

Chevrolet Sequel: Reinventing the Automobile

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ABSTRACT

Sequel is the third vehicle in GM's Reinvention of the Automobile and is the first zero emissions passenger vehicle to drive more than 300 miles on public roads without refueling or recharging. It is purpose-built around the hydrogen storage and fuel cell systems and uses the skateboard principle introduced in the Autonomy vision concept and the Hy-wire proof-of-concept vehicles. Sequel's aluminum structure, Flexray controlled chassis-by-wire systems and AWD system comprising a single front electric motor and two rear wheel motors make it, perhaps, the most technically advanced automobile ever built. The paper describes the vehicle's design and performance characteristics.

INTRODUCTION

The "reinvention of the automobile" around the two emerging technologies of fuel cell propulsion and chassis-by-wire controls started with a "2020" vision concept, AUTOnomy, that was shown at the 2002 North American International Auto Show and a drivable proof of concept vehicle, Hy-wire, using available state-of-the-art hardware, that was introduced at the 2002 Paris Motor Show. Hy-wire was the world's first drivable fuel cell-by-wire vehicle but was not designed to meet manufacturing, performance or safety standard requirements.

The third phase of this "reinvention of the automobile" was intended to demonstrate the world's first fuel cell vehicle that provides comparable performance with conventional internal combustion engine vehicles (Figure 1). The Sequel was introduced at the 2005 NAIAS and was driven by the media beginning in 2006. An unprecedented 300 miles zero emissions driving range by the media on public roads using a single tank of fuel was demonstrated in May 2007 while driving in New York state from Honeoye Falls to Tarrytown. The Sequel emits no tailpipe pollution, only water vapor.

This is the first time that a vehicle has ever demonstrated the ability to travel 300 miles between refueling without creating any pollution. The Sequel accomplished this on a typical driving route on a warm day while having acceptable or superior performance in

all other areas (acceleration, fuel economy, braking, steering, spaciousness, air conditioning, noise, etc.).

Name	Autonomy	Hy-wire	Sequel
Introduction	2002 North American International Auto Show	2002 Paris Motor Show	2005 North American International Auto Show
Mission	Concept Model Describing "Reinvention of Automobile" Around Fuel Cells & X-by-Wire	Proof-of-Concept & World's First Drivable Fuel Cell by-Wire Vehicle	300 Miles ZEV demonstrating the new DNA of the reinvented automobile around electrification
Key Technologies	• Solid Hydrogen Storage • Fuel Cell • 4 Wheel Motors • Chassis-by-Wire	• Fuel Cell • Chassis-by-wire	• Fuel Cell • Lithium Ion Battery • Rear Wheel Motors • Chassis-by-wire
Performance Attributes		• 60 miles range • Limited to 40 mph • 0-60 mph in ~ 20 s • FWD • Provocative Interior	• 300 miles range • ~ 90 mph top speed • 0-60 mph in ~ 10 s • AWD & 4 wheel steer • Credible and innovative Interior

Figure 1: Comparison of the various program stages

Sequel is an advanced technology vehicle platform offering several opportunities for developing expertise in the emerging field of electrified vehicles. Examples include fuel cell hybrid propulsion controls, wheel motors, chassis-by-wire integration, fuel cell thermal management and aerodynamics integration, aluminum space frame lower dominant structure and a hermetically sealed HVAC system.

Safety is a key element in vehicle development. Sequel's analytical model for vehicle crashworthiness analysis incorporates the unique elements of Sequel (aluminum structure, chassis-by-wire, fault-tree analysis and hydrogen storage safety). Through fault-tree analyses of usage in the real world environmental conditions, determination of the root causes, probabilities and mitigation strategies were an integral aspect of the Sequel's development.

