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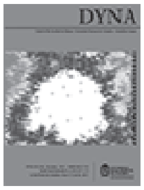

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Simulation of a hydrogen hybrid battery-fuel cell vehicle

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Abstract

This paper describes a vehicle simulation toolbox developed under Matlab® environment, which can be used to estimate the range of a vehicle battery, or a fuel cell/battery hybrid system. The model is function of mechanical and physical variables that depend not only on the vehicle but also on the ground. This toolbox can be extended to GPS tracking files by means of reading data file plug-ins. Even standard drive cycles can be simulated. Battery and hydrogen consumption, hydrogen storage tank level, battery state of charge, power consumption and fuel cell energy production, maximum range and maximum number of cycles for a real route can be determined. The model facilitates the prediction of the vehicle range and the hydrogen and energy consumption. Real route simulation gives a good approximation of the vehicle speed close to real-life services instead of using driving cycles that are quite arbitrary approximations to a real route.

Keywords: fuel cell vehicles; hydrogen, hybrid vehicles; simulation tool, battery.

Simulación de un vehículo híbrido de hidrógeno con batería y pila de combustible

Resumen

Este artículo describe una herramienta de simulación bajo el entorno de Matlab®, que puede ser utilizada para estimar la autonomía de un vehículo con baterías o híbrido con pila de combustible y baterías. El modelo es función de variables mecánicas y físicas que dependerán no solo del propio vehículo sino también del terreno. Su uso es extendido para recorridos obtenidos mediante dispositivos GPS y para ciclos estándar. Pueden obtenerse diferentes variables de salida tales como: el consumo de hidrógeno y batería, el nivel hidrógeno, el estado de carga de la batería, la potencia consumida, la producción de energía por parte de la pila, el máximo alcance del vehículo y el máximo número de ciclos finalizados. La simulación de rutas reales proporciona una buena aproximación de la velocidad del vehículo para usos, en lugar de utilizar ciclos de conducción estándar, obteniendo así aproximaciones bastante arbitrarias para una ruta real.

Palabras clave: Pila de combustible, hidrógeno, vehículos híbridos, simulación, batería.

1. INTRODUCTION

Automobiles are the major cause of urban pollution in the 21st century [1-3]. Fuel cell hybrid vehicles are a new emerging automotive technology that could reduce urban pollution, facilitate compliance with the Kyoto Protocol and reduce our dependence on oil [4,5].

Some automotive manufacturers have made commitments to introduce electric and fuel cell vehicles and hybrid fuel cell systems [6]. The prediction of performance and range is very important for their viability. Computing tools allow us to perform a rapid and economical evaluation of a proposed vehicle's performance [7].

Currently controllers for hybrid electric cars are based on parallel schemes with batteries and fuel cells, and the introduction of fuel cells into hybrid electric power systems principally extends the autonomy of the vehicle and the demanded power peak is only managed by the reversible energy storage system (batteries), allowing a drastic reduction on the fuel cell size [8,9].

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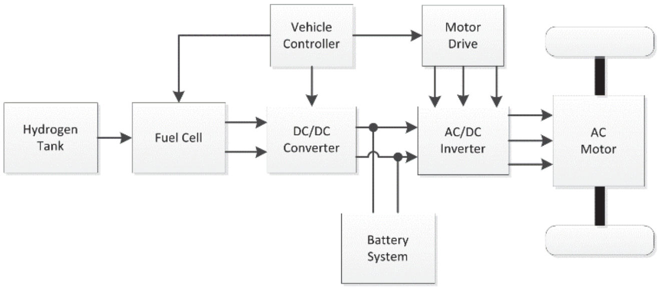


Figure 1. Fuel cell hybrid vehicle configuration.
Source: The authors

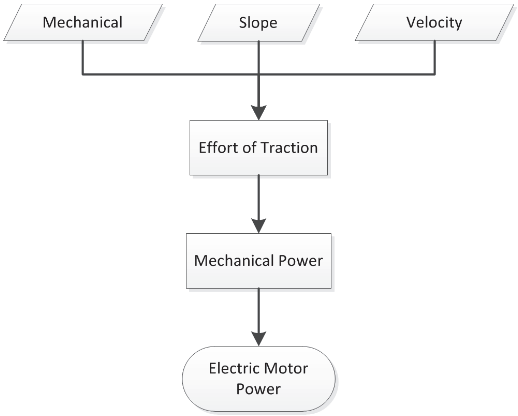


Figure 2. Electrical motor power output estimation.
Source: The authors

Fuel cells usually work in a steady-state mode for the average power demanded, and the excess of power yielded is then available to be used in the recharging process [10].

