Energy Sources Sizing for Hybrid Fuel Cell Vehicles Based on Statistical Description of Driving Cycles

Alexandre Ravey, Nicolas Watrin, Benjamin Blunier and Abdellatif Miraoui
Transport and Systems Laboratory (SeT) – EA 3317/UTBM
University of Technology of Belfort-Montbéliard, France
Emails: (alexandre.ravey,nicolas.watrin,benjamin.blunier,abdellatif.miraoui)@utbm.fr

***Abstract*— This paper describes a new methodology to size the energy source of a hybrid vehicle based on statistical description of driving cycles. This methodology is applied to a fuel cell based collection truck for which the driving pattern is very specific. Randoms driving cycles are then generated allowing the distribution of the average powers and energies to be computed. The analysis shows that even for a 2,500 kg truck, a 3,5 kW fuel cell stack is sufficient, allowing the fuel cell system to be downsized compared to classical solutions using several tens of kilowatts fuel cell systems.**

I. INTRODUCTION

In transport applications Proton Exchange Membrane Fuel Cells (PEMFC) appear to be suitable in some cases and niche markets as they provide a very good tank-to-wheel efficiency compared to internal combustion engines [1], [2]. In cities, hydrogen gives the chance to have zero-emission vehicles. However, even if the tank-to-wheel efficiency is good, the wheel-to-tank efficiency has to be carrefully studied to have the most clean and environment-friendly hydrogen production [1], [3].

In this paper, only direct hydrogen fuel cells for transportation applications are considered. The hydrogen fuel is stored on board and is supplied by a hydrogen production and fuelling infrastructure. For other applications than vehicles (*i.e.*, distributed stationary power generation), the hydrogen can be fuelled with reformate produced from natural gas, liquified petroleum gas or renewable liquid fuels. For electronic devices in small equipments, methanol and sometimes hydrogen are the fuels of choice in fuel cell systems.

The technical challenges and objectives for fuel cell systems in transportation applications are given by the Department of Energy (DOE) [4]–[8]. The major challenges are the cost and the durability. To become competitive with internal combustion engines ($25–$35 per kilowatt), the price of the fuel cell system, including all the subsystems, has to be reduced down to about $35 per kilowatt[1]. The durability with cycling of the system should meet the requirements of automotive applications and extend their lifetime up to 5,000 hours[2] (around 240,000 kilometers). They have to be able to start and work with temperatures ranging from $-40\,^{\circ}$C to $+40\,^{\circ}$C. In these temperature conditions, the start-up time up to 50 % of the rated power (80 kW) has to be as small as possible: 30 seconds at $-20\,^{\circ}$C and 5 seconds at $+20\,^{\circ}$C.

The size and the weight of current fuel cell systems have to be reduced drastically to meet the automotive compactness requirements, which apply both for the fuel cell stack and also for auxiliary components like the compressor, the expander, humidifiers, pumps, sensors, the hydrogen storage, etc. The specific power and the power density requirements for the fuel cell system are 650 W/kg, 650 W/l and 2, 000 W/kg, 2, 000 W/l for the stack itself.

The transient response of the stack is also a key issue and depends mainly on the air supply system inertia: the transient response from 10 % to 90 % of the maximum power should be lower than 1 s.

The aim of the paper is to show how hybridization can help to reach these targets especially for urban vehicles such as collection trucks which have very special driving mission profiles depending on many parameters. It shows that on the one hand, a peaking power source (PPS) can improve the system performance and fuel economy, on the other hand, the PPS permits the fuel cell system to be drastically downsized, by reducing at the same time the price of the fuel cell system, that is the most expensive part of the overall system.

The first part of the paper presents the collection truck and its driving mission profiles which are very differents compared to the ones that can be found in the litterature [9], [10]. The second part of the paper gives the specific methodology based on random cycles generation to size both fuel cell stack and batteries which have to be as small as possible. Finally conlusions are drawn based on the simulations results.

