F2008-SC-039

Preliminary Study of a three-wheel tandem powered by a PEM fuel cell

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KEYWORDS
Three-wheeler, Tilting system, Hydrogen, Reformer, Fuel consumption

ABSTRACT
This paper gives an overview of a vehicle concept. The challenge was to carry out a two-month preliminary study out of a broad theme inviting us to "create a car for two, weighing less than 400kg, supplied by less than 15kw and respectful of the Euro5 standard."

The vehicle is a three-wheel tandem using an alternative propulsion system with PEM fuel cells. Therefore, this project is perfectly in line with the greatest issue that automotive engineers have to face currently, that is to reduce greenhouse emissions. The main problems with the use of hydrogen are storage and consequences of industrial production. This promising system (invented by Nuvera) enables onboard production of hydrogen by means of a fuel processor that can convert any fuel into hydrogen.

INTRODUCTION

Background of the project

Fig.1: vehicle basic design

The project began in January 2008 and was carried out by four students of a French engineering school called ENSIETA. All four are specialized in automotive engineering, and this short study is meant to put in common their knowledge acquired within this field. The subject was proposed by the SIA (French branch of the FISITA). It invited us to "create a vehicle around the theme "Zen", with two seats, weighing less than 400kg (+ maximum 100kg of batteries if necessary), supplied by less than 15kW, and respecting at least the Euro5 standard". This paper will give a quick overview of the work done to answer these specifications, showing more precisely the choices that have been made.

A project in line with current issues

The subject particularly interested us as it fits perfectly today's demand:

- the lowering fuel consumption (and CO_2 emissions) goes along with weight reduction
- the average of people traveling in each car is less than two, so smaller and lighter cars are sufficient
- the engine limitation proposed, 15kW, is adapted to city and suburb driving (that makes up most of the journeys) and is meant to limit emissions
- the Euro 5 standard is imposed to limit environmental damage due to pollution

Target definition

After brainstorming around the theme "Zen", it was decided to create a car for mostly urban couples driving out of the city for the weekend.

Therefore, the vehicle will mainly be used for city driving but must also carry the people to the countryside nearby. In the specifications we defined, a minimum autonomy of 200 km was fixed, and it was decided that a maximum speed of 110km/h should be reached.

The vehicle must be simple, non-sportive, and as less constraining as possible.

GLOBAL ARCHITECTURE

General layout

Passenger arrangement:

As mentioned above, the vehicle will only be equipped with two seats, and is mostly meant for couples. We thought about bringing the people closer together with a tandem layout, as on a motorcycle.

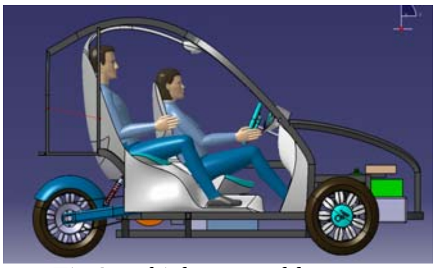

Fig.2: vehicle general layout

Chassis layout:

The weight reduction issue, altogether with the idea of lowering fuel consumption, made us reflect about all the elements that could be omitted because not essential. One of the simple ideas that came out was the omitting of a wheel, as three are sufficient for constituting a vehicle. Also, this goes well with our choice of installing two people in tandem: such a three-wheeler is a real intermediate between a car and a motorcycle. However, as we will see further, three wheels generate stability problems in corners, so a tilting system has to be added, thus increasing the weight.

Vehicle body:
Again, in order to minimize fuel consumption while conveying a “Zen” image, the car body design was made with soft forms, and a good aerodynamic coefficient (here estimated close to 0.3). Its final shape evokes a cocoon or bubble.

Motorization

Staying concerned about weight reduction and knowing that we do not aim a sportive behavior (the vehicle will not be subjected to important accelerations), we considered that having only one wheel motorized would be sufficient. Depending on the wheel arrangement it will either be at the front or rear. Rear wheel drive generally makes a vehicle tend to oversteer. This occurs mostly while accelerating in corners, as the rear tires loose their lateral potential. However, the acceleration capacities of our vehicle are quite low, so this is not a major problem.
We also thought about using an in-hub motor in the single wheel, but this would add considerable unsprung weight, which has mostly bad effects: less grip, road irregularities transferred more easily… Ride quality and wheel control would be affected.

