Energy system analysis of the fuel cell buses operated in the project: Clean Urban Transport for Europe

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Received 17 September 2007

Abstract

During the project Clean Urban Transport for Europe (CUTE), which ended in May 2006, 27 fuel cell buses were operated in nine European cities. In this paper key performance parameters from the operation of the fuel cell buses in the project are reported, the energy system of the bus is analysed and drive cycle tests in five cities are presented and analysed. The focus of the paper is on fuel consumption and optimisation potential but experiences of, and recommendations for, evaluation in large demonstration projects are also presented. The results show that although the total fuel cell system efficiency was found to be high (36–41%), the fuel consumption was higher for the fuel cell buses than for diesel buses. Since the CUTE buses were a pre-commercial generation of fuel cell buses, with standard auxiliaries and extensive reliability measures, large fuel consumption reduction is possible. Suggestions on how to increase the efficiency is presented in this paper. Minimising the reliability measures would decrease fuel consumption by about 20% and lowering the weight by 2 tonnes would decrease fuel consumption by another 10%. Hybridisation in combination with using electrical auxiliaries could save an additional 5–10% or more.

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Keywords: Bus; CUTE; Drive cycle; Duty cycle; Fuel cell; Urban traffic

1. Introduction

1.1. Background

The fuel cell bus demonstration project Clean Urban Transport for Europe (CUTE),1 which ended in May 2006, was a historical project. It was the first field trial where a substantial number (27) of fuel cell buses of the same kind was operated simultaneously. Before the CUTE project, mostly small fleets of one to three fuel cell buses had been demonstrated in the world [1]. They were usually operated in one or two cities, and only a few were operated in regular traffic. The largest demonstration project before the CUTE project was the Xcellsis/Ballard phase 3 programme, where six buses operated during 2 years (1998–2000) in regular service in Chicago and Vancouver [2]. In 2002 an estimated total of about 31 fuel cell buses had previously been built and operated worldwide [1]. The CUTE project doubled that amount.

The CUTE project was initiated and co-ordinated by DaimlerChrysler and funded by the European Commission. The objective of the project was to demonstrate and evaluate the new technology used for the Citaro fuel cell buses, including the hydrogen (i.e. fuel) infrastructure. The number of buses as well as the diversity of operation conditions, in addition to the total amount of kilometres and hours driven in the nine participating cities, presents a unique possibility for evaluation of the feasibility of current hydrogen-powered fuel cell vehicles. Besides the 27 CUTE buses, another six buses of the same kind were operated within the associated projects ECTOS (Reykjavik/Iceland, also funded by the EU) being a forerunner to CUTE and STEP (Perth/Western Australia) starting somewhat later. In addition, three more similar buses started operating in Beijing, China, in November 2005.

The nine cities participating in the CUTE project were Amsterdam, Barcelona, Hamburg, London, Luxembourg,

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- More information about the CUTE project can be found at www.fuel-cell-bus-club.com.

0360-5442/$ - see front matter © 2008 Elsevier Ltd. All rights reserved.
doi:10.1016/j.energy.2008.01.001
Madrid, Porto, Stockholm and Stuttgart. Three buses were operated for 24 months in each city. The first bus started operating in Madrid in May 2003. Most other buses started operating in the autumn of 2003 or at the beginning of 2004. The cities had different refuelling infrastructures (for more information on infrastructure, see the final report [3]) and also different approaches to operating the buses. Some operated the buses on a regular route in regular traffic from the start, while some let the buses run in addition to the regular traffic until the reliability of the buses had been proven. Another difference in operation was that five cities operated the buses on only one or two routes (Amsterdam, London, Porto, Stockholm and Stuttgart), three cities operated the buses on three to five routes (Barcelona, Hamburg and Madrid), while one city (Luxembourg) operated the buses on all routes. Also, the operation conditions differed widely in the cities. Some cities are hilly, for example, Barcelona, Luxembourg, Porto and Stuttgart, others are flat, for instance Amsterdam, Hamburg and London. Madrid is hot and dry while London and Stockholm are cold and humid.

In Stockholm the CUTE project was co-ordinated by the City of Stockholm and involved the Stockholm Public Transport (SL), the bus operator Busslink, the energy and gas distributor Fortum and KTH (the Royal Institute of Technology). KTH was engaged via Busslink to be responsible for evaluating the operation of the buses from a climate perspective, as leaders of work package 4.

1.2. Prior publications and other fuel cell bus projects

Some first experiences of the CUTE project have previously been published by Haraldsson et al. [4]. This paper focused on the operation in Stockholm and the fuel consumption from a climate perspective. General experiences from the ECTOS project in Reykjavik have been published by Maack and Skulason [3] in a paper discussing the future hydrogen economy on Iceland.

Other more recent fuel cell demonstration projects are the Japan Hydrogen and Fuel Cell (JHFC) demonstration project and the California Fuel Cell Partnership (CaFCP) demonstration. In Aichi, Japan, eight hybrid fuel cell buses operated for a 6-month period in 2005. Some results from this trial have been presented on the JHFC homepage [6]. In California seven buses are currently (2007) in operation according to the CaFCP homepage [7]. Four of these buses are van Hool buses with fuel cell systems from UTC Power and a hybrid driveline. Three of these are operated by AC Transit, in Oakland, and one by SunLine Transit Authority, in Palm Springs. A report on preliminary evaluation results from the three hybrid vehicles operated by AC Transit was published by NREL in February 2007 [8]. The other three buses in the California Fuel Cell Partnership are Gillig buses powered with the same type of fuel cell system as the CUTE buses, i.e. the P5-2 fuel cell module from Ballard power systems. These buses were operated by Santa Clara Valley Transportation Authority (VTA) in San Jose. A report on the evaluation results from the period March 2005–July 2006 was published by NREL in November 2006 [9].

Fuel consumption characteristics of regular diesel buses in public transport have previously been analysed by, for example, Ang and Fwa [10] and within the SORT project [11]. A comparison of fuel consumption for one of the CUTE buses used in Porto with on-board measured data from a Citaro diesel bus is made by Frey et al. [12]. There are to our knowledge, besides the above-mentioned papers, few scientific publications regarding fuel cell bus demonstration projects.

1.3. Contribution of this paper

This paper presents conclusive operational results for the bus operation in the CUTE project as well as results from tests performed on the buses during the project. The conclusive operational results in Section 3 include average speeds and fuel consumption figures for the entire project period as well as the reported availability and number of road calls. In Section 4, the energy system of the bus is explored by analysing on-board measured data from a drive cycle test in Stockholm. Complementary tests of the base consumption of the bus were made and are analysed in Section 4.3.1. In addition, consumption of selected auxiliary systems was measured and an estimation of their influence on the average fuel consumption in regular traffic is presented in Sections 4.3.2 and 4.3.3. To analyse differences in fuel consumption due to different operating conditions, on-board measured data from drive cycle tests in five cities are analysed and compared in Section 5. The analysis and the results presented are mainly focused on fuel economy. The results are compared with fuel consumption characteristics of regular diesel buses and with previous, and ongoing, fuel cell bus demonstration projects. Recommendations for future projects as well as technical recommendations for minimising the fuel consumption of fuel cell buses are given in Section 6. The findings presented in this paper have previously, to some extent, been presented at the final CUTE Congress held in Hamburg in May 2006 [13] as well as in the final brochure of the project [3] and in the report to the European Commission (deliverable 2-restricted).

2. Methodology

2.1. Data collection in the CUTE project

A huge amount of data was collected continuously throughout the CUTE project. The coordinators of the project (and supplier of the buses), DaimlerChrysler, and the supplier of the fuel cell system, Ballard, had installed measurement equipment on-board the buses to monitor the system’s performance on a twice per second basis. This was apart from evaluation and maintenance purposes done to ensure safety and reliability. All these data were obviously
not analysed by any of the work packages in the project. However, when performing tests, Ballard supplied data from this measurement equipment to the test coordinators. These data in this paper are referred to as Ballard data. Some of the data supplied were raw operating data, for example time, electric motor speed, torque request, vehicle speed and hydrogen tank pressure. Some were by Ballard-processed data, such as fuel consumption, fuel cell efficiency and power consumption of some of the auxiliaries.

In Stockholm, additional GPS systems with barometric altitude measurement functionality were purchased and installed in the buses in order to sample vehicle speed and altitude (i.e. road grade) during drive cycle tests.