II. RANDOM DRIVING CYCLE GENERATION USING STATISTICAL DESCRIPTION OF THE VEHICLE'S CARACTERISTICS

Standardized cycles such as standardized European driving cycle (EEC Directive 90/C81/01) cannot be used for such applications as the vehicle, a collection truck, has very special driving mission profiles depending on many parameters such as the driveaway distance, the collection truck capacity, the distance between the houses, the working speed, the driveaway speed (cruising speed), etc. An adapted and representative

[1]2015 targets. The 2010 target is $45 per kilowatt
[2]20,000 hours in steady state conditions

978-1-4244-8218-4/10/$26.00

driving cycle has to be used in order to properly size the energy source, a fuel cell system (stack power and hydrogen tank) in this case. The methodology is based on random driving cycle generation based on a statistical description of many influencing parameters.

A. Statistical descriptions of vehicle's caracteristics

This study is based on a collection truck during its working time. In this case, as shown in 1(a) a driving cycle describes the trip between the garbage center (driveaway) where the truck starts empty, the collecting phase (mission) and the return when the truck is full (driveaway back). During this trip (turnaround), several quantities are randomly choosen based on real statistical data which may differ between cities:

- *Driveaway distance:* distance between the center and the first house (2,000 m to 5,000 m);
- *Driveaway speed:* speed between the center and the first house (20 $\mathrm{km\,h^{-1}}$ to 50 $\mathrm{km\,h^{-1}}$);
- *Working speed:* speed between two houses (10 $\mathrm{km\,h^{-1}}$ to 15 $\mathrm{km\,h^{-1}}$);
- *Working distance:* distance between two houses (28 m to 66 m);
- *Collection time:* time to collect the garbarge of one house (35 s to 50 s),
- *Garbage weigth:* weight of the garbage of one house to be collected in the truck (12 kg to 28 kg);
- *Road slope:* (-8 % to 8 %).

All of this parameters are changing at each step of the mission. Each of the parameters possible values are described by a normal distribution (1):

$$f(x;\mu,\sigma) = \frac{1}{\sqrt{2\pi\sigma^2}}\, e^{-(x-\mu)^2/(2\sigma^2)} \quad x \in \Re \tag{1}$$

where μ is the average value and σ is the standard deviation.

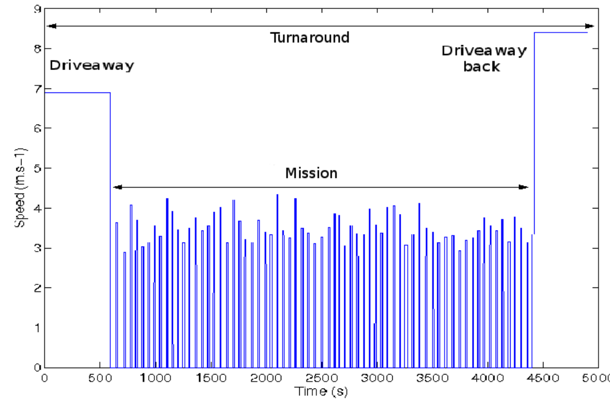
B. Driving cycle generation

Based on the statistical distribution of the parameters, it is possible, at each step of the turnaround, to randomly select the parameters to generate a driving cycle.

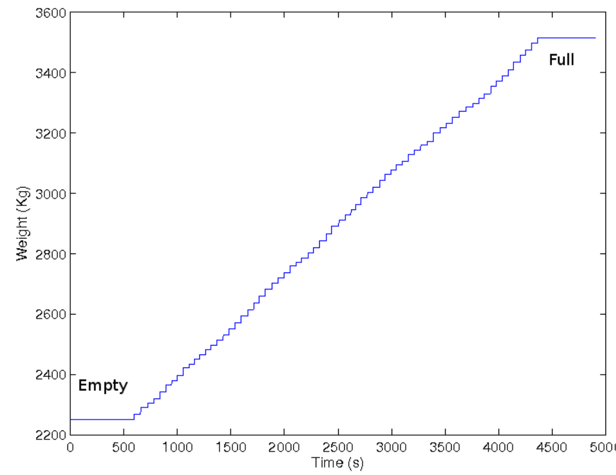
The end of the mission depends if the truck is full or not. A complete turnaround is described as follows:

1) The empty truck goes out of the center: driveaway distance, driveaway speed and slope values are randomly picked up;
2) The truck collect the first bin: garbage weight and collection time values are randomly picked up;
3) If the truck is not full, working distance, working speed and slope values are randomly picked up, and the cycle continues from the step 2 until the truck is full;
4) When the truck is full, driveaway distance, driveway speed and slope values are randomly picked up.