Wheel arrangement

We had to choose between a single wheel front and two wheels at the rear (“1+2”), or the opposite configuration (“2+1”). We compared these two layouts relatively to different criteria, including: dynamic behavior, steering, and esthetics.
For the dynamics aspect, we preferred having a vehicle with an understeering tendency as it is safer (more controllable in corners). We compared both configurations in this respect (1). As mentioned before, rear driving (layout 2+1) will tend to generate oversteering, but this effect stays limited in our case as accelerations stay low. Moreover, considering only the chassis, this same vehicle, heavier at the front and with an important front roll resistance, will naturally tend to understeer. On the opposite, with a single wheel at the front (layout 1+2), the vehicle will naturally tend to oversteer in corners at its limit of adhesion (as the rear is lagged behind). Also, braking in a turn will destabilize a car with a single front wheel, whereas acceleration will destabilize the one with one rear wheel; as the brake forces are a lot more important than the acceleration forces (three wheels concerned instead of one and the acceleration capacities of the vehicle are low), the latter is preferred.
Moreover, a 2+1 configuration allows the vehicle to be guided with two wheels, thus allowing a classic steering system.
For an esthetics point of view, this same configuration is once again more attractive: the vehicle resembles more like a common car as the frontal design is the most determinant.

Architecture specifications

The final dimensions of the vehicle (obtained at the very end of the project after a few loops in the calculations) are the following:

External dimensions	
Wheelbase	2m
Wheel-track	1.2m
Width	1.36m
Lengtht	2.98m
Height	1.69m
Ground clearance	0.13m

Weight & distribution			
	Empty vehicle	1 driver (+75kg)	Maximum charge (+150kg +30kg of luggage)
Weight	426kg	501kg	606kg
Mass distribution	65/35	60/40	55/45
CG height	420mm		395mm

TILTING SYSTEM

Stability of 3-wheelers

Three-wheelers can have severe stability problems in corners if they are not well prepared to affront the g-forces. We need to take this into account for our design.

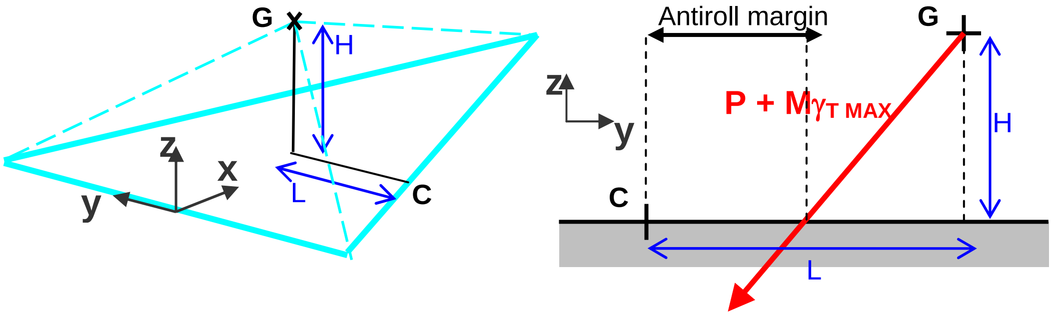

Fig.3: polygonal base of 3-wheelers and anti-roll margin

Indeed, vehicle stability depends directly on the height of the center of gravity (G): if the external forces resultant in G points out of the base (triangle constituted by the three wheels), the car will rollover. Therefore we need to insure that with the maximum lateral acceleration that the car could be subjected to (before slipping: it depends mostly on the tires chosen), the resultant will keep on pointing towards the inside the triangle. We can notice that the higher G is and the smaller the track is, the more easily the car can rollover. Therefore, G must be the lowest possible and closer to the front, and the track wide enough. However, with the dimensions fixed previously, we calculated that our vehicle will have important stability problems. Therefore, we need to find a way of shifting the center of gravity towards the opposite direction than the one naturally followed in corners, thus shifting the resultant force inside the base. This can be obtained by tilting the vehicle towards the inside of the corner.