Besides the measured data collected by the on-board logging system, manually read data were reported by the maintenance personnel and bus drivers in each city in an Excel sheet named the Mission Profile Planning (MIPP), henceforth referred to as MIPP data. These data included the refuelled amount of hydrogen, kilometres driven, approximation of passenger load, bus maintenance and repairs, etc. The MIPP sheets were introduced quite late in the project. The first city started reporting in September 2003 but many waited until December 2003. Furthermore, the importance of the collection of these data was not clear to all involved, which resulted in varying quality of reported data. Also the definition of some key parameters differed from city to city, for example availability and passenger counting. In addition, comparing the reported fuel consumption on a daily basis with fuel consumption data from Ballard indicates that there were major disturbances in the MIPP data, such as gaps in the data for some periods and abnormally high consumption values for others. The latter might be due to the measurement equipment on the dispensers, which have been known to report faulty numbers if the refuelling is aborted manually, or to the human factor while reporting. The largest errors noted are however non-systematic and cancelled out when calculating averages over the entire period. Hence, although these data are not as reliable as the Ballard data, they may be used to estimate trends in, for example, fuel consumption and they give an indication of how different conditions affect the buses.

2.2. Definitions and terminology

- **Availability**: The availability is a criterion of quality for a system. Availability is defined as the degree to which a system or component is operational and accessible when required for use [14]. Regular maintenance may limit the downtime and increase the availability. In the CUTE project the availability was defined as the days of downtime in a month divided by the total number of days reported during that month. The total number of days reported was supposed to be every day of the month but since not all operators reported every day it was not possible to decide whether or not the buses had been available for operation during these days. Since a full day is the resolution of the definition, maintenance scheduled around service hours are not included in the downtime.

- **Reliability**: The reliability is the ability of a system or component to perform its required functions under stated conditions for a specified period of time [14]. In the CUTE project the aim was to prove the reliability of the buses and especially the fuel cell system under different European conditions with focus on climate, traffic and topography. The number of technical failures or incidents and the number of road calls are ways of measuring the reliability of the buses.

- **Average speed**: In this paper, the average speed is calculated in two ways. From the MIPP data, average speed over the entire project period is calculated as the total amount of kilometres driven divided by the total amount of hours in operation. For specific tests the average speed is presented as an average of the vehicle-speed data measured in the bus and provided by Ballard.

- **Fuel consumption**: The fuel consumption is presented as the mass (kg) of hydrogen consumed per 100 km or litre diesel equivalents per 100 km. In this paper the fuel consumption is calculated in two different ways. From the MIPP data the fuel consumption is calculated from the refuelled amount of hydrogen and divided by the total amount of kilometres driven. For the specific tests the fuel consumption is calculated from the instantaneous hydrogen consumption provided in the Ballard data. The fuel consumption stated in litre diesel equivalents is calculated using the lower heating value (LHV) of hydrogen, i.e. an energy density of 120 MJ/kg. For diesel an energy density of 42.5 MJ/kg and a density of 0.85 kg/l are used.

- **Drive cycle**: The definition of a drive cycle used in this paper corresponds to a scheduled bus route and operation in regular traffic. Depending on route characteristics, a drive cycle is in some cases a one-way trip and sometimes a round trip.

- **Energy efficiency**: Energy efficiency is the degree to which a system or component performs its designated functions with minimum consumption of resources [14]. Several different efficiencies are presented in this report:
  - the electrochemical efficiency, which is the efficiency of the fuel cell stack defined as the ratio between the useful, direct current, energy output from the unit and the chemical energy input,
  - the fuel cell system efficiency, which includes not only the electrochemical efficiency but also the consumption of the fuel cell system auxiliaries as well as losses due to reliability measures used for the fuel cell system, and
the powertrain efficiency, which is the efficiency from fuel input to mechanical power to the automatic gearbox.

For electrical auxiliaries converting energy, mechanical to electrical or vice versa, the efficiency is defined as the ratio of energy out to energy in, i.e. a measure of the losses in the conversion. For auxiliaries such as door openers, kneeling system, etc., the efficiency is defined as the ratio between energy theoretically needed to perform the specific task and the energy actually used.

2.3. The tests performed

This paper presents some general results from the MIPP data as well as specific results from drive cycle tests and specific auxiliary tests. The methodologies of the tests are briefly described in the corresponding section.

3. General experiences of the bus operation

3.1. Availability, incidents and road calls as performance indicators

One of the main goals of the CUTE project was to show that the fuel cell buses were reliable enough to be used in normal operation and the buses were designed with this in mind, more details on the bus design is found in Section 4.1. To be able to monitor the availability, the operators reported if the buses where in service or not in the MIPP sheets. The availability, presented in Fig. 1, was calculated as the total number of days that the buses were reported to be in service (i.e. not out of service due to maintenance, repair or infrastructure failure) divided by the total number of days reported. The total number of days reported should be every day of the month but since not all operators reported every day it was not possible to decide whether or not the buses had been available for

![Fig. 1. The availability calculated as days of bus in service divided by the total number of days reported. Below, the availability of reported data.](image-url)
operation during these days. When the first buses started to operate in Madrid in May 2003, the MIPP sheets had not yet been introduced and some initial problems were thus already solved when the other cities started to operate their buses. Also, even though the MIPP sheets were used, the availability was not reported during the first months of operation in some cities (e.g. Hamburg, London, Stockholm and Stuttgart, see Fig. 1). Therefore this period is not part of the calculated availability. The combination of these two factors means that the availability presented for the project period is somewhat higher than the actual availability of the buses during the entire project period.

The availability reported was high (75–99%) with the exception of Barcelona (60%) that had an incident with impure fuel, which contaminated the hydrogen storage. The hydrogen storage was sent away for inspection and cleaning, and the buses were out of operation for over 3 months. As mentioned, full days is the resolution of the definition of availability, and maintenance scheduled around service hours combined with few and well-educated drivers is the key to the high availability achieved in Stuttgart. The general opinion among the participating cities was in fact that the buses were more reliable than expected.3

Part of increasing the availability is to decrease the number of incidents and road calls. DaimlerChrysler monitored the incidents and road calls from the beginning of the project. The number of incidents per 1000 km, calculated as an average of the nine CUTE cities by month of operation (i.e. month 01 is in May 2003 for the first bus in Madrid and February 2004 for all three buses in Stockholm), decreased from 16 incidents per 1000 km for the first month of operation to about 2.5 in the last month of operation. Also the number of road calls (RC), i.e. occasions when the buses for some reason had to be towed back to the bus depot, decreased from 5 road calls per 1000 km (200 km between RC) in the first month of operation to 0.5 (2000 km between RC) at the end of the project, see Fig. 2. The fuel cell hybrid buses operated by AC transit in Oakland had an overall RC rate of 480 km between RC in the first 8 months of operation [8] and the VTA fuel cell buses had 1445 km between RC as an average from March 2005 to July 2006. However, since the definitions of RC differ between the projects, the figures are not directly comparable. Not all road calls are actual breakdowns. In the CUTE buses there was an alarm system where a red alarm indicated that the bus driver should stop the bus and call for assistance. A reason for the decrease in road calls could be that the number of events causing a red alarm was intentionally decreased during the project as the reliability of the technology was proven. In addition, some red alarms could later in the project be handled by a technician, via telephone or on location, without towing the bus, i.e. not defined as a road call.

A conclusion drawn from the reported availability and number of incidents and road calls is that the buses worked well after some initial problems were solved. The approach with designing the buses for problem-free operation was therefore successful. Worth mentioning is also that the number of incident and road calls did not increase at the end of the project. This is an indication that the maintenance and repair was well organised and also that the technology itself was not causing any major problems even after 24 months of operation, with an increasing average of hours operated per month [3].

3.2. Fuel consumption

The strategy of the fuel cell bus operation differed considerably between the participating cities. This can be seen in Table 1 where some key indicators, such as kilometres and hours of operation, average speed and fuel consumption, calculated from the MIPP sheets, are presented as averages over the entire project period. Average speed was calculated from the total amount of kilometres
driven and total hours of operation i.e. including stops or breaks with the bus still running. Policies for turning off the bus during breaks etc. might have been different from city to city and may also have been changed during the project. The average fuel consumption was calculated from the refuelled amount and the total amount of kilometres driven. The calculated average fuel consumption should not be regarded as the exact fuel consumption while in traffic, since a considerable amount of refuelled fuel most likely was spent while idling, during for example start-up or maintenance. This would give a systematic error towards higher fuel consumption figures for the average values calculated from the MIPP sheets. This is confirmed by the fact that the fuel consumption, measured during the drive cycle tests presented later in this paper, was in all cases lower than the average fuel consumption calculated from MIPP data.

The average fuel consumption calculated from the MIPP data indicates that the fuel cell buses demonstrate an energy consumption that is higher than that of a conventional diesel bus. The fuel cell buses consumed 20.4–30.0 kg hydrogen per 100 km, which is equivalent to a fuel consumption of 67.8–99.7 l diesel per 100 km. The estimated fuel consumption for a conventional 12 m diesel bus from the SORT drive cycles (i.e. not specifically for the diesel Citaro) range from 39 to 50 l per 100 km [11], on a flat route with 3.2 tonnes load. Tests performed by Ang and Fwa in 1989 on different bus models showed an actual fuel consumption ranging from 20 to 75.5 l per 100 km [10]. These figures show that the fuel consumption of the fuel cell buses is above or in the upper range of the fuel consumption of conventional diesel buses. This is also confirmed by the measured fuel consumption in Porto presented by Frey et al. [12]. However, the fuel cell buses were, as mentioned, not designed for low fuel consumption but for high reliability. An interesting observation is that the three cities with highest fuel consumption, Barcelona, Madrid and Porto, are among the cities that operated the fewest kilometres and hours.