The driving cycle is built by assembling all the steps. A graphical representation of the speed profile of one of the generated driving cycles is shown in Figure 1(a) and the time evolution of the vehicle weight is given in Figure 1(b).



(a) Speed profile



(b) Truck weight profile

Fig. 1. Vehicle speed and mass profiles

Five thousands of driving cycles are generated and each of them are analysed to determine the average power, the turnaround energy, the time of one turnaround and other useful quantities. The overall results give output distributions (average power, turnaround time, etc.) based on the input distributions.The resulting distributions can be analyzed to correctly size the fuel cell stack and the peaking power source.

III. Simulation of five thousands generated driving cycles based on the vehicle's model

A. Vehicle's model

The Newton's second law is used to determine the instantaneous power demand of the vehicle at each step of the simulation [11]:

$$m_v(t)\,\frac{\mathrm{d}}{\mathrm{d}t}\,v(t) = F_t(t) - \Big(F_a(t) + F_r(t) + F_g(t) + F_d(t)\Big) \tag{2}$$

$$\begin{aligned} P_v(t) &= v\,F_t(t) \\ &= v\left(m_v(t)\frac{\mathrm{d}}{\mathrm{d}t}v(t) + F_a(t) + F_r(t) + F_g(t) + F_d(t)\right) \end{aligned} \tag{3}$$

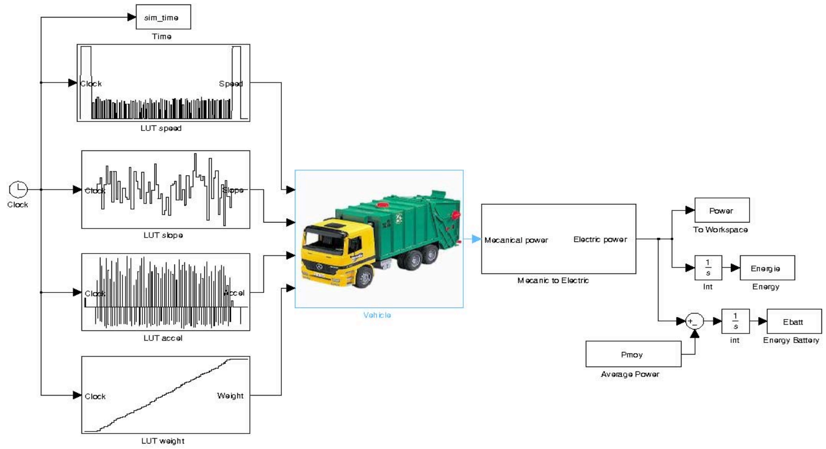


Fig. 2. Simulink vehicle's model

where F_a is the drag force, F_r the rolling friction, F_g the force caused by gravity when driving on non-horizontal roads, F_d the disturbance force that summarizes all other effects and F_t is the traction force which depends on speed and acceleration.

$$F_a = \frac{1}{2} \rho \, A \, C_x \, v^2 \tag{4}$$
$$F_r = m_v(t) \, C_r \, g \, \cos(\alpha) \tag{5}$$
$$F_g = m_v(t) \, g \, \sin(\alpha) \tag{6}$$

$m_v(t)$ is the vehicle mass in kilograms: it has to be noted that in this case, $m_v(t)$ depends on the time. α is the road slope, in radians. The matlab simulink vehicle's model is shown in Figure 2. The model parameters are: the speed, the slope, the acceleration and the weight for each step of simultation. The truck has the following characteristics:

- Empty weight: 2,250 kg;
- Mass when fully loaded: 3,500 kg;
- Front surface (A): 7 m^2;
- Drag coefficient (C_x): 0.75;
- Rolling coefficient (C_r): 0.015;
- Drivetrain efficiency: 0.8.

B. Simulation

Figure 3 shows the sequential algorithm used to run the simulation twice. Each generated driving cycle are simulated using the vehicle's model and the instantaneous power $P(t)$ at each time step, the average power $\bar{P}$ and the total energy E at the end of the turnaround can be computed using (7), (8) and (9), respectively:

$$P(t) = \frac{P_v(t)}{\eta_d} \tag{7}$$
$$\bar{P} = \frac{1}{T_{\text{turnaround}}} \int_0^{T_{\text{turnaround}}} P(t) \, \mathrm{d}t \tag{8}$$
$$E = \bar{P} \cdot T_{\text{turnaround}} \tag{9}$$

where η_d is the drivetrain efficiency and $T_{\text{turnaround}}$ is the total time of the turnaround including all stops, working and driveaway times.

