PRHYDE-Protocol for heavy-duty hydrogen refuelling

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Refuelling Protocols for Medium and Heavy-Duty Vehicles

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Protocol for heavy-duty Hydrogen refuelling

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FUEL CELLS AND HYDROGEN JOINT UNDERTAKING

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Opportunity for Paradigm Change

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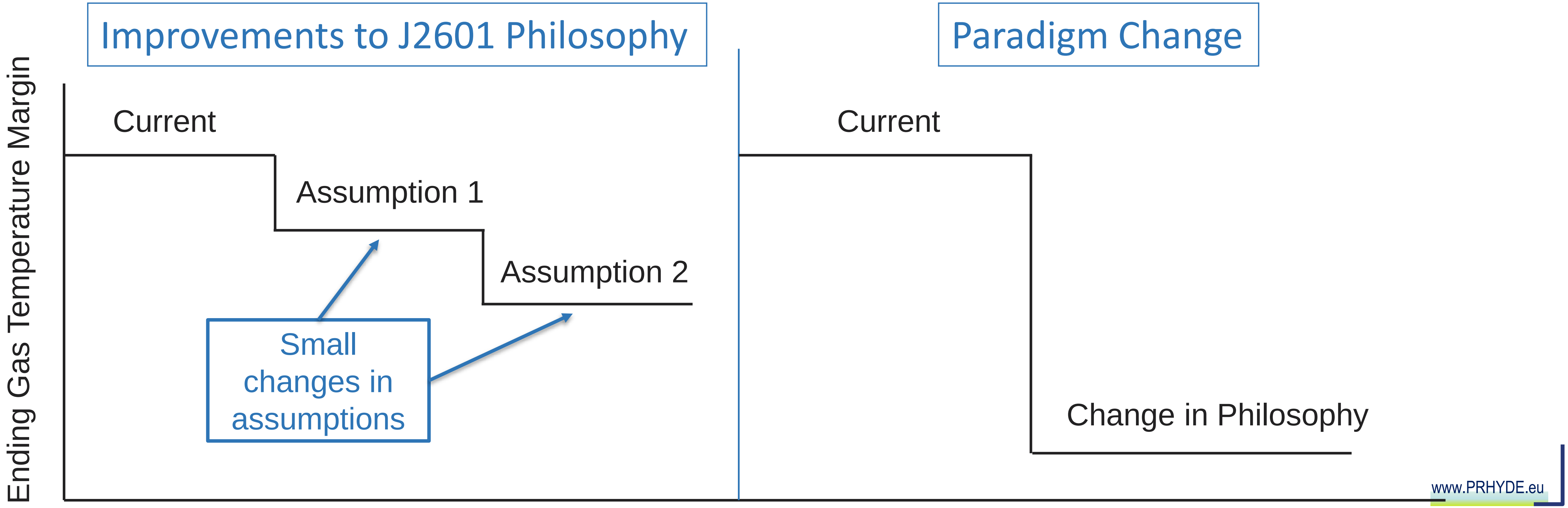
- HD fueling offers a new opportunity for a change in thinking – a paradigm change!
- HD vehicle market is still immature so there are no legacy vehicles or stations that we must consider
- The time is ripe for changing the existing paradigm and developing fueling protocol concepts that can
    1) Improve 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



Fueling Protocol Philosophies or "Types"

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

Vehicle CHSS Information Used	Gas Temp Margin	Performance Acceptable?	Pre-cooling Temp	Station Costs	Vehicle Costs	Non-Comm Fueling?	Comment
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

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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**

Protocol Approach	Advantages	Disadvantages
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