4. Energy system analysis of the fuel cell buses

4.1. Description of the bus

The fuel cell buses in the CUTE project were based on the conventional 12 m Mercedes-Benz Citaro low-floor city bus. The aim when designing the bus in 1999–2000 was not to realise the ultimate future urban bus but to demonstrate and prove that hydrogen-powered fuel cell buses may function well in daily operation in urban transport systems in Europe. This means that maintainability, reliability and cost were important design parameters and that the buses were designed for high reliability and durability rather than fuel economy. High reliability and availability is demanded by bus operators in order to keep their timetables and to fulfil operation contracts, in the long run, for them to stay competitive. Another important aspect is that the acceptance of a new technology is affected by the initial encounters with the technology. Therefore, it is important that this first encounter is a positive experience for the public, the bus drivers and the operators and for this reliability is a key factor.

In the fuel cell buses, the fuel system and internal combustion engine have been replaced by a high-pressure (350 bar) hydrogen storage system, two polymer electrolyte (PEM) fuel cell stacks with balance of plant components (fuel cell auxiliary systems), a DC/AC inverter and a central electric motor. The general bus layout is shown in Fig. 3. The central electric motor powers a standard low-floor rear axle through an automatic gearbox, similar to the configuration of the conventional bus. Most auxiliaries except those specific to the fuel cell system are standard

<table>
<thead>
<tr>
<th>Site</th>
<th>Kilometres of operation (km)</th>
<th>Hours of operation (h)</th>
<th>Average speed (km/h)</th>
<th>Average fuel consumption (kg H₂/100 km)</th>
<th>Average fuel consumption (l diesel/100 km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Amsterdam</td>
<td>109,098</td>
<td>6040</td>
<td>18.1</td>
<td>21.6</td>
<td>71.8</td>
</tr>
<tr>
<td>Barcelona</td>
<td>37,654</td>
<td>2927</td>
<td>12.9</td>
<td>27.4</td>
<td>91.0</td>
</tr>
<tr>
<td>Hamburg</td>
<td>104,473</td>
<td>6443</td>
<td>16.2</td>
<td>20.4</td>
<td>67.8</td>
</tr>
<tr>
<td>London</td>
<td>100,250</td>
<td>7226</td>
<td>13.9</td>
<td>24.0</td>
<td>79.7</td>
</tr>
<tr>
<td>Luxembourg</td>
<td>142,068</td>
<td>7942</td>
<td>17.9</td>
<td>20.9</td>
<td>69.4</td>
</tr>
<tr>
<td>Madrid</td>
<td>87,008</td>
<td>6296</td>
<td>13.8</td>
<td>28.8</td>
<td>95.7</td>
</tr>
<tr>
<td>Porto</td>
<td>46,929</td>
<td>5283</td>
<td>8.9</td>
<td>30.0</td>
<td>99.7</td>
</tr>
<tr>
<td>Stockholm</td>
<td>91,580</td>
<td>9448</td>
<td>9.7</td>
<td>26.6</td>
<td>88.4</td>
</tr>
<tr>
<td>Stuttgart</td>
<td>129,283</td>
<td>11,312</td>
<td>11.4</td>
<td>22.1</td>
<td>73.4</td>
</tr>
</tbody>
</table>

CUTE average | 94,260                      | 6991                   | 13.6                 | 24.6                                   | 81.9                                     |

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*a*The total number of kilometres reported in the MIPP sheets.

*b*The total hours of operation reported in the MIPP sheets.

*c*Average speed calculated from total amount of kilometres driven and total hours of operation.

*d*Average fuel consumption calculated from refuelled amount of hydrogen and kilometres driven.

*e*Average fuel consumption calculated in diesel equivalents from refuelled amount of hydrogen and kilometres driven.
auxiliaries, also found in conventional buses. All auxiliaries are powered mechanically, either directly via gears or a belt from a specially designed gearbox (mounted at the rear end of the central electric motor) or via the three generators producing electricity for the 24-v system. The hydrogen storage and main components of the fuel cell system are located on the roof of the bus. The supercharger, for air supply to the fuel cell system, and some pumps are powered by the central electric motor and consequently located at the rear end of the bus.

The extra weight of the fuel cell and hydrogen storage systems makes the fuel cell bus approximately 3 tonnes heavier than a regular bus.

4.2. Energy system analysis—mapping the energy flow in the bus

For a proper energy analysis a total energy mapping of the bus was needed. To illustrate the energy flow Sankey diagrams were used. The diagram gives an average overview of the energy flow, and is not representative for a specific time during the drive cycle but for the complete cycle. Fig. 4 shows a Sankey diagram based on average Ballard data, i.e. on-board measured data, from 8 drive cycle tests on a demonstration route in Stockholm. Consequently the data represent the special conditions for that particular route at the time of the tests. The demonstration route, called the Waterline, was a flat route with low average speed and a generous timetable; hence, much time was spent idling.

The baseline in the diagram is the total power input, calculated from instantaneous fuel consumption, in grams per second, using the lower heating value of hydrogen. The instantaneous fuel consumption is calculated from the current drawn from the fuel cell stack, measured on-board, and an empirical estimate of the hydrogen purge. Purging is used to remove nitrogen and other gases that might be present at the anode side of the fuel cell and is a standard procedure for PEM fuel cell systems. The frequency and duration of the purge is a matter of system design. Frequent purging increases the reliability and durability of the system. The purge is on average 4% of the total energy input during the tests.

The fuel cell output is calculated using actual fuel cell current and fuel cell stack voltage. The electrochemical efficiency in the fuel cell stack is calculated as the ratio between the fuel cell power output and the fuel cell power input. The electrochemical efficiency was 66% on average during the test and the losses (including purge) in the fuel cell stack constitute 33% of the total fuel input.

Some of the power from the fuel cell is directly consumed (dumped) in an electric resistor producing heat to the heating/cooling loop in the bus. Throughout the test about 11% of the total power input was dumped. This so-called
The energy flow analysis shows that savings in power consumption of the auxiliaries and/or traction generate a reduction of hydrogen consumption of three times (1/0.347) the size of the saving. This is due to the additional decrease in losses in the fuel cell, inverter and motor plus reduced consumption of the fuel cell system auxiliaries. These potential savings are however to a large extent opposed by the previously mentioned power dump. The minimum current limitation, causing the power dump, is used to increase the lifetime of the fuel cells since the lifetime of the fuel cells is increased if they are operated with a steady flow of hydrogen. This is a choice in the design of these fuel cell stacks and the fuel delivery system and is not a limitation of the polymer electrolyte fuel cell technology itself. A consequence of the power dump is that one of the advantages with the fuel cell disappears: since the efficiency of a fuel cell is higher at lower loads it would, without the power dump, present large fuel saving potentials for urban buses, which usually operate at low average speeds and with many stops—consequently having low average power demands. Another disadvantage of the power dump is that the fuel cell buses consume fuel while decelerating, for example when going downhill, in situations when regular Otto and diesel buses have virtually no consumption.

Instantaneous power consumption data from the tests reveal that the power dump is about 15 kW at standstill and up to 30 kW when the acceleration is negative, see Fig. 5. At standstill the mechanical auxiliaries are powered by the motor. The mechanical auxiliaries are, for example, the regular auxiliaries such as air compressor in the pneumatic system, the alternators in the 24-v system and the air conditioning compressor, but also the fuel cell system specific auxiliaries such as the supercharger and pumps and fans for the cooling system. To power these auxiliaries there is a minimum motor speed limitation, similar to the idling motor speed of a regular internal combustion engine. The minimum motor speed is set to 600 RPM and corresponds to 15–17 kW: fuel cell output minus the power dump during standstill (idling), in Fig. 5. The power dump increase while decelerating is explained by the fact that the auxiliaries are driven by the momentum of the bus while decelerating. Hence, less or no power is needed to run the motor and more power is dumped. The power dumped while decelerating is the maximum power dump. This means that energy saving measures would have effect only during the fraction of time when more than 30 kW is used if the minimum current limitation is kept.

4.3. Tests for detailed energy system analysis

In the data used for the energy system analysis there were some “unknowns”, for example the power for traction was calculated from the torque request and not from the actual power provided and the unspecified auxiliaries were calculated as the residue. To find a reasonable estimate of the base power needed for traction...
and the power consumption of the unspecified auxiliaries, some additional tests were performed.