As each turnaround driving profile is different, the average power or any other quantities such as the total time ($T_{\text{turnaround}}$) for each turnaround will varies. For example Figure 4 represents the statistical distribution of the total time of a turnaround.

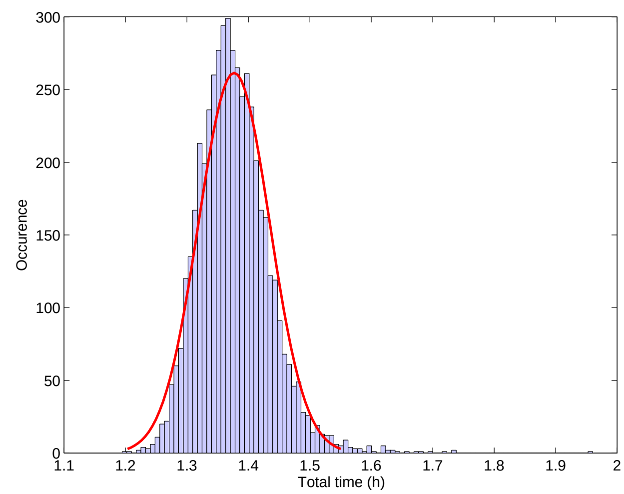


Fig. 4. Total time distribution ($T_{\text{turnaround}}$)

After this first simulation, a second one is run with the same driving profile using the average power obtain in the first one, to determine the energy profile along the time of second source (battery) (10) and, the corresponding capacity (11).

$$E_{\text{battery}}(t) = \int P_{\text{current}}(t) - \bar{P}(t) \, \mathrm{d}t \tag{10}$$
$$C_{\text{battery}} \, (\text{Wh}) = E_{\text{battery max}} - E_{\text{battery min}} \tag{11}$$

This results are then exploited to size both energies storage sources (fuel cell power, size of the hydrogen tank, battery power and mass).