A tool to analyze and evaluate all of these vehicles is necessary so that a study of their technical and economic viability can be conducted [11].

2. Modelization Issues

The numerical model used for the hybrid vehicle simulation consists of several components. These components are specialized simulation modules separated in several m files. Every file has input and output parameters to be defined by the user before running the simulation. In the model, the vehicle dynamics, the electric motor, the battery block and the fuel cell have been considered [12,13].

Fig. 1 shows the fuel cell hybrid vehicle configuration used in the toolbox “SimuBus”.

Vehicle dynamics Mechanical Power Simulation Model

This component consists of a longitudinal dynamic model of the vehicle. In Fig. 2, the flux diagram corresponding to the electrical motor power output calculation is presented. The variables considered are the vehicle mechanical features, road slope and instantaneous vehicle speed.

The mechanical traction effort should be directed toward moving the vehicle [14]:

$$P_{mechanical} = (F_{rr} + F_{ad} + F_{hc} + F_{la}) \cdot v \cdot \eta_g \qquad (1)$$

where F_{rr} is the force required to overcome the rolling resistance; F_{ad} is the force required to overcome the aerodynamic drag; F_{hc} is the component necessary to overcome the weight of the vehicle when it is climbing; F_{la} is the linear acceleration of the vehicle and η_g is the efficiency of the gearbox.

In terms of function inputs, vehicle mechanical properties must be known:

- Vehicle mass and front area.
- Rolling and aerodynamic coefficients.
- Gear ratio and efficiency.
- Regenerative ratio, in the case of a self-generation hybrid vehicle circulating over a negative slope path.

As output, the electric motor power output can be obtained.

Electric Motor Model. Input Electrical Power

Once the output mechanical power of the electric motor is calculated, the electrical power demand can be calculated too. To do this, the motor efficiency, or if that is not possible, the motor losses must be known. The losses are classified in four types [12,15,16]:

- Copper conductor losses
- Iron losses
- Friction and windage losses
- Constant losses (due to electronic control)

By calculating the efficiency and using the angular speed and motor torque, the electric power input can be determined. Adding the auxiliary element power demand, the total electric power demand that the batteries and/or the fuel cell must supply can be obtained.

Thus, the equation to calculate the electric power as a function of the mechanical power, the electric motor efficiency (η_m) and the auxiliary power (P_{aux}) is as follows:

$$P_{electric} = P_{mechanical} \cdot \eta_m + P_{aux} \qquad (2)$$

In this model, the user can set a limit factor to prevent the electric motor from exceeding a specific torque value. In Fig. 3, a flux diagram representing the calculation algorithm based on the input mechanical power and the electric motor efficiency is presented.