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

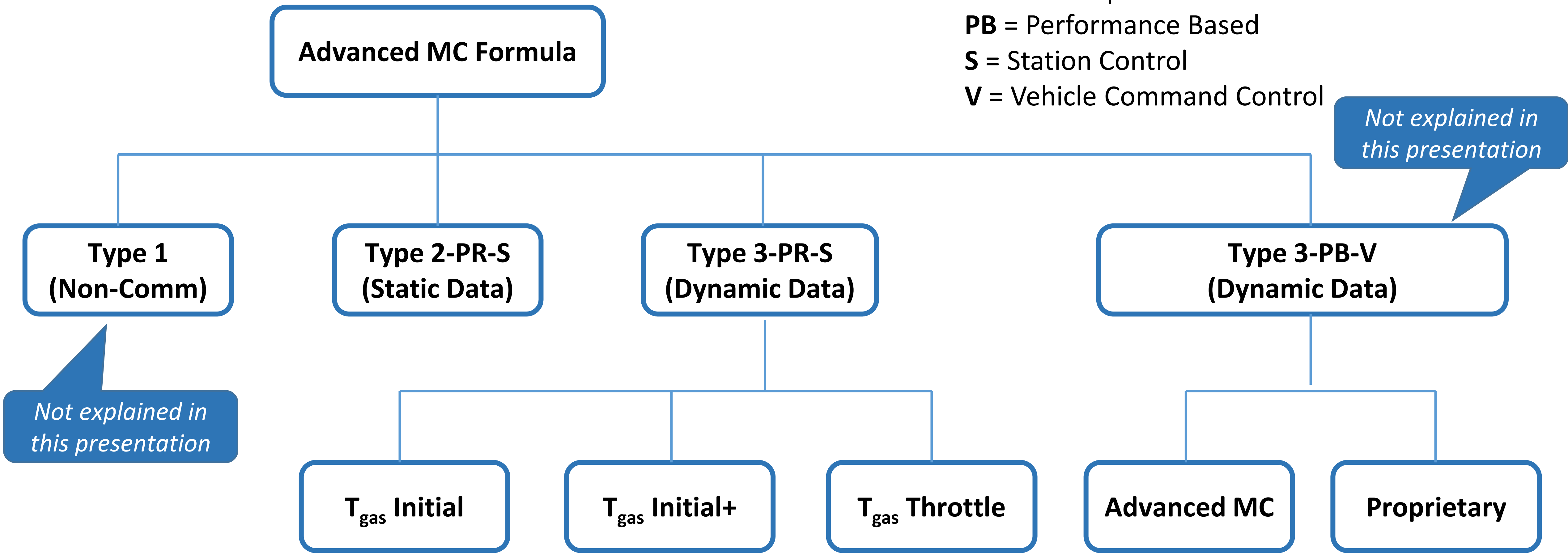
- **Does station control the fill, vehicle control the fill, or combination**?
- **<u>Must also define what "control" means</u>**
  - **Command control** – calculation of control parameters
  - **Physical control** – mechanical elements responsible for controlling the flow of hydrogen
- It is very unlikely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

Command Control	Advantages	Disadvantages
Station (Type 1, 2, or 3)	▪ **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)	▪ **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**
Vehicle (Type 3 only)	▪ **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)	▪ **Higher functional safety** requirements **on vehicle** (higher cost) ▪ **Vehicle has more responsibility / liability**

- There are both advantages and disadvantages to command control by station or vehicle

Advanced MC Formula Framework

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



- 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

Overview – MC Formula: Key Control Variables

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

- **MAT**, t_{final}, and **PRR** are calculated every second

MAT → t_{final} → **PRR**

Advanced MC Formula – How it Works

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- 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**

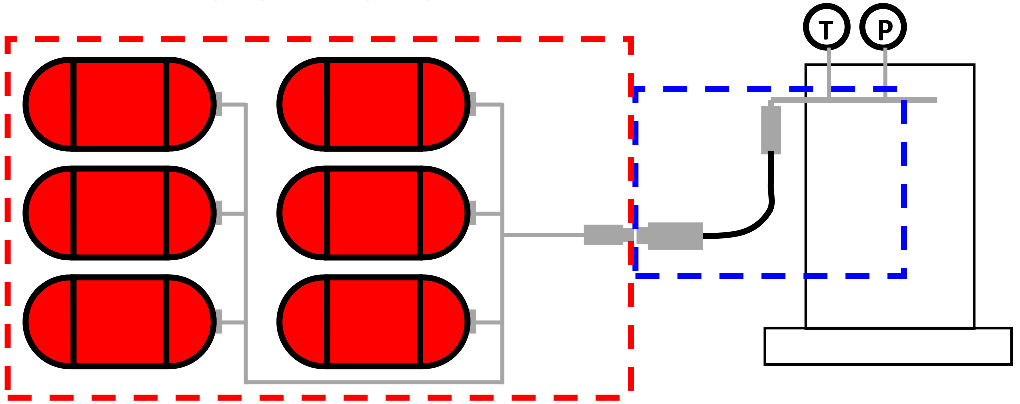
Advanced MC Formula – How it Works (Derivation)