Benchmarking of existing solutions

Active versus Passive (1):

Alike motorcycles, three-wheelers can tilt by means of a free control of the driver; but it must lean sufficiently to counter-balance the maximum sideforces that can pull it outside the corners. Active titling control can tackle the problem by itself, with ECU signals providing control output to lean actuators. A great advantage of such systems is the fact that the driver does not have to lean himself in order to balance the whole vehicle, which is rather physical and contradictory with a “Zen” atmosphere. The vehicle is simply driven by the user just like any ordinary four-wheeler: in corners, the tilting system controls everything itself.

Well-known systems (2):

Most of the existing tilting systems use hydraulic energy to tilt the vehicle. The activators are mainly cylinders that either tilt the body relatively to a whole axle (like the Carver), control the suspension vertical translations (Suspension Citroën Activia), or change the axle geometry to tilt the whole chassis (Mercedes F300 Lifejet).

Fig. 4: the Carver

We decided to adapt this last solution (F300) to our vehicle. Indeed, it seemed to be the most compact, the lightest, and the best-adapted to our layout.

Mechanism:

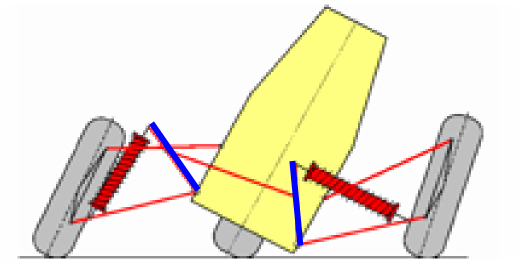

Fig.5: A draft of the F300 suspension

Fig.6: the Mercedes F300

The Mercedes F300 tilting system is based on a double wishbone suspension. It is composed of a hydraulic cylinder that operates the front dampers by means of two rods (in blue on the figure). The cylinder pushes the rod outside the corner and rises up the strut, while pulling the opposite rod. Thanks to the double wishbone geometry, this movement forces the body to lean. The wheels follow the movement and tilt as well, but with different camber angles depending on the suspension geometry. The rear wheel, linked to the body, will tilt with it. Therefore, motorcycle wheels or special wheels intermediate between car and motorcycle ones (specially developed for this concept) must be used at all three corners.

Adaptation to our vehicle:

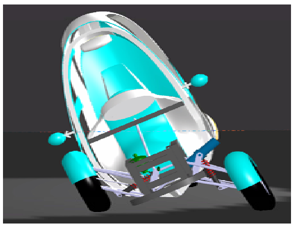

Fig.7: our vehicle at its maximum leaning

We dimensioned the F300 tilting system in order to reach a lateral acceleration of 1.2g without rolling over and adapted it to our vehicle. Calculations demonstrate that it must lean up to about 23°. By security, we chose to impose ourselves a maximum lean of 30°. This feature has an important impact on the design.

After having adapted its dimensions to our vehicle, we modeled the system in CATIA in order to see how it performs. This allowed us to optimize its geometry, knowing that we wanted a maximum leaning angle of 30º. In particular, for this specific angle, we wanted to guarantee the following:

- a camber < 45º for the external wheel and a minimum ground clearance of 100mm
- a suspension geometry keeping good characteristics
- no rod buttress effects
- a minimization of the maximum cylinder force

The model also allowed us to notice important features that were not anticipated:

- the center of gravity has a quasi-horizontal displacement for small tilting angles, while it shifts vertically when they become higher
- the track width decreases quite a lot while the vehicle tilts (by more than 200mm for 23º), which generates additional stability loss; thus justifying the margin chosen for the maximum leaning angle.

ENGINE

<u>Choice of the type</u>

We compared thermal and electric engines relatively to various criteria that we selected: noise and vibration, maintenance, supplying (autonomy and facilities), weight, compactness, price and pollution. An advantage of thermal engines is that the purchase price will be reasonable as their technology is well mastered, while electric motors supplied by batteries are expensive mostly because of the precious metals they use. Nevertheless, the use of electric engines has some advantages that suit perfectly our seeking for “Zen”: it emits low noise and vibrations; the mechanism is soft and requires low maintenance. Moreover, as it has a constant torque on the entire utilization range, no gear box is required.