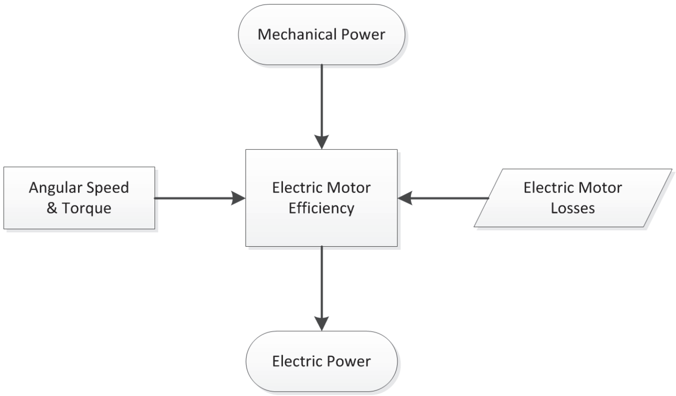


Figure 3. Electric motor efficiency.
Source: The authors

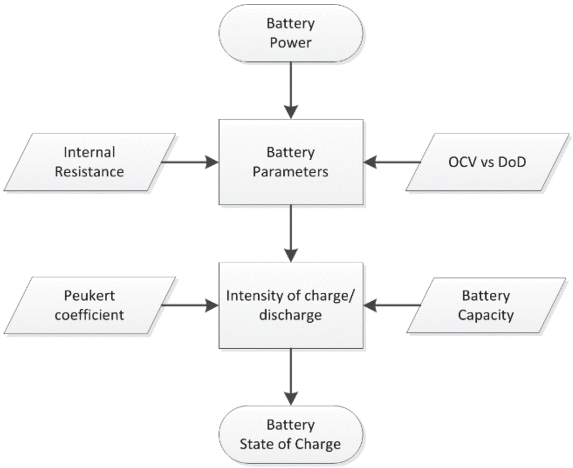


Figure 4. Battery model. Battery state of charge estimation
Source: The authors

Battery Model

The battery model is constructed from a simple equivalent circuit. For the model, it is necessary to know the internal battery resistance (R), the charge/discharge plot (open circuit electric potential versus depth of battery discharge), which is different for every type of battery technology considered in this simulation (lead acid, nickel-cadmium, lithium, etc.). With this value and the power required, the discharge current can be calculated:

$$I_{discharge} = \frac{E - \sqrt{E^2 - 4RP_{bat}}}{2R} \qquad (3)$$

For the charge, the same calculation is used, but with a different sign. In addition, the Peukert effect will be considered [6]. This effect is considered because the maximum battery capacity changes as a function of the discharge intensity, decreasing for high discharge intensities.

The Peukert equation makes it possible to correct the battery discharge by means of Peukert's Coefficient (*k*). Therefore, the equation modeling the discharge depth of the battery depends on the ratio between the amounts of charge spent or supplied (different signs) and the battery capacity corrected by Peukert's Coefficient [14].

$$DoD = \frac{\delta t \times I^k}{C_p} \qquad (4)$$

The necessary inputs are as follows:

- Battery type (Lead Acid, Nickel-Cadmium, Metal-Hydride, Lithium-Ion or Zebra).
- Number of cells.
- Peukert's Coefficient.
- Minimum allowed battery state of charge.

Fig. 4 shows the flux diagram for the battery state of charge estimation model:

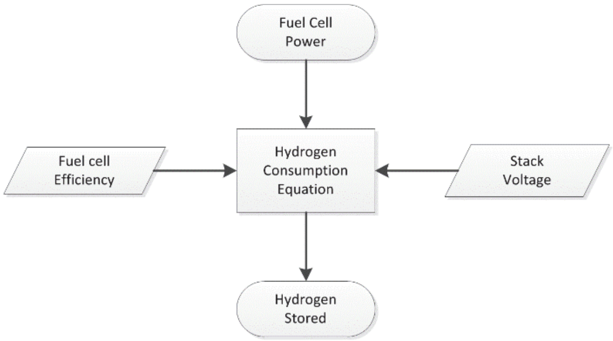


Figure 5. Flow diagram for the hydrogen utilization rate
Source: The authors

Fuel Cell Model

Considering that this is a hybrid vehicle simulation, what has actually been constructed is a hydrogen consumption model rather than a fuel cell electric power model.

An equation to model the hydrogen intake as a function of power demanded by the fuel cell (by the motor and the auxiliary systems) can be used.

Thus, based on the simple reaction stoichiometry [17], Faraday's Constant, the fuel cell efficiency [18] and the stack potential, the following equation is obtained:

$$H_{2_{usage}} = \frac{P_{electric}}{2V_cF} \qquad (5)$$

This equation depends only on the power demanded by the fuel cell. It yields the hydrogen mass flux, in moles per second, which makes it possible to know the hydrogen tank fill level at every moment. The inputs are the demanded power, the minimum hydrogen tank level and the maximum power output of the fuel cell, as shown in Fig. 5.

Logic Controller

A logic control model for the vehicle energy management was developed (Fig.6).

The management depends on the parameter SoC_HYB and SoC_MIN. Both parameters are related to the battery state of charge (SoC). Therefore, their values are critical to obtain the best battery performance. The SoC_HYB is used to change the energy management from an electric pure mode (serial mode) to a hybrid mode with battery and fuel cell (parallel mode).

