**PRHYDE - Protocol for heavy-duty hydrogen refuelling**

Call Identifier FCH-04-2-2019:
Refuelling Protocols for Medium and Heavy-Duty Vehicles

Presenter: Claus Due Sinding, Nel Hydrogen

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Opportunity for Paradigm Change

- HD fueling offers a **new opportunity for a change in thinking** – a paradigm change!
- HD vehicle market is still immature so there are no legacy vehicles or stations that we must consider
- The **time is ripe for changing the existing paradigm** and developing fueling protocol concepts that can
  1. Improve hydrogen fueling performance
  2. Improve the overall safety of hydrogen fueling
  3. Minimize the total cost of ownership (TCO)
  4. Provide a “universal” protocol framework for ALL vehicles using compressed hydrogen storage

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**Improvements to J2601 Philosophy**

- **Current**
  - Assumption 1
  - Assumption 2

  **Small changes in assumptions**

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**Paradigm Change**

- **Current**
  - Change in Philosophy
## Fueling Protocol Philosophies or “Types”

Fueling Protocol Philosophies are categorized based on the vehicle CHSS information used by the Protocol.

<table>
<thead>
<tr>
<th>Vehicle CHSS Information Used</th>
<th>Gas Temp Margin</th>
<th>Performance Acceptable?</th>
<th>Pre-cooling Temp</th>
<th>Station Costs</th>
<th>Vehicle Costs</th>
<th>Non-Comm Fueling?</th>
<th>Comment</th>
</tr>
</thead>
</table>
| 1 None                       |                | Maybe                   | T40              | ↑            | ↓            | Yes               | ▪ J2601 philosophy  
▪ Worst case assumptions about most things  
▪ Fueling history assumed  
▪ Station fully responsible (and liable) |
| 2 Static Data                | -              | Yes                     | T30?             | -            | -            | Yes               | ▪ CHSS assumptions eliminated  
▪ Some crucial worst-case assumptions eliminated  
▪ Fueling history assumed  
▪ Station and vehicle share responsibility / liability although most is still on station side |
| 3 Dynamic Data (CHSS gas temp) | ↓              | Yes                     | T20?             | ↓            | ↑            | Maybe             | ▪ Most crucial worst-case assumptions eliminated  
▪ The gas temp can be used in different ways  
▪ Direct use or to screen for fueling history  
▪ Station & vehicle share responsibility / liability |

- There are three primary protocol philosophies upon which a fueling protocol can be structured.
- Within each of these philosophies, different fueling methods can be constructed and utilize (e.g. table-based & MC-Formula).
### Performance-Based vs Prescriptive Approaches

Besides the Protocol Philosophy or Structure, **a protocol can be either be prescriptive or performance-based**

- J2601 is an example of a prescriptive approach
- J2601-2 and J2601-4 are examples of performance-based approach

<table>
<thead>
<tr>
<th>Protocol Approach</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
</table>
| **Prescriptive**   | - Consistency of fueling performance for end customer  
                     - Much easier to validate stations because only need to validate the implementation, not validate the fueling method itself  
                     - Already developed, so no development costs  
                     - Open and fair to all companies both small and large | - Less room for innovation  
                                                                 - More difficult to get a fueling method approved (e.g. effort for MC Formula) |
| **Performance-based** | - More room for innovation  
                         - Allows for competition between companies | - High development costs  
                                                                 - Less fair for small companies (must spend on development)  
                                                                 - Allows companies to corner the market through IP |

- For a given protocol philosophy / structure, the protocol can either be prescriptive or performance-based
- There are advantages and disadvantages to both approaches
Station Control vs Vehicle Control

In addition to the protocol philosophy, prescriptive vs performance-based, another factor is the protocol control:

- Does station control the fill, vehicle control the fill, or combination?
- Must also define what “control” means
  - Command control – calculation of control parameters
  - Physical control – mechanical elements responsible for controlling the flow of hydrogen
- It is very unlikely that the vehicle will implement physical control, although it is theoretically possible
- Vehicle could, however, implement command control

<table>
<thead>
<tr>
<th>Command Control</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Station</strong> (Type 1, 2, or 3)</td>
<td>▪ May not require advanced bi-directional communications (lower cost) ▪ One-stop shop – station determines both command and physical control ▪ Lower functional safety requirements on vehicle (lower cost)</td>
<td>▪ Higher functional safety requirement on station (higher cost) ▪ Stations typically have lower processing power than vehicles so it may be more difficult to implement a complex algorithm on station PLC ▪ Station has more responsibility / liability</td>
</tr>
<tr>
<td><strong>Vehicle</strong> (Type 3 only)</td>
<td>▪ Vehicles inherently have high processing power on-board – it may be easier and lower cost to implement a complex algorithm on vehicle ▪ Lower functional safety requirements on station (lower cost)</td>
<td>▪ Higher functional safety requirements on vehicle (higher cost) ▪ Vehicle has more responsibility / liability</td>
</tr>
</tbody>
</table>