In order to enable or exploit the AUTOnomy vision, the Sequel required considerable innovation in nearly all aspects of the vehicle, such as:

- **Propulsion and Thermal:** Ground-up vehicle design to significantly improve range, acceleration and heat rejection; rear wheel motor drive and chassis-by-wire reinforces long-term vision of AUTOnomy

- **Chassis:** State-of-the-art chassis performance enabled by drive-by-wire and wheel motors. Mechanical backup for steer-by-wire accommodates high speed driving and allows by-wire development
- **Electrical and Controls:** Fault-tolerant system is possible with first use of Flexray communications protocol. Controls and electrical architecture is optimized for safety, efficiency and performance across propulsion and chassis-by-wire systems
- **Structure:** Aluminum structure combines elements of spaceframe, body-on-frame and body frame integral construction. Lower dominant and body structures are integrated to offer styling flexibility and mass reduction
- **Exterior and Interior:** Form follows function with unique exterior styling that accommodates the fuel cell's unique heat rejection needs; the instrument panel exploits the relocation of the hermetically sealed HVAC system underhood

VEHICLE PERFORMANCE

Sequel proves that it is possible to create a truly superior vehicle when designed “ground-up” around fuel cells and drive by wire. In addition to providing new capabilities (enabled by electrification), this approach also addresses some design challenges facing a fuel cell when it is integrated into a conventional internal combustion engine vehicle or ICEV. These constraints include adequate driving range while meeting requirements for safety standards and for interior/cargo space, and having adequate heat rejection on a hot day while using air conditioning. Figure 2 shows how a ground-up design can, in theory, address some of the challenges facing conventional fuel cell vehicles.

METRIC	CHALLENGE	ENABLER(S)
Range	Package space for hydrogen storage	• Sandwich floor • Tunnel • Wheel motors
	Lightweight vehicle structure	Aluminum structure and closures
Acceleration	Power and torque	• High voltage battery • Wheel motors • Control strategy
Heat Rejection	Sufficient cooling on a hot day	• Grille openings • Airflow behind radiator • HVAC condenser relocation
Safety	Protection of hydrogen storage	Storage system location

Figure 2: Benefits of a ground-up fuel cell vehicle approach

The Sequel’s chassis architecture (Figure 3) shows how this theory was translated into a specific design. The Sequel’s chassis design builds on the AUTOnomy concept and exploits the combination of a sandwich floor (augmented with a tunnel) and front end package space.

The arrangement illustrates the approach to achieving sufficient hydrogen storage to provide the vehicle with 300 miles range; other approaches did not provide the appropriate balance for occupant packaging, vehicle proportions, underbody structure integrity, crash performance and hydrogen storage (range). Figure 4 shows the actual hydrogen storage system hardware.

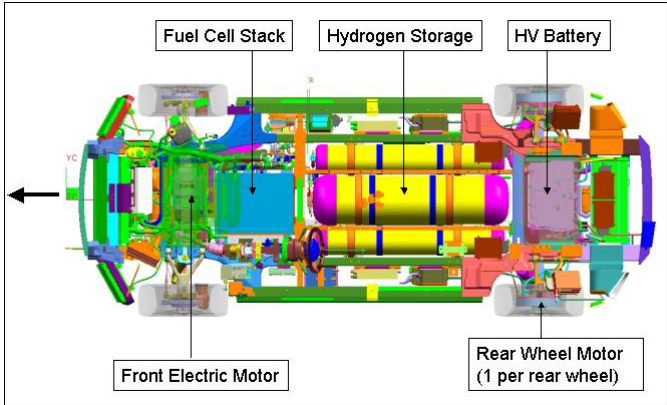


Figure 3: Sequel’s chassis architecture enables improved performance

The specific advantages that the fuel cell propulsion system provides include:

- Higher fuel economy and zero tailpipe emissions
- Lower levels of noise and vibration
- Faster acceleration, particularly from launch (low-end torque)

Further benefits, which help to make the vehicle have truly compelling performance, may come from adding by-wire technology to the vehicle, such as:

- Greater active and passive safety improvement
- Improved maneuverability and more precise ride and handling
- Enhanced comfort (adjustable steering effort, less shake through the steering wheel)

Finally, in addition to the technology performance enablers, the fuel cell-enabled “skateboard” architecture creates additional vehicle benefits, such as:

- An inherently low center of gravity with “command of the road” seat height
- An “ideal” 50:50 weight distribution
- Package space for hydrogen storage to improve range

PROPULSION AND THERMAL SYSTEM

A key driver for the Sequel program is to create the world’s first ZEV with 300 miles range, based on an adjusted Federal Test Procedure cycle, and on real world driving (higher ambient temperature, varying speed and terrain, air conditioning usage, etc.). The

other two major considerations are integrating a hydrogen storage system to meet safety requirements and to have minimal impact on interior design.