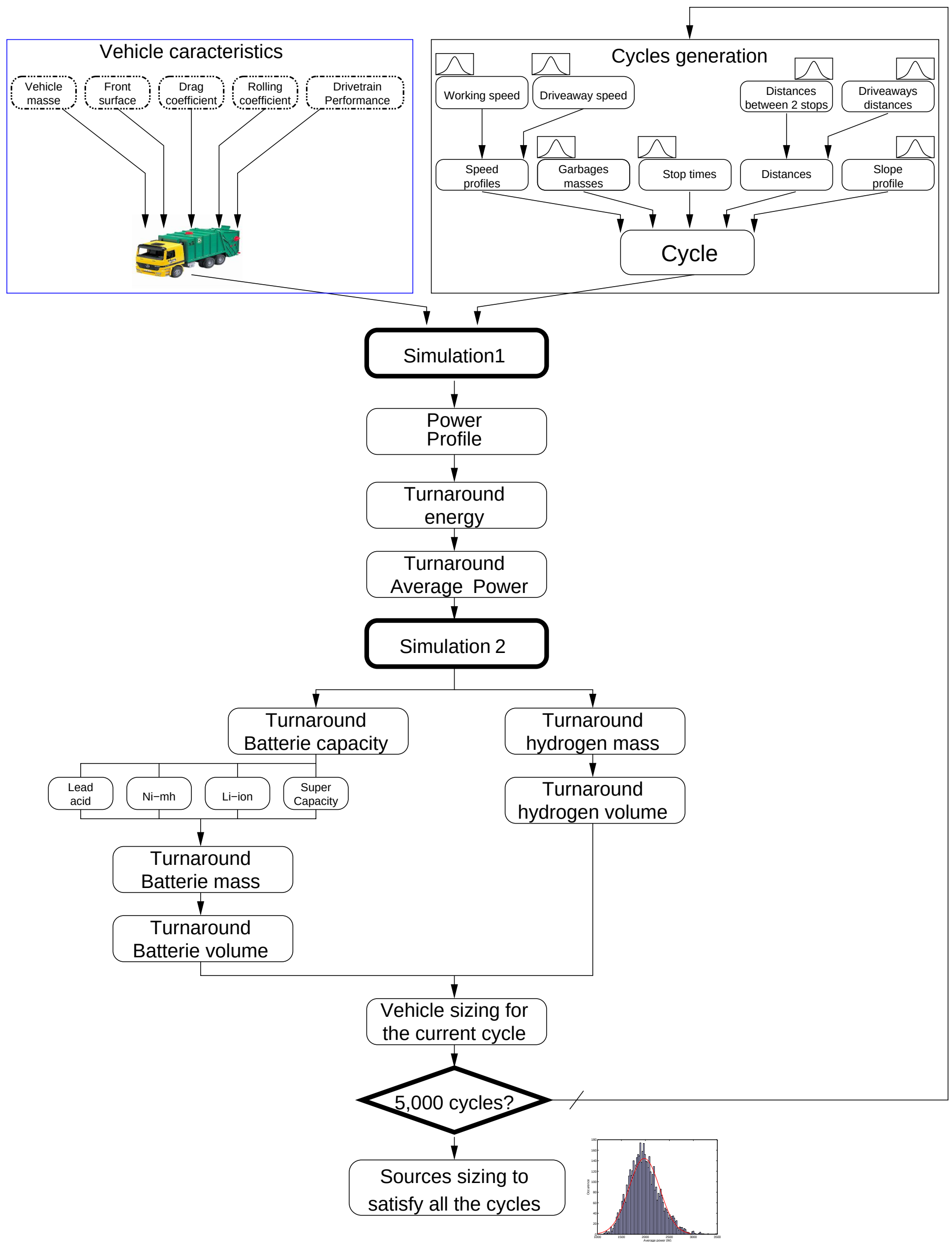


Fig. 3. Algorithm principle

IV. Fuel cell stack power needs

A. Average power and energy distributions

After a simulation of 5,000 turnarounds the average power distribution is computed and given in Figure 5. It can be clearly seen that the distribution of the average powers is a normal distribution.

The average power distribution shows that the maximum average power required for one turnaround does not exceed 3,4 kW. A 3,5 kW fuel cell stack will satisfy 100 % of the simulated cases based on the choosen parameters. These results will permits the fuel cell stack and the hydrogen quantity to be choosen depending of how much turnarounds are planed for one day. Moreover, if the hydrogen infrastructure permits the use of a fast recharge station, the hydrogen tank do not need to be sized for one day needs but only for a couple of turnarounds. The hydrogen storage tank sizing methodology is given in part(VI-C). It is assumed that the fuel cell will run constantly at 3,5 kW, also during stop phases (when the truck is collecting garbages). The average power can be substracted to the instantaneous power to determine the power needed by the peaking power source [12].

V. Peaking power source energy needs

Once the average power is determined, a second simulation is ran to determines the energy (10) and capaciting (11) of

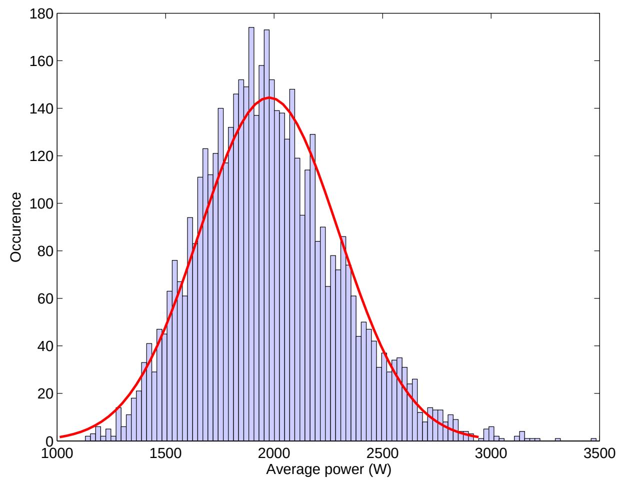


Fig. 5. Turnarround average power distribution with 60 % breaking recovery

second power source. The results are given in Figure 6. The battery capacity is sized to run in continous mode: the initial and final battery's states of charges are the same. The fuel cell recharge the battery when the power needed by the vehicle is under the average power of the fuel cell (3,5 kW). These results shows that the maximum battery capacity does not exceed 2,8 kWh. A batteries pack with 3 kWh will satisfy 100 % of the simulated cases based on the choosen parameters.

