

Design Considerations for Hydrogen Management System on Ford Hydrogen Fueled E-450 Shuttle Bus

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ABSTRACT

As part of a continuous research and innovation effort, Ford Motor Company has been evaluating hydrogen as an alternative fuel option for vehicles with internal combustion engines since 1997. Ford has recently designed and built an Econoline (E-450) shuttle bus with a 6.8L Triton engine that uses gaseous hydrogen fuel. Safe practices in the production, storage, distribution, and use of hydrogen are essential for the widespread public and commercial acceptance of hydrogen vehicles. Hazards and risks inherent in the application of hydrogen fuel to internal combustion engine vehicles are explained. The development of a Hydrogen Management System (H2MS) to detect hydrogen leaks in the vehicle is discussed, including the evolution of the H2MS design from exploration and quantification of risks, to implementation and validation of a working system on a vehicle. System elements for detection, mitigation, and warning are examined. Various analysis techniques are used to show the effectiveness of the chosen design.

INTRODUCTION

Ford Motor Company has been evaluating hydrogen internal combustion engines (H2ICE) since 1997. Ford has built several prototype H2ICE vehicles since then and tested them in-house to gain basic engineering knowledge. In 2003, Ford decided to build a fleet of H2ICE vehicles for lease to customers to assess their acceptance of H2ICE vehicles and gain additional engineering knowledge. The customer vehicle is an Econoline (E-450) shuttle bus with: up to 12 seats; a

Triton 6.8L V10 engine modified and optimized to burn gaseous hydrogen; a fuel system with storage at up to 350 bar (5075 psig) and delivery at 4.8 bar (70 psig); and a hydrogen management system (H2MS) which is the focus of this paper. It should be noted that the fuel system design encompasses many factors, such as materials selection, pressure relief valves, and component placement in the vehicle, which inherently reduce the particular hazards of storing and handling compressed hydrogen gas. The H2MS was designed to supplement those existing factors by detecting hydrogen leaks in the vehicle, mitigating their effects, and notifying the driver.

The H2MS design team built upon prior experience of Ford's hydrogen fuel cell, compressed natural gas, and prior prototype H2ICE programs to produce a unique hydrogen management system for the E-450 H2ICE shuttle bus [1]. The team also found prior work by other researchers to justify using helium as a surrogate for hydrogen in tests required to evaluate the early H2MS design [2] [3]. This enabled most of this work to be done using helium, thus minimizing the amount of testing with hydrogen which was only done to verify the final design.

As part of the design process to meet the system requirements in all operating modes and vehicle compartments, the team chose to perform physical prototype testing, Computation Fluid Dynamics (CFD) analysis, Fault Tree Analysis (FTA), and Failure Modes & Effects Analysis (FMEA). The objectives for this testing and analysis were: define potential failures modes and mitigation opportunities; perform trade-off studies to

support design decisions; and verify the efficacy of the resultant design.

DESIGN CONSIDERATIONS AND DECISIONS

The H2MS was designed to achieve these high-level objectives:

1. Provide two levels of response according to detected hydrogen levels:
 - a. Notify the driver when a low hydrogen concentration is detected in the vehicle, take actions to reduce that concentration, and allow continued vehicle operation (to complete its present trip and then proceed to a maintenance facility).
 - b. Notify the driver more urgently when a high hydrogen concentration is detected in the vehicle, take actions to reduce that concentration, allow continued vehicle operation (to reach a safe location to stop), and prevent further vehicle operation until hydrogen concentrations in the vehicle are measured to be safe.
2. Monitor sensors for proper operation and notify driver if service is required.
3. Allow continued vehicle operation with any single fault in H2MS (to complete its present trip and then proceed to a maintenance facility).

HYDROGEN PROPERTIES - Hydrogen is the lightest element and the smallest atom. It can pass through very small openings and it rises and dissipates rapidly in air. The range of flammable volumetric concentration in air is 4% to 75%. Because hydrogen is odorless and colorless, normal human senses can not detect a leak, and so some other detection method must be provided. In the E-450 H2ICE vehicle, the hydrogen fuel is always in the gaseous state.