A supplying issue:
However, the main problem of electric engines is the way they are currently supplied.
While fuel is available in gas stations and thermal cars can be filled up within a few minutes only, the charging of batteries is very long and energy consuming. This is, of course, contradictory with our concern about environment and “Zen” feeling. Moreover, with the technologies currently introduced to the auto-market, the autonomy cannot reach the ones of conventional thermal cars. For a basic passenger thermal car, 40L allows more than 500km of autonomy, whereas an important volume of batteries (about 250kg) is required. This encumbers and weighs down the vehicle a lot.
Fuel cells could be an alternative to batteries, as electricity can be created directly on board and hydrogen is very compact (it has a mass energetic density of approximately 120 MJ/kg versus 42.7 MJ/Kg for gas). However, the problem of hydrogen is, once again, its storage. Indeed, as shown in the following table, its volumetric energy density is very low:

	Hydrogen (1bar)	Hydrogen (700 bars)	Gas	Diesel
Density (kg/L)	0.0000898	0.06286	0.702	0.855
Mass energetic density (MJ/kg)	120	74.8	42.7	41.9
Volumetric energetic density (MJ/L)	0.010776	4.7	30.0	35.8

Fig.8: comparison of fuel characteristic at ambient conditions ((3) with values reevaluated)

Whereas an important mass of gas is obtained within a small volume, it is the opposite for hydrogen. For instance, 1L of gas contains 30 MJ of energy at ambient temperature and pressure conditions; to obtain the same quantity of energy, about 2800 L of hydrogen are needed. A solution could be the compression of hydrogen, but with 700 bars, the energy remains high: 6.4L. Therefore, to attain the autonomy required, important volumes are needed; and the transporting of highly pressurized gas is not recommended. On the other hand, the use of liquid hydrogen can not be envisaged as it is obtained for about -235ºC.

An environmental issue:
We must not forget one of the major constraints of this project: the environmental issue.
Thermal engines today still reject too many polluting gas and/or CO2. On the other hand, batteries can not be recycled and require a significant industrial production of electricity, which is very energy consuming. The compression of hydrogen at a large scale implies the development of special equipments and a lot of energy consuming as well. Therefore, because of the energy required to compress the hydrogen gas, the supply chain for hydrogen actually has lower well-to-tank efficiency compared to gasoline!

Conclusion on the choice:
For their autonomy and supplying facilities, thermal engines seem more practical, and less constraining in terms of architecture. However, for the power required (less than 15kW), there does not exist bi-cylinder engines but only mono-cylinder ones that are very noisy, rotate fast and vibrate a lot (contradictory with “Zen”). On the other hand, while electric motors are softer, their greatest problem is the way they are currently supplied in electricity.
The ideal would be to find a way of supplying the electric engine with energy already existent in stations, in order to keep the softness and compactness of an electric motor along with the autonomy and facility of a thermal engine.

Solution – Mobile Reforming (4), (5):
While searching for possible solutions in papers recently released, we discovered the “mobile reforming” technology. It is still in its prototyping phase but car makers such as Renault are already considering its use, which could facilitate the transition towards hydrogen vehicles.

Indeed, although it is not produced yet, we found the concept very interesting and promising, so we decided to use it within our vehicle, as if it actually existed.

Fig.9: Nuvera reformer

The principle is to transport a mini reforming unit creating hydrogen from gas or any other hydrocarbon, thus supplying the fuel cell. The reformer is able to transform a chemical energy with a good energy/volume ratio, like gas, into an energy with an excellent energy/mass ratio: hydrogen. It is directly available and consumed, which eliminates the storage problem. The chemical reactions created within the reformer are the same ones as the ones used in industries mass-producing hydrogen. However, the peculiarity of Nuvera's reformer is the use of a vaporeforming and partial oxidation of hydrocarbon procedures within a same unit, in order to increase the global output of both reactions. Indeed, the vaporeforming reaction is an endothermic reaction whereas partial oxidation is exothermic. The heat created by the last one can then be used to perform the first one. The reaction is therefore called autothermal reforming, and as the firm claims, provides an efficiency of about 80% (with an installation supplying 70kW).

