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PROFESSIONAL PAPER

TEST EXPERIENCES WITH THE DAIMLERCHRYSLER FUEL CELL ELECTRIC VEHICLE NECAR 4

The DaimlerChrysler fuel cell electric vehicle NECAR 4, a hydrogen–fueled zero–emission compact car based on the A–Class of Mercedes–Benz, is described. Test results obtained on the road and on the dynamometer are presented. These and other results show the high technological maturity, reliability and durability already achieved with fuel cell technology.

The environmental problems caused by the intensive use of fossil fuels, as well as their limited availability, are demanding a more rational and efficient utilization of our primary energy resources. Since a considerable part of the global energy consumption is related to transportation, car manufacturers are called on to develop and commercialize environmentally cleaner and more efficient vehicle propulsion systems. Among all alternatives, proton–exchange membrane fuel cells (PEMFC) are probably the most promising power source for future–generation vehicles. DaimlerChrysler has accepted its responsibility and recognized the future potential of fuel cell electric vehicles (FCEVs). The company has assumed a leading role in the development of FCEVs; the goal is to introduce them to the market by the year 2004.

In order to better achieve its ambitious goals, the former Daimler–Benz AG formed a strategic alliance with Ballard Power Systems, Inc. (Vancouver, Canada), a leading company in PEMFC technology, in 1997 to develop and commercialize PEMFCs for transportation applications. As a result of this joint venture, the company XCELLSiS (formerly *dbb* Fuel Cell Engines) was founded. Its task is the development and commercialization of complete fuel cell systems (stacks and auxiliaries) for FCEVs based on Ballard FC stacks. Later in the same year, Ford Motor Company joined this alliance and brought with them ECOSTAR, a leading manufacturer of electric motors for EVs and formerly an exclusive subsidiary of Ford. Figure 1 shows schematically the ownership structure.

DaimlerChrysler's commitment to FCEV technology is evident considering the several demonstration vehicles that were developed and introduced in recent years. As early as in 1994,

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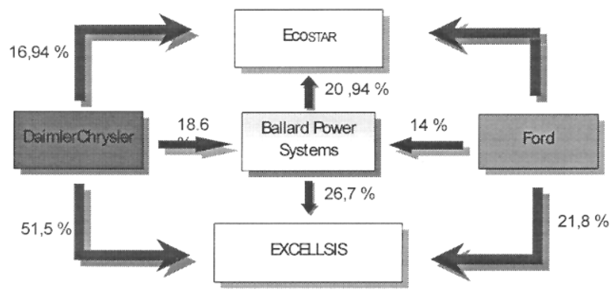


Figure 1. Ownership structure of the DaimlerChrysler–Ballard–Ford fuel cell alliance

Daimler–Benz demonstrated the feasibility of using fuel cells for vehicle propulsion with the introduction of the *New Electric Car I* (NECAR I). NECAR I was literally a "rolling lab": a two–seat transporter whose cargo space was almost completely filled with the fuel cell system and the compressed–hydrogen gas (CH_2) tank. Just two years later, in 1996, Daimler–Benz introduced NECAR II, a much more compact car (a six–seat minivan), also fueled with CH_2, and demonstrated that FCEVs have the potential to reach mass production maturity in the mid term. NECAR 3 (1997), a compact car with two seats based on the A–Class of Mercedes–Benz, is the first FC passenger car worldwide that runs on a liquid fuel: methanol. Hydrogen is generated on board by methanol reforming. This concept unifies the infrastructural advantages related to a liquid fuel similar to gasoline or diesel with the very low emissions (NECAR 3 meets the Californian SULEV standard) and high efficiency of the fuel cell technology. In March 1999, DaimlerChrysler introduced NECAR 4 (Figure 2), a compact car also based on the A–Class of Mercedes–Benz offering enough space for five passengers. NECAR 4 is fueled with liquefied hydrogen (LH_2); it is the car with the longest range (approx. 450 km) worldwide that meets California's standards as a true zero–emission vehicle (ZEV). The FC system has already become small enough to remain invisible, hidden in the sandwich floor of the A–Class. Finally, in November 2000, two further

Figure 2. NECAR 4: The first ZEV with high range (1999)

FCEV's based on the A–Class were introduced: NECAR 4a, an improved NECAR 4 fueled with CH_2, which was unveiled at the opening event of the California Fuel Cell Partnership in Sacramento, and NECAR 5, the most advanced methanol–fueled FCEV worldwide.