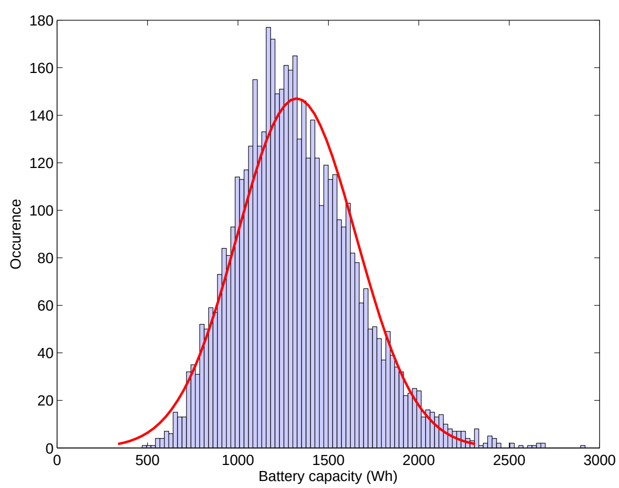


Fig. 6. Size of battery capacity with 60 % breaking recovery

VI. Practical Sizing of Both Energy Sources

A. Fuel cell and Battery capacity for several braking recovery rate

Table 1 shows the average power of the vehicle and the battery capacity needed for the truck for several breaking recovery rates. For this study due to repeated starts and stops, it is assumed that the recovery of braking energy rate is 60 % [13].

Braking recovery	Average Power (W)	Battery Capacity (Wh)
0 %	2,500	1,400
30 %	2,370	1,340
60 %	2,100	1,300
100 %	1,780	1,250

TABLE I

Fuel cell and Battery capacity for several braking recovery rates

B. Size of the battery pack

Table 2 shows the mass and the volume of differents peaking power sources technologies based on the specific power and energy density given in [14]. This table is based on an energy recovery of 60 %. It shows that ultracapacitors are not suited for this vehicle configuration because the energy required is too high.

Type	Mass (Kg)	Volume (L)
Lead-acid	300	120
Nickel-metal	65	20
Lithium-ion	55	20
Ultracapacitors	250	12,500

TABLE II

Size of the second energy source pack for several technologies assuming a 60 % energy recovery during braking phases.

C. Size of the hydrogen tank

Once the fuel cell power is know, the quantity of hydrogen can be calculated to satisfy all the cycles. The mass and volume of hydrogen on board are deduced from the energy provided by the fuel cells. Currently most of the hydrogen tanks are pressurized to 300 bar, with a minimum pressure of 30 bar. Knowing the power of the fuel cell and the duration of one turnaround, it is possible to calculate the energy needed. Then, the distribution mass of hydrogen is determined (Figure 7). From the mass, the number of moles ($n_{\text{turnaround}}$) and subsequently the volume of hydrogen can be deduced as shown in Figure 8.

To ensure a proper hydrogen supply of the fuel cell, the pressure in the tank has to be higer than 30 bar for a 300 bar tank. Consequently, all the hydrogen in the tank cannot be used and an extra amount of hydrogen (n_{extra}) must be added. This extra amount must be taken into account to calculate the final volume of the hydrogen tank.

From the ideal gas law,

$$P_{\text{H}_2} \cdot V_{\text{H}_2} = n_{\text{H}_2} \cdot R \cdot T \tag{12}$$

with

$$m_{\text{H}_2} = \frac{E}{LHV \cdot \eta_{\text{FCS}}} \tag{13}$$

$$n_{\text{H}_2} = \frac{m_{\text{H}_2}}{2 \cdot M_H} \tag{14}$$

$$n_{\text{H}_2} = n_{\text{turnaround}} + n_{\text{extra}} \tag{15}$$

Where LHV is the lower heating value of hydrogen ($LHV = 120.1\,\text{MJ/kg}$), η_{FCS} is the fuel cell hydrogen efficiency and M_H is the hydrogen molar mass.

