity with a heat loss of 37%. While the losses in the dc/ac (inverter) and electric motor add up to 6%, the bus accessories including pumps and air compressor contribute with 23%. Here, the air compressor power demand is the main parasitic loss and uses some 15% of the total fuel cell power output. Taking the losses into account, the remainder power available to the traction including gearbox, etc. is about 23% of the fuel input energy. In comparison, tests of a hybrid electric fuel cell bus resulted in a significantly higher part of the energy input (i.e., fuel), 43% available for traction [8].

In general, changing the design of the fuel cell module balance of plant and/or implementing a hybrid driveline design will improve the efficiency of the driveline of the fuel cell buses. For instance, by replacing the central motor with a number of smaller electric motors and dc/dc power conditioners, the losses connected to the gearbox and belt-drive of the fuel cell compressor and bus accessories may be reduced. Today, many components run continuously even when they are not in use and therefore cause unnecessary fuel consumption. In addition, the turn-down ratio for the fuel cell current (i.e., fuel cell power) is limited by the fuel delivery technologies available at the time of design. The minimum current drawn from the fuel cell system is higher than the minimum load for the accessories. As a consequence, excess power is dumped to a resistor. As much as 8 kW of electricity in average was rejected as heat from the fuel cell system via the dump resistor during the tests on the demonstration route. If the excess power of the fuel cell system could be used within the system, e.g., charging an energy storage device, instead of being simply dumped into a resistor and dissipate as heat into the cooling system, the overall efficiency of the propulsion system may be improved. Improved fuel delivery components would resolve the turndown problem. Hence, by controlling the power from the fuel cell more efficiently, 20% of hydrogen would be saved.

Another approach could be to use a hybrid design for the driveline, allowing a battery or other energy storage device to power assist at accelerations and to recover the brake energy. Still, any alterations to the driveline risks causing additional complexity, weight and cost. Furthermore, although efficient, hybrid drivelines for heavy-duty vehicles of today, are not yet proven to be robust. Hence, there is a trade-off between a high efficiency and low fuel consumption on one side and robustness and ease of maintenance on the other side. In addition, one of the project's goals is to demonstrate the *feasibility* of the fuel cell technology and to increase the awareness of the technology of the public. It does not serve this goal of the project if the buses appear to be in the workshop for service very often. As will be shown in the maintenance and other sections further on in the paper, the cautious approach for robust design of the fuel cell driveline seems to have worked out well and people is positive towards the fuel cell buses.

7.2. *Comparison of fuel consumption for fuel cell and diesel buses*

A preliminary comparison of the average fuel consumption between a fuel cell bus and diesel bus, both Mercedes-Benz Citaro buses of similar sizes, was performed on the bus route 66 in Stockholm in September 2004. The Citaro diesel buses are equipped with Euro 3 (205 kW) engines and the curb weight is approximately 2000 kg lower than for the fuel