Additionally, DaimlerChrysler is engaged in the development of fuel cell city buses. The LH_2–fueled *New Electric Bus* (NEBUS, 1997) is the first demonstration unit. Six similar city buses were tested by customers as a part of the P3 demonstration project in Chicago and in Vancouver. City buses will be the first market segment addressed. DaimlerChrysler has announced the commercialization of 30 city buses starting at the end of 2002 (NEFLEET project).

For fuel cell passenger cars, methanol is considered to be one of the most suitable fuels – mainly due to its easier onboard storage and smaller infrastructure impact as compared to pure hydrogen. Regarding the Californian market, however, only direct–hydrogen FCEVs will meet the ZEV standards (methanol: SULEV). For vehicles operated in fleets (city buses, taxis) hydrogen will generally be the best fuel alternative.

After having demonstrated the general feasibility of FCEVs over the last six years, DaimlerChrysler is already carrying out extensive field testing and has accumulated several thousand kilometers and hours of experience with the operation of FCEVs in this period. Among others, the reliability and durability of FCEVs could be successfully demonstrated.

In this paper, we focus on the fuel cell demonstration vehicle NECAR 4 (1999). A technical description of this vehicle is given together with experimental results obtained both on the road and in the laboratory.

NECAR 4: Technical Description

NECAR 4 (Figure 2) is a five–seat compact car with front–wheel drive based on the A–Class of Mercedes–Benz. Its dimensions are 3.57 m length, 1.72 m width, and 1.58 cm height. The A–Class has a double – or sandwich – floor, which offers extra space for holding non–conventional components and makes this model particularly suitable for conversion into FCEVs. The original ICE was replaced by an ECOSTAR trans–axle asynchronous electric motor with a peak power output of 55 kW at the shaft. The electrical power is supplied by a fuel cell system delivered by XCELLSiS and based on two 35–kW Ballard stacks à 160 cells fueled with pure hydrogen. Since the only exhaust product is water, NECAR 4 meets California's standards as a true ZEV. A cryogenic tank (manufactured by Linde AG) with a storage capacity of 5 kg LH_2 provides the fuel necessary for a drive of approximately 450 km – the longest range a ZEV has ever reached. Figure 3 shows the packaging of the main components. The complete fuel cell system (both stacks and all auxiliaries, such as the air compressor responsible for the air supply, coolant pumps, etc.) fits into the sandwich floor of the A–Class; the LH_2 tank is installed behind the rear axle and occupies only a small part of the trunk, which can still hold luggage.

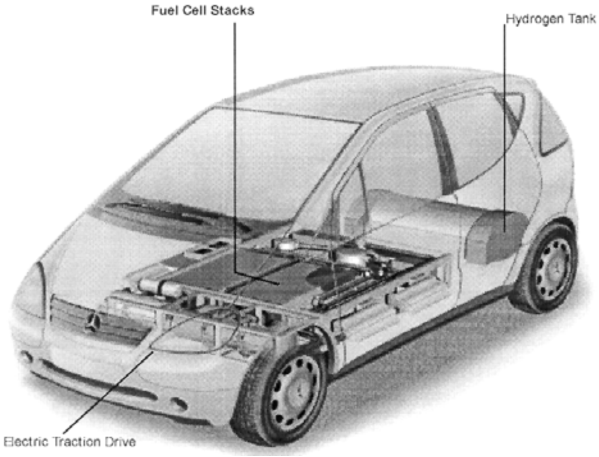
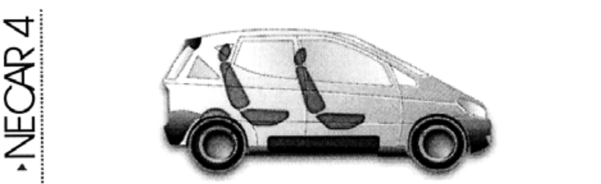