4.3.1. Tests and analysis of base consumption

To evaluate the base consumption of the CUTE buses two different tests were performed, namely a constant speed test and a roll-out test. From these tests the base consumption at different speeds were obtained and the power for traction as well as the power consumption of the unspecified auxiliaries were estimated. The analysis was made for different vehicle speeds so that the results could be used to compare average values from the drive cycle tests, presented later in this paper. This approach is however not entirely accurate since most power-consuming auxiliaries are motor speed dependent and not directly vehicle speed dependent. The motor speed at different vehicle speeds is determined by drive mode and gearbox settings, which varied between cities.

The constant speed test was performed at five different speeds 10, 20, 30, 40 and 50 km/h on a flat route (airport runway) and all auxiliaries possible to control were turned off (no AC, no door openings, etc.). The test mass of the vehicle was 14,520 kg, corresponding to the bus, the driver and the 3 test coordinators. The bus was accelerated to the designated speed, which was maintained as long as possible, limited by the length of the runway. Each test was performed four times to obtain reliable consumption figures. For the higher test speeds the acceleration period was longer and the time spent at constant speed was hence shorter; thus the data for the lower speeds are more reliable. The data were filtered for data with no acceleration and within a speed range of ±3 km/h, from each designated speed. The measured fuel consumption and consumption for some system components are presented in Table 2; the corresponding system efficiencies are presented in Tables 3 and 4.

In Table 3 it is to be noted that although the electrochemical efficiency is higher for lower speeds, the overall efficiency of the fuel cell system is lower. This is mainly due to the power dump. In fact, the fuel cell system efficiency at 10 km/h would be comparable to the fuel cell system efficiency at 50 km/h if the power dump was removed.

In all calculations so far the torque request has been used for estimating the traction, but for higher speeds the torque request was not always met. Even for data filtered for zero

![Fig. 5. Power dump, fuel cell output, acceleration and speed over a short period (200 s) of a drive cycle test performed on the Waterline in Stockholm, July 7, 2004.](image)

![Table 2

Power consumption and losses for bus system components](image)
acceleration and positive torque request (i.e. the auxiliaries could not be driven by the momentum of the bus) subtracting power for traction, calculated from torque request, from fuel cell output minus power dump and specified auxiliaries gave negative results at times. Around 10% of all data for 20, 30 and 40 km/h gave a negative difference, less often for 10 km/h (only 3%) and more often for 50 km/h. This indicates that the torque request is not representative as power for traction. If the power for traction calculated from the torque requested was a fair estimation of the power needed at constant speed, the difference would be positive at all times since it also includes all auxiliaries not specified in the Ballard data, i.e. not measured on-board. It is therefore concluded that the traction calculated from the torque request variable is inappropriate as a measure of traction for higher speeds and a more accurate estimation of power for traction is needed. For solving this problem, a roll-out test was performed on one of the fuel cell buses in Stockholm. The roll-out test was used to quantify the running resistance of the bus, which includes air resistance, rolling resistance, gradient resistance and inertia (whenever accelerating), see Eq (1). The active force bringing a vehicle forward, \( F_x \), equals the total running resistance:

\[
F_x = 0.5 \rho A c_x v^2 + m g f_r + m g \sin \alpha (m + m_f) \cdot \ddot{x},
\]  

(1)

where the force from accelerating the vehicle mass, \( m \ddot{x} \), and moment of inertia in all moving parts, \( m \ddot{x} \), are included. In Table 4 the parameters used in the vehicle motion equation are described. By integrating this equation with respect to time, a function of initial and final vehicle speeds is obtained. By letting the vehicle free-roll, i.e. \( F_x = 0 \), from different speeds and measuring the distance travelled before coming to a stop, the rolling resistance coefficient \( f_r \) and drag resistance coefficient \( c_x \) may be calculated.

The rolling resistance coefficient calculated was 0.0113 and the drag resistance coefficient was found to be 0.7. By multiplying the motion equation, Eq. (1), with vehicle speed, the rolling resistance expressed in kW is obtained. This resistance includes friction in the transmission from the gearbox to the wheels, and also the friction between the wheel and the road, where the latter is the normal definition of rolling resistance. The power of the drag resistance is calculated in a similar way. The rolling, drag and total (sum of the two) resistances in kW as function of the vehicle speed for the fuel cell bus are displayed in Fig. 6. The figure shows the resistance at two vehicle weights, the tested weight of 14,520 kg and a maximum load of 18,000 kg. The total running resistance should be interpreted as the power needed to keep the vehicle at constant speed on a flat road. For example at 20 km/h the minimum power for traction is approximately 10 kW at a vehicle weight of 14,520 kg, and about 12 kW for the maximum load, corresponding to an increase in weight of 3480 kg (approximately 50 passengers). The increase in power (2 kW) corresponds to a 10% increase in fuel consumption calculated on the powertrain efficiency and the total hydrogen consumption at 20 km/h from the constant speed test. In some cities the maximum load is 19,000 kg (70 passengers) and the difference in fuel consumption between an empty and a full bus is consequently even larger.

A factor that has minor influence on the fuel consumption for an urban bus is the air resistance. This is due to the fact that the average speed of an urban bus is very low, usually between 10 and 25 km/h. At these speeds the rolling resistance is clearly dominating, see Fig. 6.

The results of the roll-out test give an estimation of the traction needed at constant speed. Comparing this estimated traction power with fuel cell output minus power dump, losses and consumption of specified auxiliaries, from the constant speed test, gives an estimation of power consumption of the other (unspecified) auxiliaries. A polynomial regression (second order, closest fit: \( R^2 = 0.6125 \)) for motor power output minus specified auxiliaries (i.e. traction power plus unspecified auxiliaries) for the constant speed data was made and the difference between the resulting equation and the total running resistance was calculated.

The analysis showed that the minimum power consumption of the other auxiliaries (minimum because it does not include on-demand auxiliaries such as air conditioning or power for door opening and kneeling) would be 8–10 kW at all times, see Fig. 7.

---

### Table 3

<table>
<thead>
<tr>
<th>Speed (km/h)</th>
<th>Electrochemical efficiency (%)</th>
<th>Fuel cell system efficiency (%)</th>
<th>Powertrain efficiency (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>66.3</td>
<td>31.9</td>
<td>26.6</td>
</tr>
<tr>
<td>20</td>
<td>66.1</td>
<td>38.5</td>
<td>32.8</td>
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<td>30</td>
<td>65.7</td>
<td>42.8</td>
<td>36.9</td>
</tr>
<tr>
<td>40</td>
<td>64.9</td>
<td>44.9</td>
<td>39.1</td>
</tr>
<tr>
<td>50</td>
<td>64.3</td>
<td>47.7</td>
<td>41.5</td>
</tr>
</tbody>
</table>

### Table 4

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>( F_x )</td>
<td>Acting force in the ( x )-direction</td>
<td>0 (N)</td>
</tr>
<tr>
<td>( \ddot{x} )</td>
<td>Vehicle speed in ( x )-direction</td>
<td>Measured (m/s)</td>
</tr>
<tr>
<td>( \dddot{x} )</td>
<td>Vehicle acceleration in ( x )-direction</td>
<td>Not needed (m/s²)</td>
</tr>
<tr>
<td>( M )</td>
<td>Vehicle mass at test</td>
<td>14520 (kg)</td>
</tr>
<tr>
<td>( m_f )</td>
<td>Equivalent mass of rotating parts</td>
<td>658 (kg)</td>
</tr>
<tr>
<td>( \alpha )</td>
<td>The inclination of the testing road</td>
<td>0.16 (deg)</td>
</tr>
<tr>
<td>( f_r )</td>
<td>The coefficient of rolling resistance</td>
<td>Unknown (–)</td>
</tr>
<tr>
<td>( c_x )</td>
<td>The coefficient of air resistance</td>
<td>Unknown (–)</td>
</tr>
<tr>
<td>( A )</td>
<td>Vehicle’s frontal area</td>
<td>8.46 (m²)</td>
</tr>
<tr>
<td>( \rho )</td>
<td>Air density</td>
<td>~1.23 (kg/m³)</td>
</tr>
</tbody>
</table>

\( ^a \) Calculated using a moment of inertia of each wheel of 20 kg m² and a rolling radius of 0.427 m.
4.3.2. Measurements on the 24-v system

Part of the power consumption for the unspecified (not measured) auxiliaries discussed in the previous chapter is the power consumption of auxiliaries in the 24-v system. This electrical power consumption during normal driving was measured to be approximately 2.5 kW, based on measurements on the 24-v system when idling. This corresponds to approximately 5 kW of mechanical work from the electric motor (or 14 kW of fuel input) with an approximated alternator efficiency of 50% (based on data from the supplier). This means that the 24-v system is one of the major unspecified auxiliaries.

The design of the 24-v system, which is powered by three mechanically driven alternators, was chosen because of reliability reasons, but it is not an energy-efficient solution. A suggestion for future designs is to use a DC/DC converter to convert the fuel cell power to 24 v. This would save up to 7 kW of fuel input (corresponding to the losses in the alternators), hence saving 6–13% of the total fuel input.