Combining equations (12) and (15), gives:

$$P_{\text{H}_2} \cdot V_{\text{H}_2} = (n_{\text{turnaround}} + n_{\text{extra}}) \cdot R \cdot T \tag{16}$$

The pressure at the end of the turnaround is P_{extra}, so n_{extra} is given by (17)

$$n_{\text{extra}} = \frac{P_{\text{extra}} \cdot V_{\text{H}_2}}{R \cdot T} \tag{17}$$

Each hydrogen volume can be obtained using (17) in (16).

$$n_{\text{turnaround}} + n_{\text{extra}} = \frac{P_{\text{H}_2} \cdot V_{\text{H}_2}}{R \cdot T} \tag{18}$$

$$n_{\text{turnaround}} = \frac{P_{\text{H}_2} \cdot V_{\text{H}_2}}{R \cdot T} - \frac{P_{\text{extra}} \cdot V_{\text{H}_2}}{R \cdot T} \tag{19}$$

$$n_{\text{turnaround}} = \frac{(P_{\text{H}_2} - P_{\text{extra}}) \cdot V_{\text{H}_2}}{R \cdot T} \tag{20}$$

$$V_{\text{H}_2} = \frac{n_{\text{turnaround}} \cdot R \cdot T}{(P_{\text{H}_2} - P_{\text{extra}})} \tag{21}$$

where P_{H_2} is the hydrogen tank pressure in Pascal (Pa), R is the ideal gas constant $\left(R = 8.314\,\text{J} \cdot \text{mol}^{-1} \cdot \text{K}^{-1}\right)$, T is the tank temperature in Kelvin (K), n_{H_2} is the number of moles of dihydrogen for one turnaround and n_{extra} is the moles of dihydrogen at the end of a turnaround.

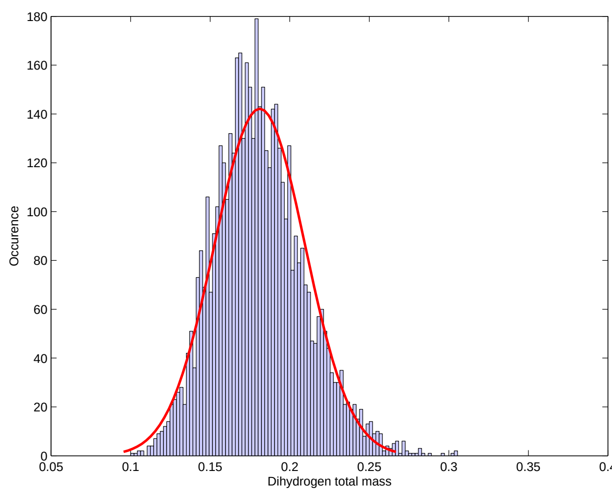


Fig. 7. Dihydrogen mass needed for one cycle with 60 % breaking energy recovery

VII. Conclusion

This paper describes a new methodology to size the energy source of a hybrid vehicle based on statistical description of driving cycles. This methodology is applied to a fuel cell based collecting truck for which the driving pattern is very specific. Randoms driving cycles are then generated allowing the distribution of the average powers and energies to be computed. The analysis shows that even for a 2,500 kg truck a 3,5 kW fuel cell stack is sufficient, allowing the fuel cell system to be downsized compared to classical solutions using several tens of kilowatts fuel cell systems.

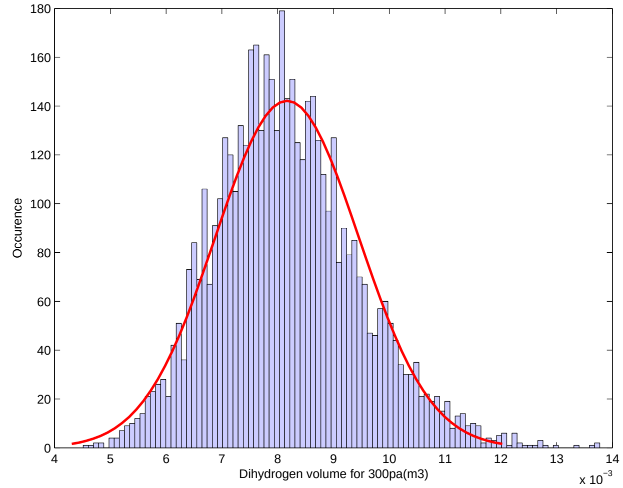


Fig. 8. Dihydrogen volume needed for one cycle with a 300 bar pressurized tank and 60 % breaking recovery

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