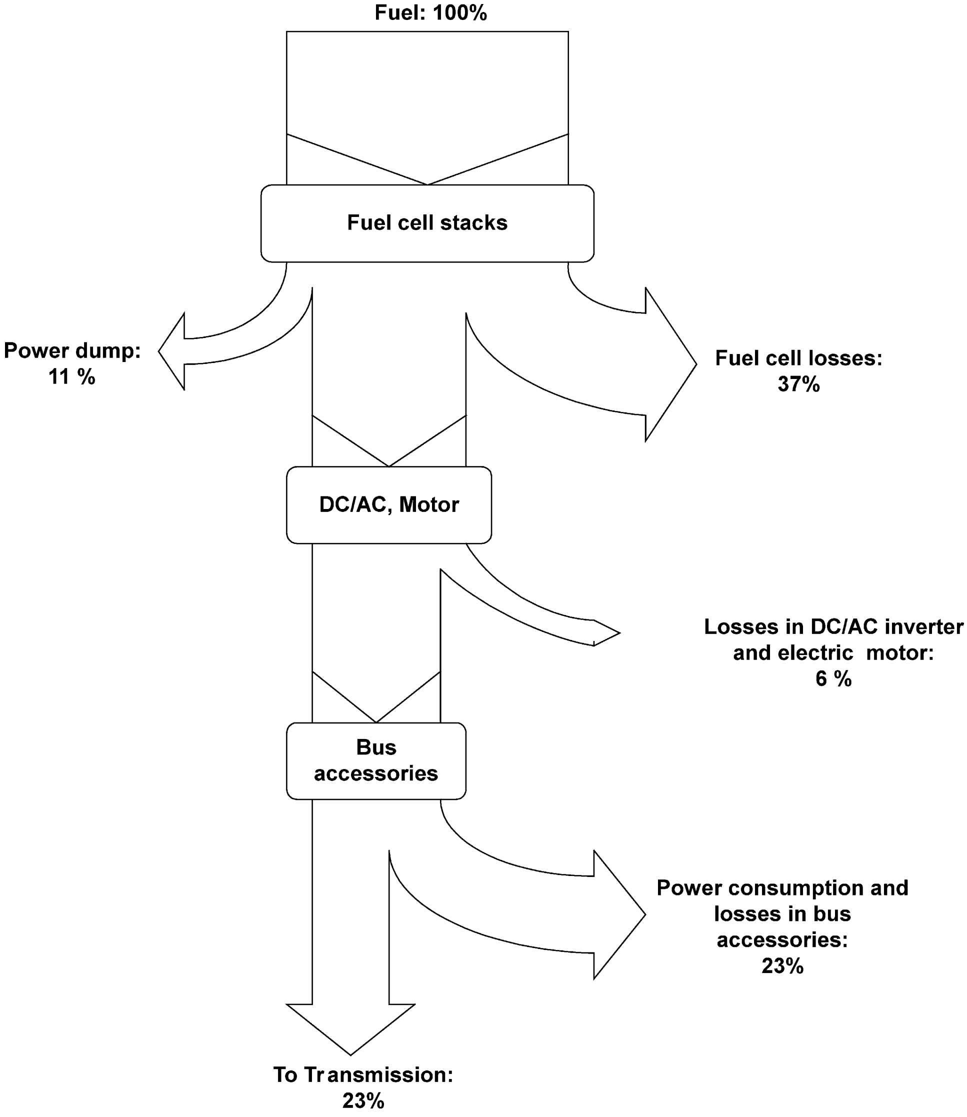

Fig. 10. Sankey diagram for a typical operation on the demonstration route.

cell bus version. The operation on the bus route 66 differs from the operation on the demonstration route by two means. Firstly, this is a well established, and commuter dense bus route in central Stockholm. Secondly, the bus route 66 is quite hilly, why the difference between the maximum and minimum altitude is rather high, about 40 m.

The buses were operated during similar conditions in parallel during 3 days on the route while the fuel consumption were monitored and recorded. The drivers that usually drive the fuel cell buses drove both buses. They were all instructed to use similar driving patterns on both types of buses. The fuel consumption was measured in terms of travelled distance and refuelled amount of fuel over a whole day rather than in an individual duty cycle, hence only a rough estimation can be provided from these data. The diesel bus consumed about 5.7 l/10 km, which is in the range of other buses in Stockholm public transit operation. The fuel consumption of the fuel cell bus was higher than that of the diesel bus, 2.5 kg H2/10 km or 8.5 l DE/10 km[1]. In comparison, ethanol-fuelled buses frequently in revenue service in Stockholm consume about 10.4 l of ethanol per 10 km or 5.8 l DE/10 km. Further investigations on bus performance on this bus route are scheduled during Fall 2004 and Spring 2005.