4.3.3. Test and analysis of on-demand auxiliaries

Besides the unspecified auxiliaries discussed in the previous section, and the 24-v system that is constantly...
powered, there are some auxiliaries that only consume power when used, i.e. on demand. Those are systems included in the pneumatic system, for example kneeling and door opening, and also for example cabin heating and air conditioning. To estimate the consumption of such systems, specific auxiliary tests were performed.

A system handling several of the on-demand auxiliaries is the pneumatic system, used for braking, kneeling and door opening. The pneumatic system consists of standard “off the shelf” components used in regular buses. Tests were performed to estimate how much the use of these systems affects the overall fuel consumption. The influence of using or not using kneeling and door openings was calculated for an average CUTE bus route, which is 10 km long and has 27 bus stops. During the tests the buses were standing still and the auxiliary system was used until the compressor was turned on. The number of kneeling and/or door-opening occasions for each compressor filling was noted. The energy consumption was calculated from the instantaneous fuel consumption in the Ballard data.

Kneeling measurements showed that each complete right-side kneeling of the bus at a vehicle weight of 14,520 kg (fuel cell bus plus 4 passengers) equals approximately 80 kJ mechanical work from the central electric motor. This is the energy needed by the air compressor to fill up the air vessels again after the kneeling. The theoretical work needed for a one-sided kneeling is calculated as

$$E_{\text{kneeling}} = \frac{m}{2} gh,$$  \hspace{1cm} (2)

where $g$ is the gravitational constant $g = 9.81 \text{ m/s}^2$. With an estimation of $h = 0.1$, i.e. lowering the fuel cell bus by 10 cm each kneeling, and given that the mass, $m$, was 14,520 kg, the theoretical work per kneeling was calculated to be 7.12 kJ. The compressed air is hence produced and utilised with an overall efficiency of 8.9%. The calculated efficiency of the pneumatic system is very low, but in line with previous research. For example Andersson [15] showed that the overall efficiency of a pneumatic kneeling system from powering the compressor to actual power lifting the bus was 7%.

The 80 kJ from the electrical motor corresponds to approximately 228 kJ power input (1.90 g of hydrogen), calculated with an approximated efficiency of 35%. Recalculating the results for a bus with 20 passengers a bus driver using the kneeling system on every bus stop during a round-trip on the CUTE average route (with 27 stops) would increase the fuel consumption by 0.51 kg per 100 km. This corresponds to 2% of the average fuel consumption in the CUTE cities, which was 24.6 kg per 100 km (see Table 1).

Each door-opening cycle (i.e. one double-door opening+closing) consumed 15 kJ from the central electric motor, corresponding to 42 kJ (0.36 g of hydrogen) to the fuel cells. This equals an increase of 0.28 kg per 100 km or 1.1% of the total fuel consumption when all three door-pairs were used, compared to when not used, at all 27 bus stops on the CUTE average route.

The air conditioning (AC) system is another on-demand auxiliary system. Additional tests were performed to investigate how the AC affects the fuel consumption. First the AC was turned off and the accelerator pedal was pressed to increase the engine speed from 600 rpm (pedal not pressed) to 2100 rpm (pedal at full travel), over a period of about 1 min. Next, the AC was turned on and the...
procedure repeated. This test was performed seven times to obtain reliable results. In Fig. 8 the motor power during the tests is presented. The data show that even when the AC was ON it was only active, i.e. AC compressor running, for about 20% of the time. Fig. 8 also shows that the difference in power out from the central electric motor when the AC is ON but not active compared with when it is disconnected is about 1.5 kW. This increase is caused mainly by the fans in the air conditioning system. The difference between when the AC is actively ON and just ON is 10 kW. During normal operation in regular traffic the AC is always on but only active when cooling is needed. The load of the air conditioning fans adds up to 4.3 kW (0.036 g hydrogen per second) of power consumption and the compressor causes an instant fuel consumption increase of 28.6 kW (0.24 g hydrogen per second) at all motor speeds, calculated at an efficiency of 35%. The difference between a cool and a hot day can be up to 5.7 kW in average fuel consumption (28.6 kW, 20% of the time), corresponding to 5.2–11.5% of the total power input during the constant speed test (somewhat less for actual operation).

The tests of on-demand auxiliaries indicated that the air conditioning alone could cause fuel consumption differences of up to 11.5%, based on the total power input during the constant speed test. Differences in the frequency of kneeling and door opening could together account for a variation in the fuel consumption of 3%. It is however less likely that the frequency of kneeling and door opening would differ to the extent calculated than the AC being constantly on in some cities while hardly being used in some cities. It should be noted that the consumption of these auxiliaries would constitute a larger part of the total fuel consumption if the energy system were optimized; hence energy saving measures are indeed still relevant.

5. Drive cycle tests in five cities

5.1. Background of the tests

To obtain reliable fuel consumption figures to analyse and compare with the MIPP data, drive cycle tests were performed on regular routes (one route per city) with the buses in regular service. These drive cycle tests were performed in five of the nine cities in the CUTE project: Amsterdam, London, Luxembourg, Porto and Stockholm. The aim of the drive cycle tests was to acquire on-board measured data on fuel consumption under known conditions. For this a special gear-shifting scheme was used to mark the beginning and end of a drive cycle so that data for the different drive cycles could be identified and retrieved from the Ballard data. Specific test protocols were used to note everything of importance, for example number of kneelings, whether the air conditioning seemed to be on, whether there were any temporary obstacles on the route of the bus etc. Also an estimation of the number of passengers was made in these protocols.

The tests in Amsterdam, London and Luxembourg were initiated by GVB\(^3\) in Amsterdam and performed, in September 2005, by the bus operators in each city. The tests consist of 2–4 drive cycles per city. In Luxembourg and Amsterdam one bus was tested. In London two different buses were used.

In Amsterdam the fuel cell buses were operated on two routes, route 35 and route 38. The drive cycle test was performed on line 35. The route is only partly in the downtown area and apart from two or three crossings it does not face heavy traffic. On parts where the traffic is heavier, bus lanes are available; about 15% of line 35 is on separate bus lanes. In London the buses were tested on route RV1 in the downtown area where they usually operated. Approximately 15% of the route consists of bus lanes, which the buses have to share with bikes and taxis. There is no priority for the bus at traffic lights. The drive cycle test in Luxembourg was performed on line 9. In Luxembourg the fuel cell buses operated on all routes. Line 9 was chosen for this test because the route is composed of basically all circumstances met at any city bus route in Luxembourg. Line 9 is partly in the downtown area and has dedicated bus lanes on 22% of the line.

The tests in Porto were initiated and performed by Instituto Superior Técnico in Lisbon. Eleven drive cycles were measured during one day in August 2004. One bus was used. In Porto the drive cycle tests were performed on Route 20, a circular line crossing the city centre with heavy traffic. Route 20 is also where the fuel cell buses were usually operated.

In Stockholm, tests were performed on three occasions: July 2004, September 2004 and March 2005. These tests were initiated and performed by KTH. Three different buses were used. During the tests in July, the buses operated on a demonstration route in downtown Stockholm called the Waterline. In September and March the buses operated a regular route, Route 66, on the downtown island of Södermalm. The test used for comparison with the other cities is one of the test days on Route 66 in September 2004. Route 66 is used since it is a route in regular traffic and the test in September is used to avoid influence of the cold temperature during the winter test period.

The main difference in the test routes is that the routes in Luxembourg and Amsterdam are only partly in the downtown area, whereas the routes in London, Porto and Stockholm are entirely in the downtown area, with more frequent stops, higher passenger load per travelled kilometre and also probably facing heavier traffic. The topography is another factor that differs. In Amsterdam and London there are hardly any inclines and declines, while in both Porto and Luxembourg the landscape is hilly with climbs of about and over 100 m on the tested

\(^3\)Municipal transport corporation Gemeentevervoerbedrijf (GVB). The public transport company in Amsterdam. Project partners and work package leaders for work package 6 in the CUTE project.
5.2. Comparing the five cities

Fuel consumption of a vehicle in regular traffic is affected by several factors, such as traffic situation, passenger load, route characteristics and driver behaviour. In real-life testing, it is difficult to separate the influence of one factor from another. In this section the focus is on the analysis of:

- Average speed and drive modes, as indicators of route characteristics and traffic situation.
- Energy flow and power consumption, as indicators of how the energy system is affected by route characteristics.

Unfortunately, there was no reliable strategy for evaluating the effect of driver behaviour or passenger load. Concerning passenger load a theoretical influence on fuel consumption of increased load was calculated from the roll-out test in Section 4.3. In this section the focus is on the analysis of:

- Average speed and drive modes, as indicators of route characteristics and traffic situation.
- Energy flow and power consumption, as indicators of how the energy system is affected by route characteristics.