If SOC is below SoC_HYB the energy management changes from the serial mode to the parallel one. For example, if the SoC_HYB is 0.5 (Fig.7) the energy management would change from serial mode to parallel mode when the SoC is below 50%.

In the parallel mode the battery is recharged with energy provided by the fuel cell and therefore the SoC rises. If SOC reaches Soc_HYB, the energy management changes from the parallel mode to the serial one. This algorithm will produce a constant switching energy management reflected in the saw-tooth graph of Fig. 7.

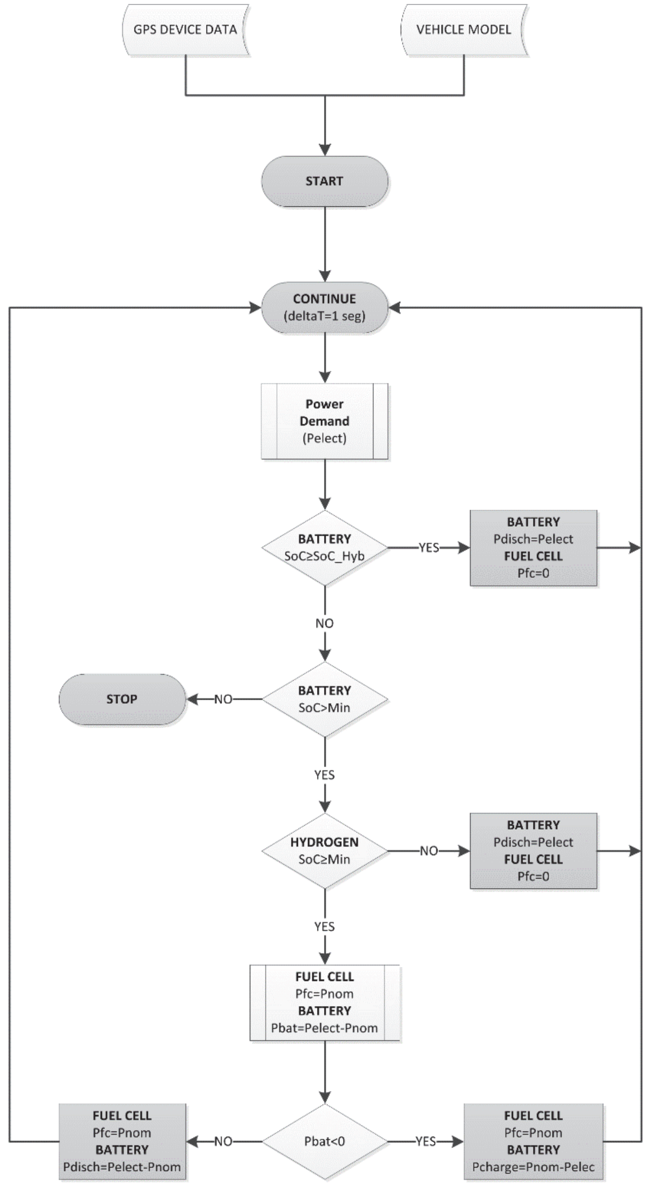


Figure 6. Summary of controller's algorithm.
Source: The authors

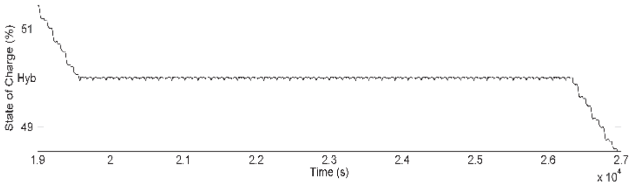


Figure 7: Example of SoC_HYB Parameter set for SoC=50%
Source: The authors

The parameter SoC_MIN specifies the minimum value of the battery state of charge. This parameter is important for almost all types of batteries since it conditions their state of health, and it could have a real influence on vehicle autonomy [19,20]. All battery manufacturers recommend an optimal SoC_Min to achieve a greater amount of life cycles.

Power distribution between the battery and fuel cell can be set in the main menu establishing a nominal power for the fuel cell. The remaining demanded power would complete by the battery every time step. This strategy about power distribution allows fuel cell to work on the steady-state mode.