7.3. Maintenance during Spring 2004

Fig. 11 shows the categories of the maintenance and service of the fuel cell buses during Spring 2004 in Stockholm. The fuel cell propulsion system, which here is defined as including fuel cell system auxiliary system and other fuel cell driveline specific components but excluding the fuel cell stack modules, dominates the overall service of the buses. In parallel to the operation and regular maintenance, the fuel

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[1] The calculations are based on the assumptions: diesel: density, 0.833 kg l^{-1}; LHV, 42.5 MJ kg^{-1} and H_2:LHV, 120 MJ kg^{-1}.

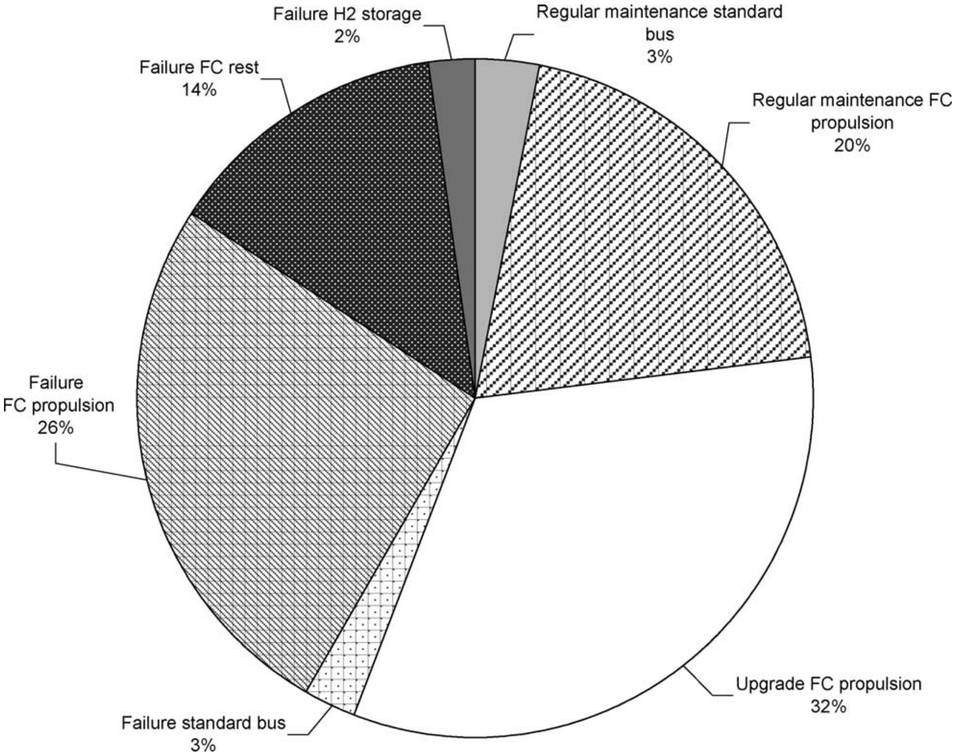

Fig. 11. An overview of the overall fuel cell bus maintenance issues during January through July 2004.

cell propulsion system and other systems were continuous upgraded and constitute half of all service. Failures of the fuel cell propulsion corresponded to about one-fourth of all service. The maintenance time, including both repair and upgrades, was initially higher averaging for all the buses of 32 h, or between 24 and 40 h per bus and month. It took 2 months for the service of the fuel cell buses to stabilise and a routine to be established. As the upgrade processes have proceeded, and the experience of the technical staff has increased, the staff is more able to identify and prevent up-coming problems. Consequently, the number of failures of different systems in the buses has been reduced.