Figure 4: The sandwich-tunnel enabler for hydrogen storage and range

Even at 10,000 psi (690 bar) the cylindrical composite hydrogen tanks have a low energy density - the internal volume required to hold 8 kg of hydrogen, or the equivalent of 8 gallons of gasoline, is about 65 gallons. This limitation dictates the length of Sequel's wheelbase and height of the sandwich floor. Although a completely flat floor, initially preferred, does enable identical diameter tanks (cost savings both during development and in production) and a more flexible interior design it forces a higher floor, requires an unacceptably high step-in and increases width, height, frontal area and aerodynamic drag. It also makes for awkward design proportions. Alternatively, the floor could be thinner but with an unacceptable reduction in vehicle range.

The design that was ultimately chosen has a tunnel to reduce step-in and a comparable floor height to similar size vehicles. The front seat passengers see no tunnel since it is only present from the front seat rearward.

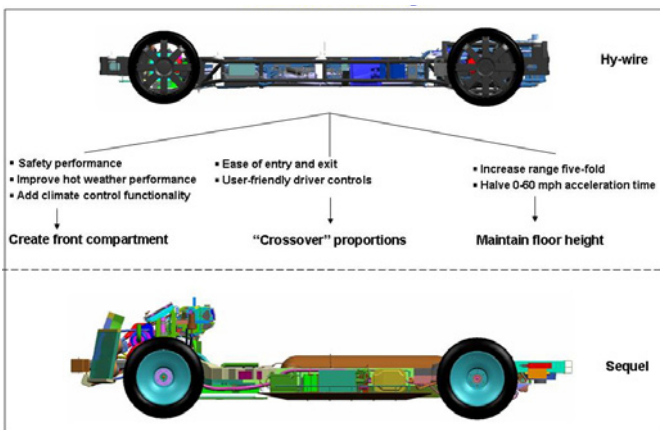


Figure 5: Evolution of design proportions from Hy-wire to Sequel

Figure 5 explains how the proportions of Sequel have been driven by three independent requirements: functional performance improvements (such as range, acceleration, hardware packaging), ergonomics (entry/egress, human vehicle interface) and vehicle structure. Another constraint is the current limitations in today's technology (hydrogen storage, redundant by-wire systems, etc.). These requirements lead the

proportions in the direction of the popular "crossover utility vehicle" design (a tall vehicle with AWD capability).

Sequel accelerates from 0-60 mph in under 10 s (and the higher low-end torque of electric drives helps to makes it launch and feel much faster). Fuel cell hybrid vehicles have 0-60 mph times that are typically slower than that of Sequel but still with satisfactory launch characteristics. This 10 s time is achievable because the fuel cell system is augmented with a high voltage (HV) lithium ion battery capable of providing around 65 kW and storing 2 kWh of electricity. The front electric motor (shown in Figure 6) is also supplemented with an additional traction system consisting of two wheel motors in the rear wheels (each rated at around 25 kW continuous) for AWD capability.



Figure 6: Sequel's fuel cell stack module and front electric traction system

The fuel cell (Figure 6) generates enough power for continuous road loads whereas the HV battery provides power boost for peak loads. Excess power generated by the fuel cell during light road load operation is used to charge the HV battery. The battery also stores captured braking energy. This augmented approach provides the following benefits over a higher output pure fuel cell system:

- Fuel cell system operation can be optimized for efficiency, extending vehicle range
- Higher fuel economy and range with regenerative braking
- Less hydrogen storage required (package space, tank cost) for a given range
- Reduced fuel cell transient /thermal requirements and extended durability
- Redundant power backup for by-wire electrical safety

A minimum of 70 kW net fuel cell propulsion system power is needed to sustain a 90 mph top speed and to provide similar performance on a 7.2% grade as most ICEVs.

The high-voltage battery is sized for acceleration requirements but energy is also important since a battery of similar power with less energy will not allow reproducible back-to-back accelerations (it will be quickly discharged with little time for recharging between hard accelerations).