Components

Knowing that the engine must be develop a maximum of 15 kW (specification), we chose a fuel cell delivering a little less power (13.2kW continuously). Therefore, the reformer must provide this power divided by the efficiency of the fuel cell (0.8): a minimum of 38kW [We considered that it already existed and estimated its dimensional characteristics by equivalence with the 70 kW one already developed by Nuvera]. As the fuel cell supplies a voltage of 48V, we chose an engine functioning with a 48V input (lift-truck engine) to avoid using a clipper or booster for instance, which would affect the global efficiency. In parallel, to compensate transitory phases and reach more than 15kw when significant acceleration are required, we added two packs batteries connected in series and supplying altogether 43.2 V.
The transmission, linking the engine to a single rear wheel, is composed of a simple belt.
The fuel cell and reformer (the most voluminous), have been positioned at the front of the vehicle (around the tilting mechanism); the engine and the batteries are underneath the seats.

Overall system

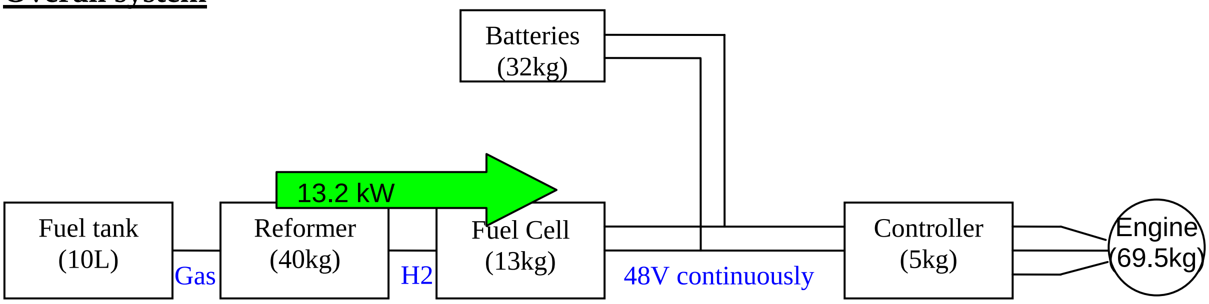

Fig.10: Power system overview

The whole system weighs approximately 170kg (about 100kg for the engine supplying), which is not negligible.
Both the reformer and the fuel cell work continuously. If the engine requires less power than the 13.2 kW delivered by the fuel cell, the batteries will receive the surplus and charge. On the contrary, if it requires more, additional power will be taken from the batteries. During braking, the engine becomes generator and adds power to the 13.2 kW (if we do not take into account the efficiencies) already sent to the batteries.

In constant phases, the reformer evacuates CO2 at 180°C. However, there exist no vibrations linked to the opening and closing of valves as for thermal engines, so the muffler is not necessary. Therefore, one meter length of tube is sufficient to lower the temperature of gas. Nevertheless, the fuel cell creates heat that needs to be dissipated by the use of a heater.
To control the engine according to the driver's demand, we chose a current servomechanism. Indeed, when the driver needs to accelerate, the current feeding the engine will increase the torque. Therefore, the acceleration pedal is linked to an electrical potentiometer and the output is sent to a current dimmer changing the engine charge.

PERFORMANCES

Data used:

Total weight	Cx	Frontal surface	Wheel resistance
475 kg	0.3	1.206 m²	8 daN/t

General dynamic performances

The time taken to reach 100 km/h was determined using simple dynamic calculations and simulation within a vehicle dynamics software.

	Time 0-100 km/h
Hybrid mode	13.4 s
Batteries only	16.8 s
Fuel Cell only	19.4 s

Driving performances

There exist two modes: a usual hybrid mode (fuel cell + battery), and a 100% electric mode.