Unfortunately, there was no reliable strategy for evaluating the effect of driver behaviour or passenger load. Concerning passenger load a theoretical influence on fuel consumption of increased load was calculated from the roll-out test in Section 4.3.

From the drive cycle tests some key parameters were identified and an average figure for all drive cycles in each city was calculated for every parameter, see Table 5. All parameters but the distance is calculated from Ballard data. The value of the number of stops per kilometre includes all stops, namely, bus stops, red lights, traffic congestions etc. A stop is defined as whenever the bus stands still for more than 1 s.

As for the average fuel consumption calculated from the MIPP data, the fuel consumption for the drive cycle tests is higher for the fuel cell buses than for diesel buses in general. For the drive cycle in Porto, a diesel bus was operating the same drive cycle the same day and the fuel consumption was measured on a second-by-second basis. These tests also confirm that the fuel consumption of the fuel cell buses is higher than the consumption of the diesel buses [12]. From the energy analysis in Section 4 it may be concluded that the increase is mainly due to the increased weight of the vehicle and the power dump. Up to 25% increase in fuel consumption could be explained by those two factors. It should however be noted that the tests with diesel buses in Porto showed that the diesel bus consumption was also rather high on the route, ranging from 50 l per 100 km to 75 l per 100 km [12], indicating that the route is particularly fuel demanding. Also tests in Stockholm (during winter) indicate that the fuel consumption of the diesel bus, on the test route, is at the higher end or above the fuel consumption range generally stated for diesel buses, see Section 5.3.

5.2.1. Comparing drive cycle tests with standardised drive cycles and MIPP

Average speed is one of the key indicators of route characteristics and traffic situation. For example, the standardised on-road test cycles (SORT) [6] were developed especially for urban buses, use commercial speed (i.e. average speed in operation on a route) as the key parameter for differentiating their three base cycles [11]. The three SORT cycles are the urban cycle (SORT 1), the mixed urban cycle (SORT 2) and the suburban cycle (SORT 3). The SORT cycles differ not only in commercial

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Table 5
Key parameters from drive cycle tests, averages from the test day in Amsterdam, London, Luxembourg, Porto and Stockholm

<table>
<thead>
<tr>
<th>City</th>
<th>Route</th>
<th>Date:</th>
<th>Bus identification</th>
<th>Number of drive cycles</th>
<th>Drive cycle duration (s)</th>
<th>Drive cycle distance (km)</th>
<th>Average speed (km/h)</th>
<th>Max speed (km/h)</th>
<th>Number of stops/kilometre</th>
<th>Power consumption (kW)</th>
<th>Fuel consumption (kg H₂/100 km)</th>
<th>Fuel consumption (l diesel eq./100 km)</th>
<th>Electrochemical efficiency (%)</th>
<th>Fuel cell system efficiency (%)</th>
<th>Ambient temperature (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Amsterdam</td>
<td>35</td>
<td>Sept. 13, 2005</td>
<td>PE21</td>
<td>3</td>
<td>1548</td>
<td>10.3</td>
<td>24.1</td>
<td>70.0</td>
<td>2.1</td>
<td>140.0</td>
<td>18.7</td>
<td>62.2</td>
<td>63.5</td>
<td>40.9</td>
<td>15.0</td>
</tr>
<tr>
<td>London</td>
<td>RV1</td>
<td>Sept. 6, 2005</td>
<td>PE30 &amp; 29</td>
<td>4</td>
<td>4266</td>
<td>13.4</td>
<td>10.8</td>
<td>50.5</td>
<td>5.6</td>
<td>83.0</td>
<td>23.9</td>
<td>79.5</td>
<td>65.0</td>
<td>38.5</td>
<td>21.0</td>
</tr>
<tr>
<td>Luxembourg</td>
<td>9</td>
<td>Sept. 7, 2005</td>
<td>PE16</td>
<td>2</td>
<td>3687</td>
<td>22.8</td>
<td>21.4</td>
<td>60.5</td>
<td>1.8</td>
<td>122.0</td>
<td>16.9</td>
<td>56.4</td>
<td>62.1</td>
<td>40.7</td>
<td>23.0</td>
</tr>
<tr>
<td>Porto</td>
<td>20</td>
<td>Aug. 19, 2004</td>
<td>PE27</td>
<td>11</td>
<td>2640</td>
<td>7.6</td>
<td>10.6</td>
<td>54.0</td>
<td>5.5</td>
<td>81.5</td>
<td>23.1</td>
<td>76.9</td>
<td>65.1</td>
<td>39.5</td>
<td>22.5</td>
</tr>
<tr>
<td>Stockholm</td>
<td>66</td>
<td>Sept. 10, 2004</td>
<td>PE23</td>
<td>4</td>
<td>2210</td>
<td>6.8</td>
<td>11.0</td>
<td>42.0</td>
<td>4.9</td>
<td>81.5</td>
<td>23.1</td>
<td>76.7</td>
<td>66.3</td>
<td>36.6</td>
<td>17.8</td>
</tr>
</tbody>
</table>

All parameters but the distance are calculated from Ballard data.

- All stops included (bus stops, red lights, traffic congestions etc.). A stop is defined as whenever the bus stands still for more than 1 s.
- Hydrogen fuel consumption recalculated to diesel equivalents.
- Fuel cell system efficiency including purge, power dump, electrochemical losses and fuel consumption of fuel cell auxiliaries.

---

The SORT cycles were developed in the SORT-project, initiated by the International Association of Public Transport (UITP).
speed but also in the number of stops, time idling and fuel consumption, see Table 6. In the SORT cycles fuel consumption variations due to topography are not included; hence the cycles are all flat.

For the drive cycles in the five CUTE cities (in Table 5), Amsterdam and Luxembourg had high average speeds, above 20 km/h, while London, Porto and Stockholm had lower average speeds, between 10 and 12 km/h. The average speeds are in general higher than the average speeds calculated over the entire project period, from the MIPP data presented in Table 1, and the average fuel consumption per 100 km is lower, see Fig. 9. This indicates that the operating hours reported in the MIPP files also include breaks and maintenance hours.

Comparing the SORT cycles’ characteristics, namely speed and number of stops, with the tests performed confirms that the routes in London, Porto and Stockholm are, on average, close to the urban cycle (hereafter called heavy urban) with average speeds of around 11 km/h and number of stops per kilometre between 4.9 and 5.5. It may also be noted that the Amsterdam and Luxembourg drive cycles, on average, lie between the mixed urban cycle and the suburban cycle (easy urban). In addition, the time idling, analysed in the next section, is also similar to the corresponding SORT cycles. Hence, a comparison of the measured fuel consumption with fuel consumption stated for diesel buses according to SORT is relevant.

When looking at the average fuel consumption for the tests it may be concluded that the cities with higher average speed have lower average fuel consumption, in kg H₂ per 100 km. This trend is also found in the MIPP data, see Table 1. The fact that average speed is correlated with fuel consumption for regular buses is well known. For example, Ang and Fwa [10] showed already in 1989 that the average speed together with loaded weight could be used to explain up to two thirds of the variation in fuel consumption.

Fig. 9 shows that the average speed and fuel consumption and the variations in these between the drive cycle tests in each city. Also the SORT cycles’ fuel consumption is indicated in the figure and a projection representing 1.5 times the SORT fuel consumption is shown as a line. The differences between the different cities are mainly correlated with speed and no major influence of topography could be found in the tests performed. This indicates that the topography is of minor importance for fuel consumption.

The projection of the polynomial trend line of the SORT cycles in Fig. 9 indicates that the fuel cell buses consume 50% more than what would be expected from the SORT cycles. The average fuel consumption reported from the VTA project [9] is also in line with the 1.5 projection of the SORT cycles. The Gillig buses consumed 63–66 l diesel equivalents per 100 km and had an average speed of 20.3 km/h.

### Table 6

<table>
<thead>
<tr>
<th></th>
<th>SORT 1</th>
<th>SORT 2</th>
<th>SORT 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average speed (km/h)</td>
<td>12.6</td>
<td>18.6</td>
<td>26.3</td>
</tr>
<tr>
<td>Stops per kilometre</td>
<td>5.8</td>
<td>3.3</td>
<td>2.1</td>
</tr>
<tr>
<td>Time idling (%)</td>
<td>39.7</td>
<td>33.4</td>
<td>20.1</td>
</tr>
<tr>
<td>Fuel consumption* (l/100 km)</td>
<td>50</td>
<td>42</td>
<td>39</td>
</tr>
</tbody>
</table>

*Average fuel consumption for a 12 m, 2-axle conventional diesel city bus, with automatic transmission.

Fig. 9. Average speed and fuel consumption for the test days, with range for variations between the measured drive cycles, and average values for the entire project period as reported in MIPP. The consumption of the SORT cycles is also included with a polynomial regression trend line. The grey line is a projection of the trend line representing 1.5 times the SORT consumption.
The fuel consumption for the cities with low average speed in the test is about 20% higher than that for the high-speed cities. This is the same difference as stated for SORT 1 and SORT 2. Hence the fuel consumption of the fuel cell buses show the same speed dependency as the predicted fuel consumption of regular buses on a flat route.