The battery charge process is also considered in this simulation tool. Under the hybrid mode, when it is not demanded energy from the battery, and electric power demand of the vehicle is lower than fuel cell nominal power, then energy excess is used to charge the battery. Furthermore, the existence of a regenerative brake is taken into account.

By means of these adjustable parameters, it's possible to set several configurations in order to optimize the energy control strategy and to obtain minimum emissions from the vehicle.

3. Simulation

The principal aim of this tool is to estimate the range of an electric battery hydrogen hybrid vehicle, which is achieved by applying precedent equations to a standard drive cycle (or a real path). Fig. 8 shows a toolbox's screen scheme where it is possible to select standard or real cycles and choose if the slope component is taken into account. A few standard drive cycles are preprogrammed, but it is possible to create drive cycles from GPS data (the tool permits only one-second interval cycles at present). In this case, the tool transforms standard GPS data to speed, acceleration and slope.

The other necessary inputs are vehicle characteristics (weight, aerodynamical coefficient, front area, and other parameters). In the toolbox scheme depicted by Fig. 8 it is possible to set all configuration parameters for the vehicle simulated (mechanical parameters, battery and fuel cell systems or electrical losses). Once the drive cycle is defined, a step-by-step simulation can be performed [21].

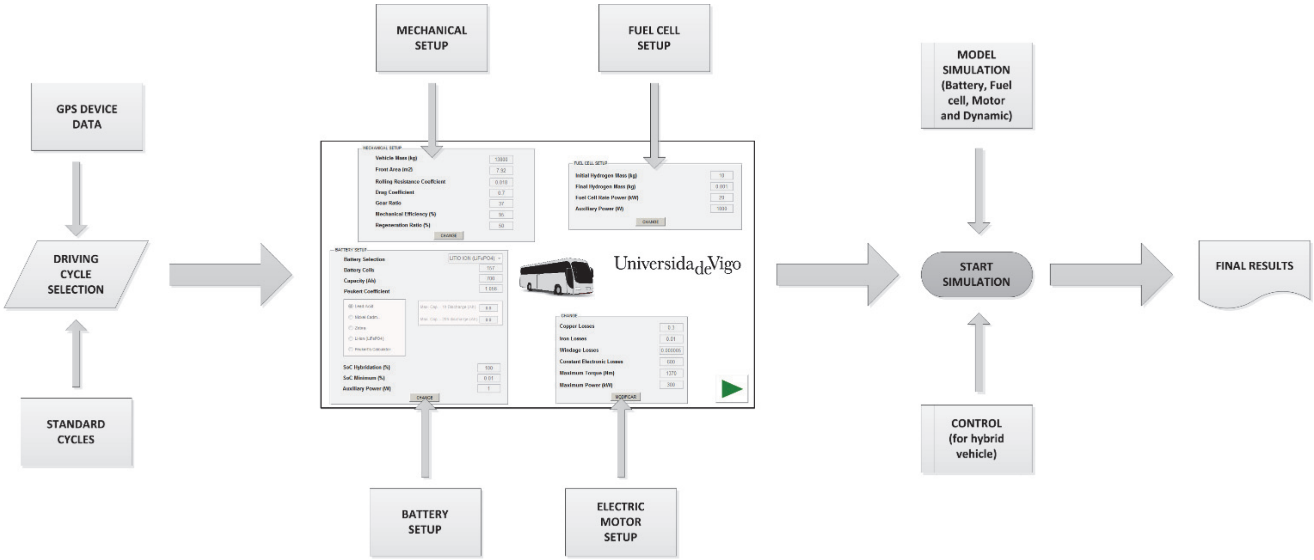
The principal output is the range, but other variables can be obtained and plotted, including the hydrogen consumption, battery system depth of discharge and remaining range.

Of course, it is possible to simulate all-electric vehicles as hybrid vehicles by assuming that the volume of hydrogen and the power of the fuel cell are equal to zero. The toolbox is designed for any type of hydrogen storage system because of the use of hydrogen mass as a variable instead of pressure or volume. The system considers only moles of hydrogen in calculations.

After the simulation has finished, several plots can be obtained, including plots of the motor torque, acceleration, demanded power for each energy system, energy efficiency, motor efficiency, charge and discharge intensities, battery status and hydrogen consumption.