Figure 3. Packaging of the fuel cell system and LH_2 tank in NECAR 4



Fuel Cell System	Gross Power (2 Stacks)	70 kW
	Specific Power	0,2 kW/kg (5 kg/kW)
Liquified Hydrogen Tank	Storage Capacity	5 kg LH_2
Drive Train	Electric Drive (asynchr.)	Peak: 55kW (at Shaft)
	Max. RPM	14,000 (12,000)*
	Transmission	10,1:1 (non-shiftable)
Performance	Max.Speed	145 (130)* km/h
	Range	450 km
Gross Vehicle Weight		1,750 kg

* Valid when RPM and Torque are limited by Software

Figure 4. Main technical parameters of NECAR 4

Figure 4 indicates the main technical parameters of NECAR 4. The maximum vehicle speed is 145 km/h if the motor is allowed to reach its maximum torque and rotational velocity of 14,000 RPM (variable of the motor control software). In order to prolong the lifetime of the motor, however, the drive tests discussed below were all carried out using a torque limitation and a maximum RPM of 12,000, corresponding to a maximum vehicle speed of about 125 km/h.

Drive Tests

Various drive tests were carried out with NECAR 4 since its commissioning at the beginning of 1999. NECAR 4 already drove a total of more than 20,000 km in about 620 h (status: 12/2000). Despite its heavy curb weight – about 300 kg more than a comparable ICE–powered A–Class vehicle – NECAR 4 shows good dynamics, drives smoothly, is comfortable and quiet.

Drive tests have been carried out on the road (around Kirchheim/Teck–Nabern and on the test circuit of IDIADA, Spain) and on a roller type dynamometer (at the Research Department of DaimlerChrysler in Stuttgart). The parameters necessary to adjust the dynamometer – i. e. the vehicle road force consisting of the tire rolling resistance and the aerodynamic drag – were determined using the coastdown method, also on the IDIADA test circuit.

Onboard Energy Requirement and Efficiency

The onboard energy consumption of NECAR 4 and the energy flow "from the tank to the wheel" were determined on the dynamometer for the New European Driving Cycle (NEDC) which consists of four city cycles (ECE) and one extra–urban driving cycle (EUDC). In our experiments, the NEDC was repeated three times; due to time limitations, only one of them included a "cold start" from room temperature. Figure 5 shows the average vehicle speed of these three cycles together with the nominal NEDC speed. Even though a relatively large deviation of the measured speed from the nominal value can be observed near the end of the cycle, these

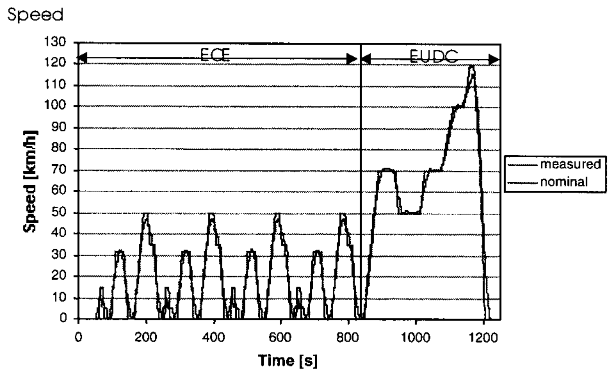


Figure 5. Nominal speed profile for the NEDC and average speed of three drive tests with NECAR 4 measured on the dynamometer