The fuel cell buses are parked outdoors at the bus depot during the night. At wintertime, an electric heater provides heat in order to keep the buses at fuel cell system temperature above freezing (the recommended minimum temperature for the fuel cell system is +5 °C [4]). However, any issues with the fuel cell buses in Stockholm have occurred in the auxiliary systems and electronics rather than in the fuel cell stacks and these issues were mainly due to technical limitations of the equipment or humidity condensation rather than cold climate-induced problems. However, low temperature related maintenance issues did occur at start-ups during the cold winter months and accounted for almost 9% of all fuel cell propulsion failures. At a few occasions, it was evident that the heat provided by the electric heater that was plugged in during cold winter nights was not enough to keep some parts of the fuel cell system from freezing (pipes and water tanks). Ballard solved these problems in May 2004 with additional insulation and re-routed heating line. In addition, after a cold night, issues with insufficient stack heating or too low start battery voltage for a proper start-up could arise, the latter a problem that seems to have occurred in other CUTE cities during wintertime as well. Some pressure sensors could also show some sensitivity to humid weather, i.e., wet snow. These cold climate-related failures occurred only in January and February, months with temperature minima well below 0 °C. Measures have been taken for these problems and the problems did not re-occur despite the occurrence of subzero temperatures in March and April. Overall, the approach for the robust design seems to be rewarded. So far, the fuel cell buses have not had any major breakdowns and the number of road calls is only three.

7.4. Availability

The availability is here defined as the percentage of planned bus operation was accomplished. The overall availability for the buses during Spring 2004 was good, about 70% initially and increasing to an average of 85% during the summer months (see Fig. 12). Also shown in the figure is the bus operation time per month. The amount of time the buses were in regular transit operation was in average 300 h per month and totalled at the end of July to more than 2000 h. The reasons for the initial variation in availability were several. Failures of the fuel cell propulsion or other systems that requires replacement of non-standard components sometimes caused

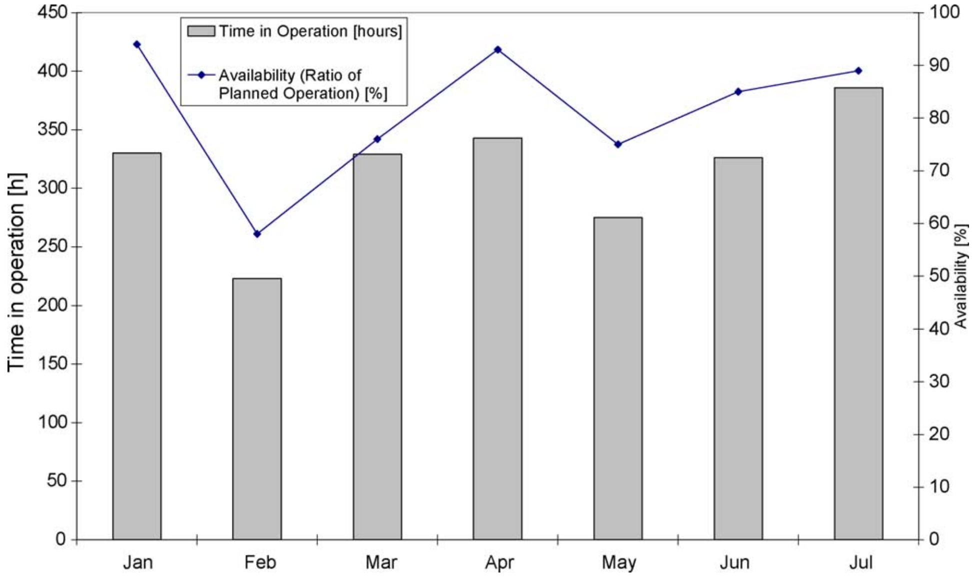

Fig. 12. The number of hours of bus operation and the availability (% of planned bus operation) during January–July 2004.

reduced availability. Lack of spare parts and some times even lack of drivers could also cause cancellation of the fuel cell bus operation.

The monthly distance and the accumulated distance are displayed in Fig. 13. During the Spring 2004, the fuel cell buses have operated in about 3000 km per month. The accumulated distance was at the end of July 24,531 km.