- Hybrid mode:
  We defined three possible uses that depend on the battery charge ratio and the performance asked by the driver.
  First, the vehicle will work on batteries during three minutes at its start up. It corresponds to the time required for the fuel cell and reformer to attain their ideal temperature. Also, we decided that energy will be provided by the batteries when there charge ratio reaches 75%. Conversely, the energy will be provided by the fuel cell when the ratio is lower than 75%.
  The last case is the performance condition: if the driver desires a significant acceleration, the fuel cell and batteries will be coupled to provide altogether the power required.
- 100% electric mode:
  It is the "zero emission" mode. It is mostly used for small displacements, as the batteries only allow an autonomy of about 86km (calculated using an NEDC urban cycle).

Consumption:
We estimated the consumption of our vehicle for different usages, using NEDC cycles supposed to represent the average driving condition in Europe.
To calculate the energy produced by the different sources (batteries and fuel cell) during these cycles, we need to consider all of the efficiencies, from the gas tank to the wheel:

	Source	
Efficiencies	Fuel Cell	Batteries
Belt	0.98	0.98
Engine	0.92	0.92
Controller	0.98	0.98
Fuel Cell	0.35	
Reformer	0.8	
Batteries		0.98
TOTAL	0.25	0.8

We can notice that the efficiency obtained with the use of our fuel cell system is low (but close to the one of a thermal gas engine). This is mostly due to the fuel cell efficiency (0.35). However, we expect that this value will soon evolve as the efficiency of fuel cells is a theme currently analyzed with a lot of attention.
To calculate the energy loss during a cycle, we took into account the extra-consumption used at the starting up when the reformer heats up (about 1.3 MJ). The fuel consumption was then calculated from the gas volumetric energy density. Taking into consideration the energy recovery, we obtain the following values:

	Consumption (L/100km)
Urban cycle	2.28
Extra-urban cycle	2.58
Mixed cycle	2.34

The consumption is higher for the extra-urban cycle as vehicle speed is higher, and the recharging of batteries lower.
Without energy recovery, the consumption within a mixed cycle is 2.61 L/100km, so we gained 10.35%.

A tank of 10L is used, allowing an autonomy of 400km.

Pollution and emissions:
Concerning pollution, as the technology uses a controlled chemical reaction, the product obtained is pure (anyways the fuel cell does not support pollutants such as NOx, CO and particulars). Moreover, the temperatures do not exceed 180°C, so we can suppose that the engine technology provides no, or very few, pollutants. Therefore, pollution can only depend on the fuel itself and its quality. For the reasons mentioned previously and as our fuel consumption is low, we believe that our vehicle would respect the Euro5 standard.
Within the system, however, CO2 is created along with the chemical reaction. Its emission is directly linked to the fuel consumption; with our vehicle, for a mixed cycle, we obtain 53 g/km. The association of European car-makers (ACEA) expects reducing the limit of CO2 emissions down to 120 g/km. Our vehicle would easily satisfy this condition.

CONCLUSION

This quick presentation of our project only gives an overview of the work that has been carried out. However, it allows us to present Nuvera's promising technology: the reformer. Indeed, although it is still in an experimental phase, we believe that it could be a good transition towards complete hydrogen vehicles.


Fig.11: rear of the vehicle

The best way to tackle the environmental problem is by lowering consumption, which mainly depends on the transmission design and its global efficiency. We believe that the coupling of a reformer with a fuel cell will probably provide a very good one soon, as the efficiency of fuel cells is improving significantly. Also, it is currently fitted to gasoline, but can be adapted to more ecologic fuels as well.
Nevertheless, the technology is still at a development phase, and is not produced yet; therefore, no prototype can be made to physically evaluate the performance of our vehicle.
Also, we obtained good consumption results because of the weight of our vehicle, another very important parameter, and this is not thanks to the power unit as it makes up 40% of the whole weight. Indeed, as it is currently, the system is very complex and voluminous. Moreover, it would probably be very expensive because of the components used and we know little about its reliability and pollution control. However, considering these issues solvable, the theory of this technology shows very few drawbacks.
Regarding the architecture aspect, the use of three wheels has some disadvantages, and the vehicle might not be included within the car category.

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The calculations (not detailed in this paper) were all made using the following lectures given at ENSIETA:

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- Raphaël MORENO “Architecture des véhicules électriques”, 2007
- Vincent SCHITT, “Dynamique du véhicule”, 2007

These were used for providing information as well, along with the following:

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