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

Utilize consensus assumptions for dispenser components

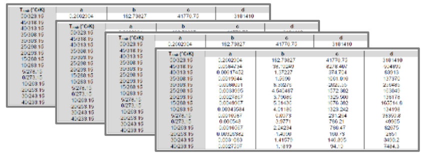


Run the model over a range of input conditions

T_{fuel} → -40 °C to X °C
T_{amb} → -40 °C to 50 °C
P_{min} → 0.5 MPa to X MPa
T_{soak} → hot soak or other
T_{gas_max} → 85 °C or X °C
Warm and Cold Dispenser

From the simulation results, derive a t-final map

Set of t-final tables stored in vehicle ECU



- ❑ **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

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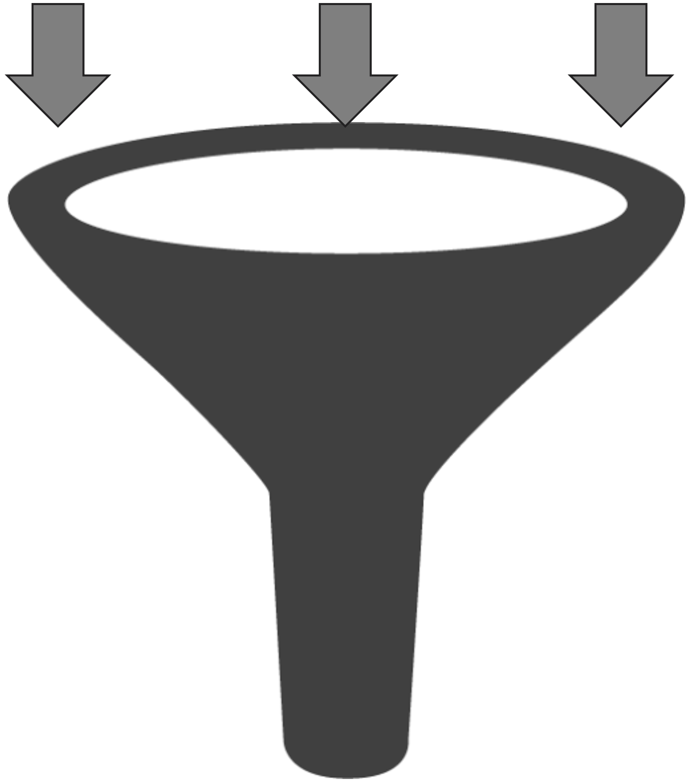
Criteria \ Fueling Concept	Static	T_{gas} Initial	T_{gas} Initial+	T_{gas} Throttle	Vehicle Control
Fueling time (under wide variety of initial conditions)	Slow	Fast	Faster	Fastest	UD
Sensor position accuracy requirement	Low	Low	Low	High	UD
Vehicle functional safety level	Low	High	High	Higher	Highest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

UD = Undetermined due to flexibility of approach

Down Selection of Fueling Concepts

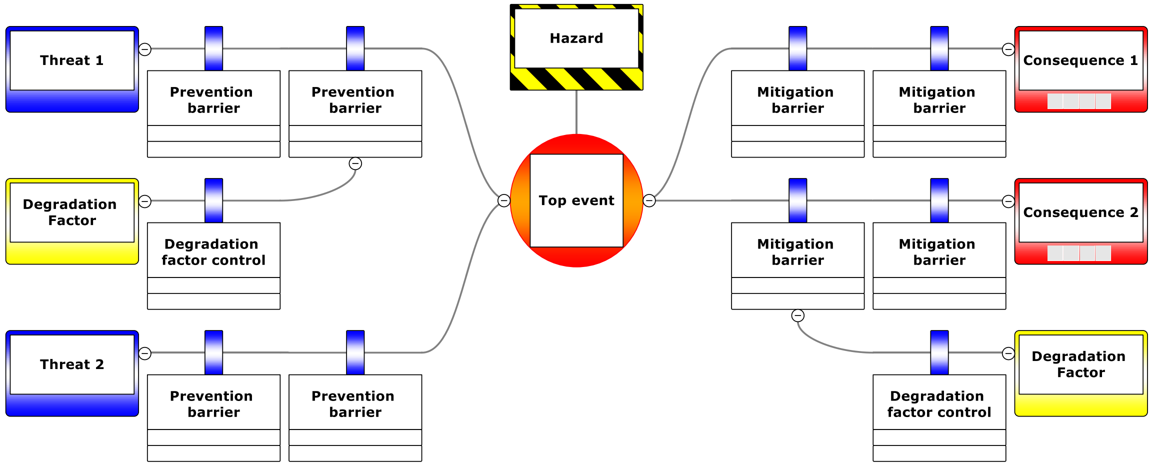
Fueling Concepts | Performance Simulations | Risk Assessment