Fig. 9 shows the speed profile obtained from a GPS mounted on a bus traveling a real urban route, plotted as a time function. In the same figure, the altitude profile is represented.

As an example of this, Fig. 10 shows the battery state of charge and the stored hydrogen variation (both versus the time variable) for the previous GPS cycle simulation with a fuel cell hybrid vehicle (an urban buss). In this case there are three examples with several configurations about fuel cell power and stored hydrogen.



MECHANICAL SETUP
Vehicle Mass (kg) 13800
Front Area (m2) 7.92
Rolling Resistance Coefficient 0.018
Drag Coefficient 0.7
Gear Ratio 37
Mechanical Efficiency (%) 95
Regeneration Ratio (%) 50

FUEL CELL SETUP
Initial Hydrogen Mass (kg) 10
Final Hydrogen Mass (kg) 0.001
Fuel Cell Rate Power (kW) 20
Auxiliary Power (W) 1000

BATTERY SETUP
Battery Selection LITIO ION (LiFePO4)
Battery Cells 167
Capacity (Ah) 700
Peukert Coefficient 1.056
● Lead Acid
○ Nickel Cadm...
○ Zebra
○ Li-Ion (LiFePO4)
○ Peukert's Calculator
Max. Cap. - 1h Discharge (Ah) 0.0
Max. Cap. - 20h discharge (Ah) 0.0
SoC Hybridation (%) 100
SoC Minimum (%) 0.01
Auxiliary Power (W) 1

CHANGE
Copper Losses 0.3
Iron Losses 0.01
Windage Losses 0.000005
Constant Electronic Losses 600
Maximum Torque (Nm) 1370
Maximum Power (kW) 300

Figure 8. Toolbox scheme
Source: The authors

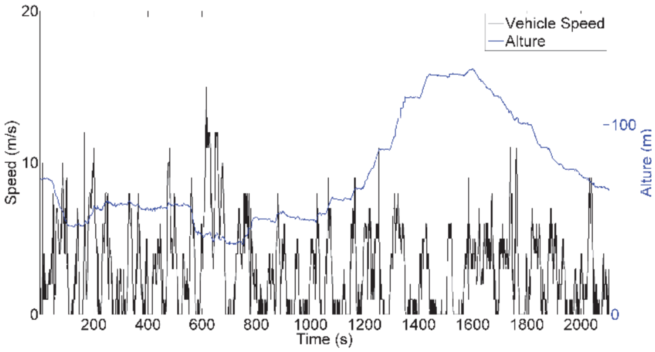


Figure 9. Urban bus GPS data
Source: The authors

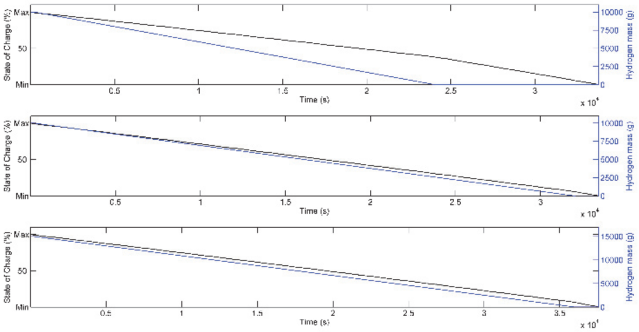


Figure 10. Simulation of an urban bus route for three different configurations of fuel cell power and stored hydrogen: 20 kW and 10 kg H2 (up), 15 kW and 10 kg H2 (middle), 20 kW and 15 kg H2 (down)
Source: The authors

A toolbox for the simulation of electric-only or hybrid electric hydrogen vehicles is presented.

The principal scope is to predict the range of batteries and/or a hydrogen tank. Moreover, the linear acceleration, angular velocity, motor torque, battery and fuel cell power, electric motor power, efficiency and hydrogen rates can be obtained.

This toolbox facilitates the evaluation of vehicle range (autonomy) for real travel, taking into account physical variables that are not taken into account in tools based on standard cycles.

The principal advantage of this tool is that it can be used in the vehicle design stage because all components are parameterizable. Also, GPS data simulation makes it possible to obtain a more precise range value than can be obtained by means of standard drive cycles because real data can be affected by parameters such as traffic density and weather and the influence of these parameters on the vehicle speed is considered

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