7.5. Impressions and experiences of the fuel cell buses

The bus drivers have shown a very positive attitude towards the fuel cell buses, although a few of them initially felt some doubts about the reliability of the buses and therefore idled the buses instead of turning the buses off at scheduled breaks in the duty cycle.

A 3-day survey of a total of 518 passengers using the fuel cell buses on bus route 66 for commuting during September was performed in order to investigate the passenger’s overall experience and acceptance of fuel cell and hydrogen technology. In the survey, the majority (77%) knew about the CUTE fuel cell bus project with the most common sources of information being newspapers and bus stops (see Fig. 14). Most passengers regarded the buses as more quiet and comfortable than ordinary transit buses. Regarding the fuel cell technology in the bus, a majority of the passengers (74%) felt that the technology was safe and 43% of the passengers wanted

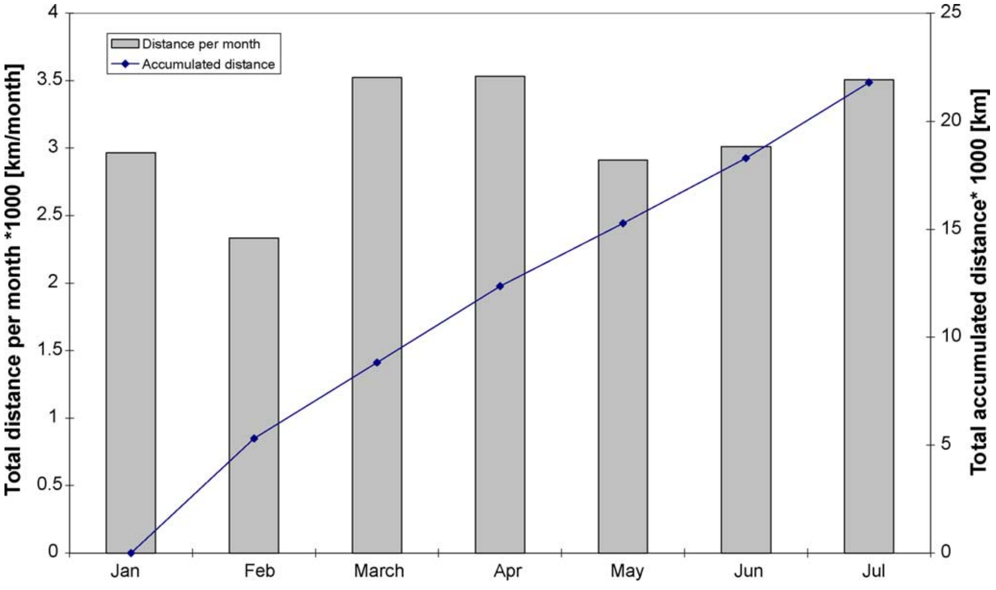

Fig. 13. The total distance per month (i.e., for all three fuel cell buses) on the left *y*-axis and the accumulated distance for all three buses during the time period of January–July 2004.

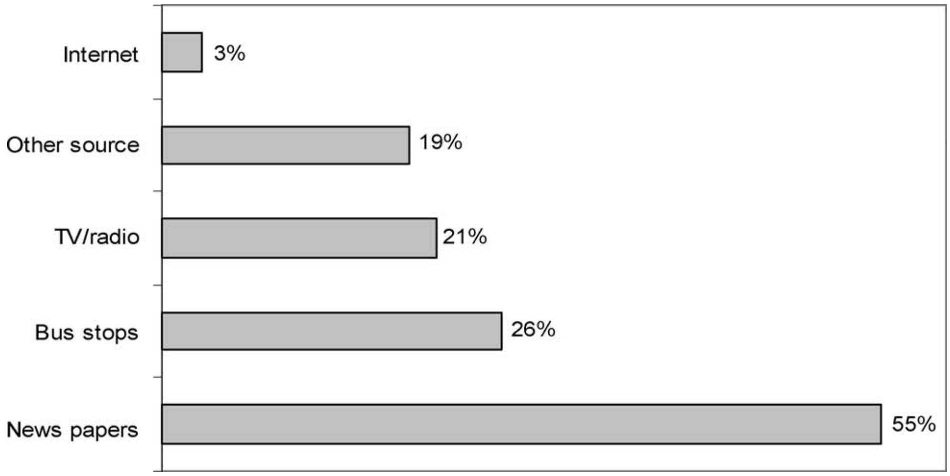

Fig. 14. Information sources of the fuel cell bus project, from survey in Stockholm.