5.2.2. Time and energy spent in different drive modes

Besides the average speed, the route characteristics and traffic situations are clearly shown in the driving pattern. To further explore different drive cycles the percent of total time and energy spent in different drive modes was calculated. The data from all drive cycles, in each city, were sorted in four drive modes defined as follows:

Idling—when the speed is zero.
Deceleration—when not idling and the acceleration is negative.
Acceleration—when not idling and the acceleration is positive.
Cruising—when not idling and acceleration is zero.

The percentages of time spent and energy consumed in the different drive modes are presented in Fig. 10. The time spent in different drive modes is valid for all types of buses on the route but the energy consumption stated is fuel cell-bus dependent.

Amsterdam and Luxembourg spent around 25% of the time and 10% of the energy idling, while the other cities spent around 35% of the time and 20–25% of the energy in that mode. Hence, there is a clear difference in the driving patterns between cities with high average speed and the cities with low average speed.

All cities spent about 10% of the total energy while decelerating and coasting, somewhat less (about 8%) for the cities with higher average speeds. For a regular internal combustion engine, this share would be close to zero since in most situations when decelerating or coasting the auxiliaries may be driven by the motor speed produced by the momentum of the bus, while fuel injection is stopped. The energy spent while decelerating is due to the previously mentioned minimum current limitation.

Acceleration, which occurs 20–25% of the time, is the most fuel-consuming drive mode for regular buses; so also for the fuel cell buses, 33–55% of the total energy is consumed in this mode.

Half of the energy spent while idling is a result of the minimum current limitation and could be eliminated or recovered if the bus were designed differently, hence reducing fuel consumption by 5% for easy urban traffic and 10% for heavy urban traffic. The other half is due to the minimum motor speed limitation, corresponding to the idle motor speed of a regular bus. If auxiliaries (fuel cell auxiliaries as well as other auxiliaries) were electrical they could instead be powered by recuperated braking energy stored in a battery or super capacitors. This kind of hybridisation could save another 5–10%, assuming that the energy may be recuperated during breaking or retardation.

<table>
<thead>
<tr>
<th></th>
<th>Amsterdam</th>
<th>London</th>
<th>Luxembourg</th>
<th>Porto</th>
<th>Stockholm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average speed</td>
<td>24.1 km/h</td>
<td>10.8 km/h</td>
<td>21.4 km/h</td>
<td>10.6 km/h</td>
<td>11.0 km/h</td>
</tr>
<tr>
<td>Time idling</td>
<td>26.5 %</td>
<td>35.8 %</td>
<td>23.3 %</td>
<td>34.1 %</td>
<td>33.0 %</td>
</tr>
<tr>
<td>Fuel consumption</td>
<td>62.2 l diesel eqv.</td>
<td>79.5 l diesel eqv.</td>
<td>56.4 l diesel eqv.</td>
<td>76.9 l diesel eqv.</td>
<td>76.7 l diesel eqv.</td>
</tr>
</tbody>
</table>

Fig. 10. Percent of time spent and energy consumed in different drive modes. Average of the drive cycle tests in the five cities. From the left: Amsterdam, London, Luxembourg, Porto and Stockholm.
Much of the energy spent while decelerating could be eliminated if the minimum current limitation were removed or recovered, consequently decreasing the fuel consumption by up to 8% for easy urban traffic, and up to 10% for heavy urban traffic.

The energy spent in the accelerating mode could partly be provided by recuperated braking energy, using the stored energy for power peaks.

5.2.3. Energy flow analysis using Sankey diagrams

The energy flows in the buses for the drive cycles in Table 5 are illustrated by Sankey diagrams in Figs. 11 and 12. All power flows, from fuel input to the power from motor, are calculated in the same way as the previous Sankey diagram (Fig. 4). Power for traction is however calculated from motor power minus power used for fuel cell auxiliaries and other auxiliaries instead of from the torque request. The other auxiliaries are set at a minimum of 8 kW. The power consumption of the auxiliaries, both fuel cell specific and others, is then reduced by the percent of time that the bus decelerates during the drive cycle.

For the cities with low average speed the average power used is lower than for the cities with high average speed and the percentage of energy used for traction is generally lower. The power dump is generally higher (11–14% compared to 7–8%) and the energy used for the auxiliaries constitutes a larger part of the total energy.

The fuel cell system efficiency including purge, power dump, electrochemical fuel cell losses and power demand of the fuel cell system auxiliaries is between 38.5% and 41.0% (see also Table 5), and the powertrain efficiency, power (fuel) in to power for automatic gearbox minus fuel cell system auxiliaries, ranges from 34% to 37%. These efficiencies are higher than the efficiencies calculated in the constant speed test due to the fact that the average power output is higher in the drive cycle tests. Due to the current design, with extensive power dump, the fuel cell buses are more fuel efficient during more demanding drive cycles. This was also noted by Frey et al. [12].

In the Sankey diagrams for the cities the energy dumped is less than the 10–20% estimated in the drive mode analysis. However, removing the power dump also reduces the losses in the fuel cells and purge; therefore the 11–14% stated in the Sankey diagrams for London, Porto and Stockholm actually corresponds to 17–19% of fuel input, and the 7.5% for Amsterdam and Luxembourg corresponds to 11.6% and 12.7%, respectively. This confirms the energy-saving possibilities estimated in the drive mode analysis.

5.2.4. Differences in power used

By studying the fuel cell power output distribution range for the different cities, it is also clear that the cities with high average speed used more of the fuel cell power spectrum. All cities use less than 50 kW from the fuel cells 60–70% of the time. The main difference is in how much time the bus uses fuel cell outputs above 110 kW and how much energy is spent in the higher power ranges. Cities with low average speed use more than 110 kW only 10% of...
Fig. 12. Sankey diagram of the average energy (power) flow in the fuel cell buses in London (left), Porto (middle) and Stockholm (right).
the time (corresponding to 24–34% of the energy), while the cities with high average speed use 110 kW or more during more than 25% of the time (i.e. 62–67% of the energy), see Fig. 13.

Since not much time is spent at higher power outputs, power peaks could be handled by an energy storage system, provided that the system can handle high power, i.e. a power buffer. This kind of hybridisation would enable down-sizing of the fuel cell system with cost and weight reductions as probable consequences. Hybridisation for handling power peaks would reduce the energy spent accelerating and cruising. Examples of this design are fuel cell buses operating in Japan and the United States, which are hybridised systems with a maximum power output from the fuel cell systems of 180 and 120 kW, respectively [6,8].

When analysing the potential for hybridization, it is also important to study the needed energy storage capacity of the energy storage system. The energy storage demands may be analysed, from instant power output from the fuel cell. In Fig. 14 the fuel cell output from one of the drive cycles in Luxembourg is shown. For this drive cycle the higher outputs occur only during short periods of time. For example, an output of more than 100 kW is used for a maximum of 42 s in the Luxembourg drive cycle. If the energy storage should handle all power peaks over 100 kW, it needs to be able to deliver 150 kW during 42 s, corresponding to 1.75 kWh. The fuel cells could be combined with power storage, energy storage, or a combination of both. If the goal of the hybridisation is to down-size the fuel cell system, it is usually high power but relatively low energy that is needed from the storage,
which indicates that the fuel cells should be combined with some kind of power storage, such as super capacitors, rather than energy storage. If the hybridisation is intended for providing energy at standstill and low speeds, as suggested in the drive mode analysis, the fuel cell should instead be combined with energy storage with higher energy storage capacity, such as batteries. The Luxembourg case where high power is needed during a rather long period is an example where neither storage technology is better than the other in terms of peak shaving, and where a combination of the two might be considered. Other aspects, such as lifetime and cost, are also important when choosing energy storage system for a new bus design and might lead to another conclusion.

5.3. Variations within cities

5.3.1. Daily variations

We have seen that the variation in fuel consumption between cities is mainly dependent on average speed. However, there are also differences within the cities. Daily variations are caused by varying traffic situation, driver behaviour and a varying number of passengers. Among the tests available, there are two occasions where the tests were performed during more than just a few hours in regular traffic, that is in Stockholm in March 2005 and in Porto in August 2004. Both tests showed that in the afternoon rush hours the percent of time standing still and the time spent driving at speeds lower than 4 km/h are increased by about 5 percentage units. In both cities the fuel consumption was increased by 10% in the afternoons.