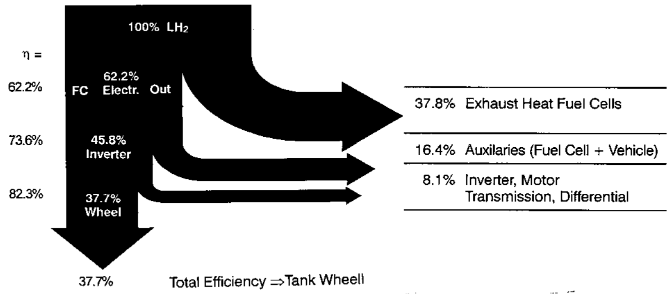


Figure 6. Energy flow in NECAR 4, measured for the NEDC using a dynamometer (average of three measurements; no cold start)

test drives still fulfill the standard because in that area – as required – full power was applied. An average hydrogen consumption of 1.1 kg H_2 /100 km, equivalent to 37.0 kWh/100 km, 4.0 l gasoline/100 km or 3.7 l diesel/100 km, was determined. This value can be regarded as very good if we compare it with the fuel economy of the lighter, ICE–powered A–Class standard models: 7.1 l gasoline/100 km for the A 140 (60–kW gasoline engine) and 4.5 l diesel/100 km for the A 160 CDI (44–kW diesel engine), which were both measured for the NEDC as well.

Figure 6 shows a Sankey diagram indicating the energy flow "from the tank to the wheel" measured for NECAR 4. The data represent the average of the three NEDC mentioned above. The gross efficiency of the fuel cell stacks is 62.2 %, i. e. on the average 62.2 % of the energy contained in the hydrogen consumed by the fuel cells is converted into electricity. The remaining 37.8 % is exhausted in the form of heat; 16.4 % of the total energy is consumed by the auxiliaries – such as the air compressor, coolant pumps and ventilator – and 8.1 % is converted into waste heat by the inverter, electric motor, transmission and differential. Thus 37.7 % of the energy contained in the H_2 fuel reaches the wheels and is used for the vehicle propulsion. The total efficiency of NECAR 4 "from the tank to the wheel" is therefore 37.7 % for the NEDC. This value is very high if we compare it with those typical for ICE–powered vehicles: 16–18 % and 22–24 % for gasoline– and diesel–fueled vehicles, respectively. The high energy efficiency is one of the major advantages of the fuel cell technology and explains why the onboard energy consumption of NECAR 4 is low in spite of its high curb weight (s. above).

Acceleration Performance

The acceleration behavior of NECAR 4 was also studied at the test circuit of IDIADA. Figure 7 shows the average speed profile over time determined from nine acceleration tests from idle to 100 km/h; 30 km/h are reached after 2.8 s, 50 km/h after 6.0 s, and 100 km/h after 26.3 s. An acceleration from 60 to 100 km/h (elasticity) takes 18.1 s. Figure 7 also compares the acceleration times of NECAR 4 with those of similar – but lighter – ICE–powered Mercedes–Benz A–Class standard vehicles. Considering that NECAR 4 is a

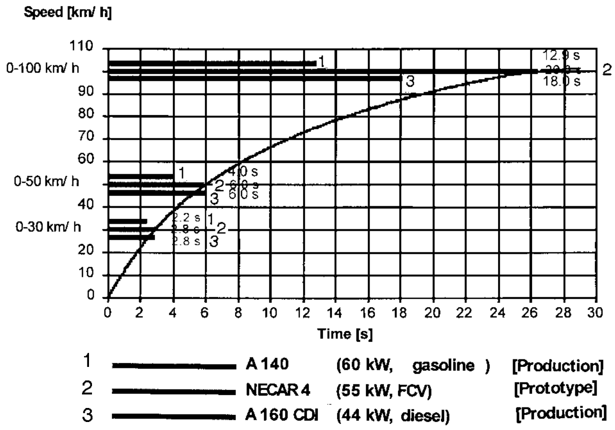


Figure 7. Acceleration performance of NECAR 4: Average of nine idle–to–100–km/h test carried out at the IDIADA test circuit