to learn more about fuel cell and hydrogen technology. The only negative, and perhaps not all too surprising, result in this overall very positive survey was about the question of paying a higher ticket price to promote more fuel cell buses in transit operation. The commuters were clearly more interested in timeliness and frequency of the buses than any potential environmentally beneficial impact of the buses.

8. Conclusions

A first evaluation of the fuel cell buses in Stockholm after the first month in revenue service has been performed. The initial fuel consumption was high, but has decreased as a result of continuous upgrades of the fuel cell propulsion system and establishment of routines among the drivers and technicians. During a representative day in revenue service in July 2004, the average fuel consumption was 2.2 kg hydrogen/10 km, corresponding to 7.5 l DE/10 km. This is still a high number, approximately 2 l higher than for a Euro 3 diesel bus of similar size.

The high fuel consumption is due to the fact the buses are small series products and built for reliability and ease of maintenance rather than high efficiency. Improvements in terms of a better fuel economy and comfort (reduced noise and vibration), and design flexibility may be achieved by implementing electrically powered auxiliary components and hybridisation of the driveline. Hybridisation, i.e., adding an energy buffer system (such as batteries or super capacitors) would enable brake energy recovery as well as fuel cell system control optimisation. This would enable operation in a more advantageous efficiency interval and minimise the need of using dump resistors to eliminate the excess power from the fuel cell—this extra power would be used to charge the energy buffer system. On the other hand, the design for robustness has been rewarded in that there has not been any major breakdown of the buses and the availability of the buses in Stockholm was high, over 70% in average. This is also shown in the positive attitudes towards the fuel cell buses of both bus drivers and the public.

Cold climate impact on the fuel cell bus operation was indicated by a higher value of the fuel consumption during the winter months. It was however not a clear indicator as other factors such as bus driver behaviour also had an impact. On the maintenance side of the bus operation, cold climate caused about 9% of all fuel cell propulsion system related failures. After proper measures, the problems did not re-occur.

Tests and evaluation of the fuel cell bus operation in the cities within the CUTE project will continue through 2005.

References

[1] Fuel Cell Vehicle World Survey 2003, Breakthrough Technologies Institute, US Department of Energy, Energy Efficiency and Renewable Energy, Feburary 2004.
[2] ECTOS information, http://www.newenergy.is/.
[3] STEP information, http://www.dpi.wa.gov.au/fuelcells/.
[4] CUTE Hydrogen Supply Infrastructure and Fuel Cell Bus Technology, Brochure, EvoBus, 2004.
[5] CUTE information, http://www.fuel-cell-bus-club.com/.
[6] Stockholm Environment and Health Protection Administration, 2004.
[7] K. Johansson (Haraldsson), P. Alvfors, The effect of drive cycles on the performance of a PEM fuel cell system for automotive applications, in: Proceedings, ATTCE 2001—Automotive and Transport Technology Congress and Exhibition, Barcelona, Spain, 1–4 October, 2001.
[8] A. Folkesson, et al., Real life testing of a Hybrid PEM fuel cell bus, J. Power Sources 118 (2003) 349–357.
[9] Vehicle registration certificates for MB Citaro fuel cell buses in Stockholm.
[10] C. Martinsson, P. Sjöbom, Hydrogen Refuelling Station including Production and Storage—Experiences from the CUTE Project in Stockholm, ÅF Teknik & Miljö AB, 2004 (in Swedish).