5.3.2. Seasonal variations

In Stockholm, tests were performed on the same route under different weather conditions. The tests in March were performed under cold conditions and these tests showed a 16.5% higher fuel consumption compared with the consumption of the fuel cell bus on the same route in September. This increase was analysed and it was concluded to be mainly due to the heating of the cabin. Under cold conditions the heat from the fuel cell is not enough for heating up the cabin, so additional heat is produced via a heating resistor. This is however something that to some extent could be built away in future designs, if the heating system is adapted to the temperature of the fuel cell, i.e. 60–80°C instead of >80°C. Also, the Citaro buses had only a single glass in the windows of the buses while the regular buses in Stockholm have double glass. During the test days in March a diesel bus of the same model as the fuel cell buses ran in parallel with the fuel cell buses. During these tests the diesel bus consumed around 771 per 100 km, which means that, for this specific test, the fuel cell bus consumed 16% more fuel than the diesel bus.

6. Conclusions and discussion

6.1. Reliability and availability

The aim of the CUTE project, and the chosen design of the bus, was to demonstrate and prove that hydrogen-powered fuel cell buses can function in daily operation in urban European transport systems rather than to show the ultimate bus. Based on the amount of kilometres driven and hours operated in the nine cities, and the high availability attained (on average about 80%), the buses have been assessed to be reliable under European conditions and hence the goal of the project was achieved. However, it is dangerous to draw too far-reaching conclusions about the maturity status of the fuel cell technology from this. It must be noted that the fuel cell buses were the subject of a comprehensive maintenance programme, much more extensive than for regular buses. Two technicians cared for the three buses, which of course is unrealistic in large-scale commercial operation.
Nevertheless, it is a promising sign for the future of fuel cells and hydrogen in public transport applications.

It should also be noted that the definition of availability should be reconsidered to clearly reflect the hours of maintenance and repair and by that better represent the actual cost for a bus operator. Reporting per day is simply too rough for making long-term and valid conclusions about the economy for operating the buses in larger fleets.

6.2. Fuel consumption and optimisation potentials

The MIPP data and the data from the drive cycle tests showed that the fuel consumption per kilometre for the Citaro fuel cell buses is higher than for regular diesel buses. This is mainly due to the increased weight of the fuel cell buses and the minimum current limitation set on the fuel cell system. The fuel consumption for the fuel cell buses was, as for regular diesel buses, strongly correlated to the average speed, despite the fact that a fuel cell engine in theory has higher efficiency at lower partial loads. The constant speed test clearly showed that the fuel cell system efficiency was lower at lower speeds due to the minimum current limitation. For the drive cycle tests the differences in the average system efficiencies were not as pronounced. The fuel cell system efficiency was 36–41%, and the powertrain efficiency (fuel input to power to automatic gearbox) was 34–37%. This is comparable to average efficiencies of modern diesel engines.

The main optimisation potential for future fuel cell bus designs consists of minimising, or if possible eliminating, the purge and power dump, lowering the vehicle weight and/or using a hybridised drive line. The analysis shows that:

- minimising the purge could reduce the fuel consumption by up to 8% and
- removing or recovering the power dump would save between 17% and 19% of fuel for heavy urban traffic and about 12% for easy urban traffic.

Hybridisation of the powertrain could be one way of recovering the power dumped. The excess power produced by the minimum current limitation could be used for charging the energy storage, instead of being dumped in a resistor. However, not all the power dumped may be recuperated since the cycling efficiency when charging and then discharging an energy storage system will result in some losses. Hybridisation could also enable down-sizing of the fuel cell system, potentially lowering the weight of the vehicle and hence saving additional fuel. This would most likely also mean lower overall cost.

The analysis of the drive modes confirmed that urban buses spend much of their time in operation standing still. Therefore, the ideal urban bus should consume virtually no fuel when no traction is needed. This may be achieved by removing the power dump and using electrical auxiliaries, eliminating the need for an idling motor. The analysis indicates that

- using electrical auxiliaries could eliminate the minimum motor speed limitation, decreasing the fuel consumption by about 10% for heavy urban traffic and 5% for easy urban traffic.

How the suggested changes would affect the fuel cell system is not considered here but all changes should be made with great care since the attitude towards the technology might be very sensitive to negative input during an introduction phase. Therefore it is recommended to focus on the reliability and to optimise the fuel consumption where possible without compromising on safety and reliability. For example, it might be wise to lower but not eliminate the minimum current limitation. Recovering the energy formerly dumped could be a solution to maintain reliability and save energy. As an example, a total hybridisation with the electrical motor being turned off at standstill and recovering the power dump would save about 30% for heavy urban traffic and more than 15% for easy urban traffic, assuming that all necessary auxiliaries are electrical and that all energy recovered can be used. Using recovered brake energy for power assist during acceleration and by this operating the fuel cell less and in more feasible power ranges would obviously save even more fuel.

The presented saving potential is higher than that presented in a study performed by Wang et al, where tests showed that a fuel-cell-hybridised drive train consumes 20% less than a pure fuel cell drive train [16]. However, very low fuel consumption has been achieved in other demonstration projects where hybridised buses are used. For example, the consumption for the AC transit buses was about 12.5 kg hydrogen per 100 km [8], while the buses used in Japan consumed 9.5 kg hydrogen per 100 km [6]. More detailed data about the drive cycles where the fuel consumption was measured and drive trains of the buses would be needed for a comparison with the fuel cell buses used in the CUTE project, but the results from these demonstration projects confirm that the potential saving of hybridisation is large.

6.3. Recommendations for bus design

Auxiliary systems such as air conditioning, 24-v alternators, door openers and cooling fans should be adapted to an electric driveline and thus powered electrically and controlled so that the systems are activated on demand to prevent idling losses. Such systems exist today but are in some cases more expensive; at least considering the initial cost (i.e. purchase) but not necessarily if calculated over the lifetime of a vehicle when maintenance and energy savings are taken into account. Other auxiliary systems such as the servo-steering, pneumatic kneeling and suspension system and pneumatic brakes are more difficult to exchange with
similar electric, electro-mechanic or electro-hydraulic systems as such systems are currently not commercially available for heavy-duty vehicles. However, today’s systems should in the short-term perspective be adapted for utilisation on demand or by other means be controlled so that idling losses are avoided as much as possible. Also the fuel cell-specific auxiliaries such as the supercharger, pumps and fans should be adapted to the electrical drive train in order to reduce idling losses and improve the fuel cell system efficiency. For example, in the present bus design the supercharger is directly driven off the engine, meaning that the compressor produces excess compressed air at times (for example at high engine speeds with low load). It also means that the engine must be on whenever the fuel cell is producing power in order to deliver enough oxygen to the fuel cell.

Hybridisation facilitates the reduction of fuel consumption, by recovering the power dump and enabling fuel-efficient idling. In addition, hybridisation enables recovery of brake energy and down-sizing as well as more optimal operation of the fuel cell system.

Concerning climate, the results showing considerably higher fuel consumption in cold weather imply that this is a factor that must be addressed when designing buses that are to be operated in countries with cold seasons. The same goes for very warm countries where the air conditioning system may contribute largely to the fuel consumption. Higher fuel consumption in extreme conditions is of course to some extent reasonable, but it is not sufficient to design vehicles only for average temperatures.

6.4. Other recommendations

Regarding urban bus operation from a general point of view, it is recommended that bus systems and routes should be planned and organised to keep the commercial speed as high as possible in order to save energy and fuel. Measures may be taken to provide buse-dedicated roads or bus lanes and priority at traffic lights to avoid unnecessary stops in traffic. Other ways of increasing the commercial speed are to reduce bus stop times as much as possible by improving the passenger flow in and out of the bus by, for example, wider doors and smoother ticket systems. With higher commercial speed it is also likely that more people would choose to travel by public transport instead of travelling by car, which of course would be beneficial for urban environment as well as for reducing traffic congestion problems.

From a project organisational view, the recommendation is to include planning of the evaluation in the early stages of the project, before the operation starts. The problems experienced with the reported data (MIPP) within the CUTE project could probably have been avoided if the evaluation phase of the project had been started earlier in the project. Evaluation targets, reporting forms, key parameter definitions, test procedures, information flow paths and responsibilities should be discussed and agreed upon before the operation starts. This was not the case in the CUTE project due to the set-up of the phases of the project.

7. Future work

A simulation model of the fuel cell Citaro has been built up with the aim to simulate/estimate the optimisation potential of the energy system design in the bus. The results of the simulations will be presented in another paper.

Acknowledgements

This work has been financed by the Swedish Energy Agency, and has partly been carried out under auspices of the Energy Systems Programme. We would like to thank Ballard and DaimlerChrysler for providing data and for kind cooperation and interesting discussions. We would also like to thank all other partners in the CUTE project, and especially the CUTE Stockholm project partners; Stockholm City, SL, Busslink and Fortum. Mårten Niklasson and Kristina Haraldsson are acknowledged for working with us within work package 4, Gonçalo Gonçalves for initiating the tests in Porto, and sharing the data, and Henk J. Jansen Manenschijn at GVB in Amsterdam for initiating the tests performed in London, Luxembourg and Amsterdam. Finally, we would like to thank Anders Lindfeldt and Handrain H. Aswad for performing the auxiliary tests in Stockholm.

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