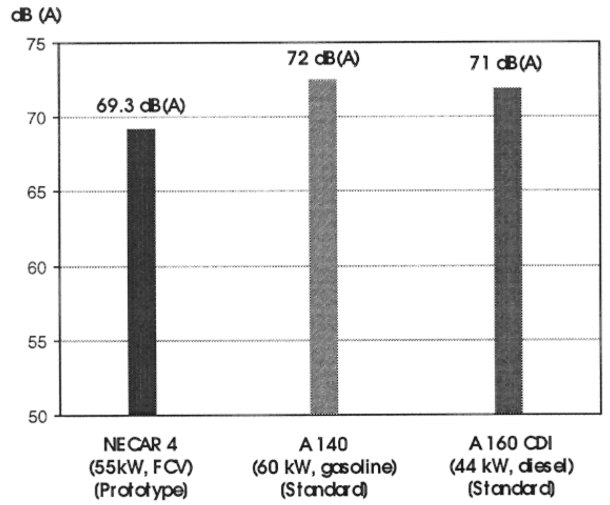


Figure 8. External noise emission of NECAR 4 and Mercedes–Benz A–Class

prototype which is not yet weight–optimized, we can affirm that this vehicle shows quite good dynamics. Comparison with the standard A–Class vehicles (Figure 7), evidences that the acceleration capability of FCEVs at higher speeds must still be improved (mainly by weight reduction).

Noise Emission

Figure 8 compares the external noise emission of standard A–Class vehicles with the one of NECAR 4 (measured in IDIADA for the "accelerated passage" test, defined by the European regulation 70/157/EWG). The noise level measured for NECAR 4 is 69.3 dB(A). The standard A 140 and A 160 CDI models of the A–Class emit 72 dB(A) and 71 dB(A) at the same conditions, respectively. Once again we observe a very good performance for NECAR 4.

Summary and Outlook

Fuel cells are one of the most promising power sources for future–generation vehicles. They show important advantages over conventional drive systems, especially regarding:

- energy efficiency and fuel economy,
- emissions (ZEV, SULEV),
- noise emissions / comfort, and
- high flexibility regarding the primary energy source used.

DaimlerChrysler has assumed a leading role in the development of FCEVs. A strategic alliance with Ballard Power Systems – a worldwide leader in the fuel cell technology – and Ford Motor Company provides important synergy effects and will help to advance this technology effectively to market maturity. For fueling fuel cell passenger cars, methanol has infrastructure– and storage–related advantages over pure hydrogen. The best fuel alternative for vehicles operated in fleets, instead, will be pure hydrogen.

After having demonstrated the general feasibility of FCEVs over the past six years, DaimlerChrysler is now carrying out extensive field tests. The driving experience already accumulated by our company, and also by customers in the frame of the P3 Bus Demonstration Program in Vancouver and Chicago, proves the reliability, durability and good driving performance of FCEVs. Important experience is also gained from the operation of FCEVs in the frame of the California Fuel Cell Partnership. In this paper, test results obtained with NECAR 4 are described in detail. They are representative for the FCEV technology in general and document the high technological maturity achieved.

A commercial breakthrough of FCEVs will be achieved only if they can offer clear comparative advantages over conventional vehicles. Experience shows that customers are not willing to pay much more for a solely environmental benefit. Advantages related to cost and performance, instead, play a much more important role in the car–buying decision.

The progress made by DaimlerChrysler and its partners since 1994 in the development of FCEVs is tremendous. However, we are still working on various aspects which require further improvement in order to guarantee a successful commercialization of FCEVs. The most important ones are:

- Cost reduction
- Reduction of weight and volume of FC systems
- Further improvement of the driving dynamics, durability and reliability
- Development of cost–effective production technologies
- Installation of a refueling infrastructure for methanol and hydrogen.

Even though this represents a big challenge, DaimlerChrysler and its partners (among them Ballard Power Systems, XCELLSiS and ECOSTAR) are confident about developing suitable solutions to all above–mentioned issues. We see a tremendous potential in the fuel cell technology and are committed to commercialize it by the middle of this decade – to the benefit of our customers and the environment.