VEHICLE COMPARTMENTATION - The design team divided the vehicle into three compartments for analysis of H2MS requirements, following the natural divisions based on each compartment's use (Figure 1). The compartments are herein called: Engine Compartment; Passenger Compartment; and Tank Compartment. Each is treated differently by the H2MS according to their use by the customer, how hydrogen is used in each, and how each is normally ventilated. The characteristics of each compartment and how adjacent compartments might interact were considered to determine H2MS requirements for each compartment such as the number and location of hydrogen sensors and the need for additional ventilation.

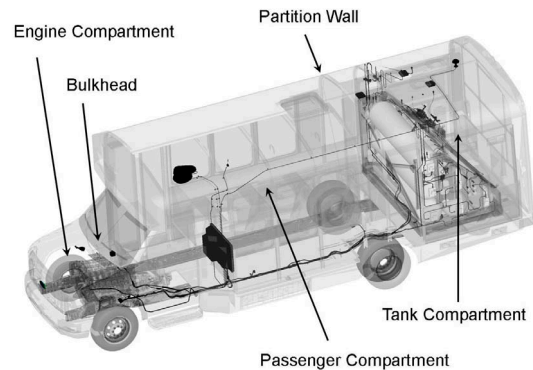


Figure 1: Vehicle Compartments

Engine compartment – The 6.8L V10 engine in this compartment provides propulsion power to the vehicle. This is also the final delivery point for the hydrogen fuel system. Two low-pressure fuel lines enter at the lower rear and connect to the fuel rails on top of the engine. The engine compartment is open at the front and bottom for ventilation both by vehicle forward motion and an engine-driven fan. It is separated from the passenger compartment by a solid metal bulkhead. All wire harnesses, tubes, or shafts passing through this bulkhead are sealed by rubber grommets.

Passenger compartment – This compartment encloses the driver and the passengers. Two low-pressure fuel lines pass underneath the passenger compartment to deliver hydrogen to the engine. The passenger compartment has separate after-market air-conditioning and heater systems located in the front and rear which only recirculate interior air. The base vehicle climate control system brings in outside air when in use. An emergency hatch is located in the roof of the passenger compartment which can also be partially opened for ventilation. Above the main windows are small sliding ventilation windows.

Tank compartment – This compartment houses six high-pressure hydrogen fuel storage tanks, associated piping, and other components to refuel, defuel, and deliver low-pressure fuel to the engine. All the fuel storage and high-pressure fuel system components, and the majority of all fuel system piping joints for the entire vehicle are in this compartment, so it has the highest potential for hydrogen leaks. It is separated from the passenger compartment by a partition wall.

HYDROGEN CONCENTRATION LIMITS AND RESPONSES – For hydrogen in air, 4% is the Lower Flammable Limit (LFL), the lowest concentration at which combustion can occur. SAE recommended practice is to manage potentially flammable atmospheres to maintain the flammable gas concentration less than 25% LFL, in this case 1% hydrogen [4]. Early in the design phase, we defined a Warning Limit and an Alarm Limit for hydrogen detected in the vehicle. The Warning Limit is the level of hydrogen at which we initiate mitigating actions, such as active ventilation, to dilute or exhaust the hydrogen to

below 25% LFL in the vehicle. Since this concentration is considered safe, continued vehicle operation is allowed. The H2MS also stores diagnostic trouble codes (DTCs) and energizes the Malfunction Indicator Lamp (MIL) on the instrument cluster to warn the driver and indicate service is required soon. For the E-450 H2ICE, this Warning Limit was initially set to the 25% LFL point (1% hydrogen). This was later changed to 0.3% hydrogen concentration to compensate for reduced sensitivity of the hydrogen sensors at extreme low temperatures. The Alarm Limit was set to 50% LFL (2% hydrogen) and when detected, the H2MS initiates a more urgent indication to the driver (separate flashing light and audible buzzer) in addition to the mitigation actions taken at the Warning Limit.