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



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- Savannah River National Laboratory
- Sandia National Laboratory
- Risktec Solutions

Performance simulations: Parameters and conditions

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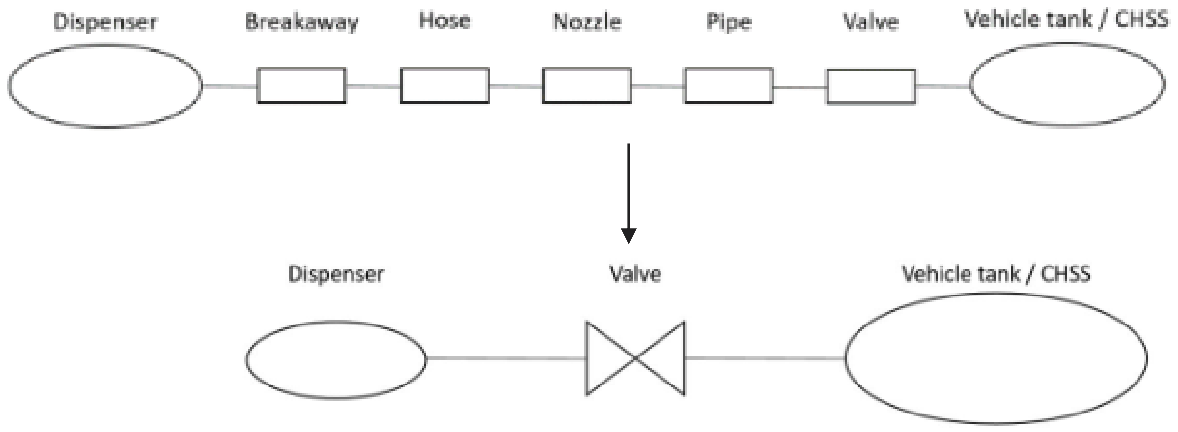
- Vehicle and station parameters used for performance simulation
- The combined system starts at dispenser breakaway and ends at vehicle vessel, represented by an Equivalent System Kv



Equivalent System Kv

CHSS Parameters	
Parameter	**Assumption**
Pressure rating	H70
Multiple vessel CHSS	Yes
Vessel size	162L
Number of vessels	9
Total CHSS volume	1458L
Vessel type	Type IV
Fuel line equivalent Kv	0.28 m3/h
Fuel line thermal mass	28.28 kg
Fuel line Characteristics	Stainless steel

CHSS Conditions		
Condition	**Assumption**	**Rational**
Initial temperature of H2 in vessel	Tamb +/- soak	SAE J2601-1
Initial temperature of vessel wall	Tamb	SAE J2601-1
Initial temperature of fuel line	Tamb	SAE J2601-1
Cold or warm dispenser?	Warm	Focus on constrain cases
Nozzle temperature fixed during fueling?	Yes	MAT also remains fixed during the fueling
Leak checks during fueling?	No	

Performance simulations: Scenarios (examples)

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

Scenario													
						Static		Tgas initial		Tgas intial+		Tgas throttle	
	T_{amb}	T_{gas0}	$T_{vessel0}$	T_{fuel}	P_0	Fueling Time	Ending SOC	Fueling Time	Ending SOC	Fueling Time	Ending SOC	Fueling Time	Ending SOC
Thermal Mass = 21 kg External surface area = 11910 cm2 Internal surface area = 6895 cm2 Kv = 0.14 m3/h	35	40	40	TBD	2								
					5								
					10								
					15								
					20								
	35	35	35	TBD	2								
					5								
					10								
					15								
					20								
	35	25	30	TBD	2								
					5								
					10								
					15								
					20								
	35	45	40	TBD	10								
					15								
					20								

Overall Advantages of Approach

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- **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 **excellen**t, 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:
  - E-mail list for PRHYDE stakeholders
    → please send e-mail to info@prhyde.eu if you want to receive or not to receive info / news
  - PRHYDE deliverables & presentation will be made available for comments / feedback
    → to be downloaded from the PRHYDE website: www.prhyde.eu
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