There are both advantages and disadvantages to command control by station or vehicle.
This framework allows for many options (even options beyond what is shown here)

Some OEMs might favor a Type 2 approach while others might favor a Type 3-PR-S or Type 3-PB-V approach

PR = Prescriptive
PB = Performance Based
S = Station Control
V = Vehicle Command Control

Not explained in this presentation
Overview – MC Formula: Key Control Variables

- Mass Average Fuel Delivery Temperature - MAT
- The time required to fill from minimum to maximum pressure under hot case conditions - \(t_{\text{final}}\)
- Variable Pressure Ramp Rate - PRR
- Target Pressure - \(P_{\text{target}}\)

MAT, \(t_{\text{final}}\), and PRR are calculated every second.

MAT \(\rightarrow\) \(t_{\text{final}}\) \(\rightarrow\) PRR
Advanced MC Formula – How it Works

- MC Formula in SAE J2601 is based on a worst-case set of boundary conditions and assumptions
- This Advanced MC Formula approach utilizes a more precise set of boundary conditions / assumptions
- Additionally, the way that the t-final control parameter is derived is more flexible
  - A table of t-final values can be derived (similar to the a, b, c, d coefficients but more flexible)
- A t-final map is derived by using a validated fueling model to run a set of fueling simulations under a variety of fueling conditions
  - This t-final map is “tuned” to the vehicle’s CHSS, maximizing fueling performance
  - The t-final map is stored in the vehicle ECU
- This framework can also facilitate a vehicle command control fueling method where the vehicle calculates the control parameters and communicates these as commands to the station to implement
- Essentially, this is an Advanced MC Formula Protocol with New and Improved Methods for t-final maps
Advanced MC Formula – How it Works (Derivation)

Each of the options on the following pages uses this same general approach for derivation

Verified Fueling Model which can model a full CHSS

Utilize actual CHSS Design & thermophysical properties

Run the model over a range of input conditions

Set of t-final tables stored in vehicle ECU

From the simulation results, derive a t-final map

Vehicle OEM inputs complete CHSS design into the fueling model using actual CHSS thermophysical properties

A verified fueling model is used to conduct fueling simulations under the range of conditions noted above

A complete set of t-final tables is derived (the fueling model could be programmed to do this automatically)

These maps are stored in the vehicle ECU

The fueling is custom tailored to the vehicle’s characteristics providing much better fueling performance
## Comparison of Fueling Concepts

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Static</th>
<th>$T_{\text{gas Initial}}$</th>
<th>$T_{\text{gas Initial+}}$</th>
<th>$T_{\text{gas Throttle}}$</th>
<th>Vehicle Control</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fueling time (under wide variety of initial conditions)</td>
<td>Slow</td>
<td>Fast</td>
<td>Faster</td>
<td>Fastest</td>
<td>UD</td>
</tr>
<tr>
<td>Sensor position accuracy requirement</td>
<td>Low</td>
<td>Low</td>
<td>Low</td>
<td>High</td>
<td>UD</td>
</tr>
<tr>
<td>Vehicle functional safety level</td>
<td>Low</td>
<td>High</td>
<td>High</td>
<td>Higher</td>
<td>Highest</td>
</tr>
<tr>
<td>Requires bi-directional communications</td>
<td>Optional</td>
<td>Possibly</td>
<td>Possibly</td>
<td>Possibly</td>
<td>Likely</td>
</tr>
<tr>
<td>Number of tables</td>
<td>Few</td>
<td>More</td>
<td>More</td>
<td>Fewest</td>
<td>UD</td>
</tr>
<tr>
<td>Complexity of fueling protocol development</td>
<td>Low</td>
<td>Medium</td>
<td>Medium</td>
<td>Higher</td>
<td>Highest</td>
</tr>
<tr>
<td>Impact of conservative assumptions on performance</td>
<td>Highest</td>
<td>High</td>
<td>High</td>
<td>Low</td>
<td>UD</td>
</tr>
</tbody>
</table>

*UD = Undetermined due to flexibility of approach*
Down Selection of Fueling Concepts