EXECUTIVE VS ADVISORY CONTROL - When designing a system intended to minimize the hazard to a hydrogen-fuelled vehicle and its occupants, a fundamental choice is whether that system can shut off fuel at the storage tank (and thereby stall the engine) if an Alarm Limit is detected. This is the 'executive' mode. Alternatively, the system could only advise the driver of an Alarm Limit, and allow the driver to continue to operate the vehicle. This is the 'advisory' mode. If a large leak should develop downstream of the fuel tanks, the leak can only be stopped by closing the fuel tank solenoid valves. However, this will result in a total loss of power from the engine with no warning. Such an unexpected power loss itself is potentially hazardous under certain driving conditions. For the E-450 H2ICE, the design team chose a mix of the two modes. In normal conditions and for Warning Limits, the H2MS is advisory. If an Alarm Limit is detected, the H2MS initially remains advisory by urgently notifying the driver of the alarm condition. The driver is trained to react to an Alarm Limit indication by stopping the vehicle in a safe location as soon as possible and turning the ignition key off. In the intervening time, the H2MS takes all mitigating actions, while still allowing the operator to drive the vehicle. After key is turned off, the H2MS remains active in the 'executive' mode and monitors hydrogen concentration in all compartments until they are below the Warning Limit. While in the executive mode, the fuel supply and starter motor are disabled to prevent further engine operation.

PASSIVE VENTILATION – This is any movement of air in or out of the vehicle due to ambient wind, vehicle motion, or density difference (due to temperature or hydrogen concentration). For the E-450 H2ICE vehicle leased to customers, passive ventilation was enhanced for the tank compartment by adding extra body openings on the floor, sides and rear wall. Enhanced passive ventilation is desirable to prevent hydrogen accumulation in the tank compartment, where the majority of the joints and fittings in the fuel system are found. An assumption for the fuel system design was that some low background rate of leakage was acceptable and the vehicle design was altered accordingly.

ACTIVE VENTILATION – This is air movement in or out of the vehicle deliberately caused by a fan or similar

device controlled by H2MS. Active ventilation allows more rapid reduction of hydrogen concentrations in the vehicle than passive ventilation, although it does require vehicle power. Hydrogen concentration in the vehicle can be reduced by either blowing outside air in or by blowing vehicle air out. This was a significant decision for the design team while considering the best mitigation action for each vehicle compartment. The passenger compartment is ventilated for mitigation by the vehicle's regular climate control system bringing in outside air. Since the intake for the passenger compartment ventilation is at the base of the windshield, hydrogen from a leak in the engine compartment could be drawn into the passenger compartment. The H2MS prevents this by disabling the climate control system fan if hydrogen is detected in the engine compartment. If hydrogen is detected in both the engine and passenger compartments at the same time, then the climate control fan is still disabled. While this will not reduce the hydrogen concentration in the passenger compartment, it will prevent it from increasing. For the tank compartment, fans were added in the tank compartment rear wall to expel air from the compartment and induce fresh air into it through added passive vents. During the design phase, it was assumed the tank compartment fans could be exposed to hydrogen concentrations above the LFL, so brushless motors were specified to eliminate any sparks.

HYDROGEN SENSORS – These are solid-state devices to measure the concentration of hydrogen in air and provide a variable voltage signal to the H2MS. The selected device provides a full scale reading at 2.2 % hydrogen but shuts down at any higher concentration to protect the sensing element. While the sensor is in this 'latched' condition, it sends a steady high signal until power is cycled to reset it. The H2MS responds to the 'latched' condition by cycling sensor power every few minutes to check if the hydrogen has dissipated below the latch threshold. The placement of the sensors is critical to ensure that any escaped hydrogen within the vehicle is sensed quickly, so the H2MS can start the mitigating action as soon as possible. The final placement of sensors was determined after testing described later in this paper.

FUEL SYSTEM SOLENOID VALVES – The H2MS operates several solenoid valves to control fuel throughout the vehicle. Each of the six storage tanks is isolated by its own valve, controlled as a group by H2MS. A separate valve on the refuel line allows H2MS to autonomously stop refueling regardless of fill station actions. Each fuel rail is isolated by a separate valve near the engine, and the H2MS controls these two valves as a group. Each group of solenoid valves is independently controllable by the H2MS to allow various diagnostic and service tests.

RESPONSE TO WARNINGS AND ALARMS – H2MS energizes the MIL on the vehicle instrument cluster for either of two conditions: a) a Warning Limit is detected, or b) service is required for an H2MS sensor or actuator. H2MS also energizes an audible buzzer and a separate flashing light installed near the instrument cluster to