Choose Fueling Concepts to be developed and tested
Risk assessment (RA) approach

- Team using bowtie framework
- Focusing on events which could affect fueling protocol (e.g., pressure sensor failure)
- RA not examining conventional vehicle/station failures (e.g., hose burst)
- Each fueling approach will be evaluated to determine what controls will be required on vehicle and station side.
- LOPA Framework for quantification
Performance simulations: Parameters and conditions

- Vehicle and station parameters used for performance simulation
- The combined system starts at dispenser breakaway and ends at vehicle vessel, represented by an Equivalent System Kv

### CHSS Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Assumption</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pressure rating</td>
<td>H70</td>
</tr>
<tr>
<td>Multiple vessel CHSS</td>
<td>Yes</td>
</tr>
<tr>
<td>Vessel size</td>
<td>162L</td>
</tr>
<tr>
<td>Number of vessels</td>
<td>9</td>
</tr>
<tr>
<td>Total CHSS volume</td>
<td>1458L</td>
</tr>
<tr>
<td>Vessel type</td>
<td>Type IV</td>
</tr>
<tr>
<td>Fuel line equivalent Kv</td>
<td>0.28 m3/h</td>
</tr>
<tr>
<td>Fuel line thermal mass</td>
<td>28.28 kg</td>
</tr>
<tr>
<td>Fuel line Characteristics</td>
<td>Stainless steel</td>
</tr>
</tbody>
</table>

### CHSS Conditions

<table>
<thead>
<tr>
<th>Condition</th>
<th>Assumption</th>
<th>Rational</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial temperature of H2 in vessel</td>
<td>Tamb +/- soak</td>
<td>SAE J2601-1</td>
</tr>
<tr>
<td>Initial temperature of vessel wall</td>
<td>Tamb</td>
<td>SAE J2601-1</td>
</tr>
<tr>
<td>Initial temperature of fuel line</td>
<td>Tamb</td>
<td>SAE J2601-1</td>
</tr>
<tr>
<td>Cold or warm dispenser?</td>
<td>Warm</td>
<td>Focus on constrain cases</td>
</tr>
<tr>
<td>Nozzle temperature fixed during fueling?</td>
<td>Yes</td>
<td>MAT also remains fixed during the fueling</td>
</tr>
<tr>
<td>Leak checks during fueling?</td>
<td>No</td>
<td></td>
</tr>
</tbody>
</table>
Performance simulations: Scenarios (examples)

- Example of a performance scenario (base case)
- Thermal mass and Kv will be varied for other scenarios

### Scenario

**Thermal Mass = 21 kg**

**External surface area = 11910 cm²**

**Internal surface area = 6895 cm²**

**Kv = 0.14 m³/h**

<table>
<thead>
<tr>
<th>Thermal Mass = 21 kg</th>
<th><strong>T</strong>&lt;sub&gt;amb&lt;/sub&gt;</th>
<th><strong>T</strong>&lt;sub&gt;gas0&lt;/sub&gt;</th>
<th><strong>T</strong>&lt;sub&gt;vessel0&lt;/sub&gt;</th>
<th><strong>T</strong>&lt;sub&gt;fuel&lt;/sub&gt;</th>
<th><strong>P</strong>&lt;sub&gt;0&lt;/sub&gt;</th>
<th><strong>Fueling Time</strong></th>
<th><strong>Ending SOC</strong></th>
<th><strong>Fueling Time</strong></th>
<th><strong>Ending SOC</strong></th>
<th><strong>Fueling Time</strong></th>
<th><strong>Ending SOC</strong></th>
<th><strong>Fueling Time</strong></th>
<th><strong>Ending SOC</strong></th>
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<tbody>
<tr>
<td>35</td>
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<td>35</td>
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</tbody>
</table>
Overall Advantages of Approach

- Advanced MC Formula provides a “framework” which accommodates a variety of options

- Type 1 (non-comm), Type 2 (static data), Type 3-PR-S (dynamic data) and Type 3-PB-V (dynamic data vehicle control) approaches are supported under this framework

- An OEM can choose which protocol Type and option to use – the Advanced MC Formula framework supports them all

- Within the Type 3 dynamic data approach, there are options beyond (or variances within) the three shown here
  - Also, an OEM has complete control and discretion in deriving the t-final maps for the vehicle CHSS

- This approach facilitates future advanced CHSS designs (Type 5 tanks, conformable tanks)

- Fueling performance should be excellent, especially with Type 3 options

- Further refinement of these approaches may allow for even better fueling performance

- Protocol development is minimal because the MC Formula control framework already exists
Contact information

- Interact with PRHYDE:
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