SAFETY AND OTHER CONSIDERATIONS IN THE DEVELOPMENT OF A HYDROGEN FUELING PROTOCOL FOR HEAVY-DUTY VEHICLES

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ABSTRACT

Several manufacturers are developing heavy duty (HD) hydrogen stations and vehicles, as zero-emissions alternatives to diesel and gasoline. In order to meet customer demands, the new technology must be comparable to conventional approaches, including safety, reliability, fueling times, and final fill levels. For a large HD vehicle with a storage rated to 70 MPa nominal working pressure, the goal to meet liquid fuel parity means providing 100 kg of hydrogen in 10 minutes. This paper summarizes the results to date of the PRHYDE project efforts to define the concepts of HD fueling, which thereby, lays the groundwork for the development of the safe and effective approach to filling these large vehicles. The project starts by evaluating the impact of several different assumptions, such as the availability of static vehicle data (e.g., vehicle tank type and volume) and station data (e.g., expected station pre-cooling capability), but also considers using real time, dynamic data (e.g., vehicle tank gas temperature and pressure, station gas temperature, etc.) for optimisation to achieve safety and efficiency improvements. With this information, the vehicle or station can develop multiple maps of fill time versus the hydrogen delivery temperature which are used to determine the speed of fueling. This will also allow the station or vehicle to adjust the rate of fueling as the station pre-cooling levels and other conditions change. The project also examines different steps for future protocol development, such as communication of data between the vehicle and station, and if the vehicle or station is controlling the fueling.

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1 INTRODUCTION

This paper summarizes several fueling concepts for HD hydrogen vehicles. The approaches are based upon an advanced version of the MC Formula fueling protocol described in the Society of Automotive Engineers (SAE) J2601 [1] and used in many light duty vehicle (LDV) hydrogen fueling stations. The research is conducted by PRHYDE (https://prhyde.eu/) which is a European based project, researching the current and future developments needed for fueling medium and HD hydrogen vehicles, predominantly road vehicles, but also other applications such as rail and maritime.

2 CONSIDERATIONS TO DESIGNING A FUELING PROTOCOL

As a starting point, the PRHYDE team needed to weigh several key parameters that would establish the structure of the fueling protocol.

Table 1 below lists the questions discussed and the decisions made by the project team. In general, the team came to a consensus on most of the discussion points, and those which did not have final agreement are discussed below.

Table 1: Key parameters for fueling protocols

Question	Description	PRHYDE Decision
Communications		
Are the communications signals from the vehicle trusted by the station?	If the signals are trusted, then data, such as compressed hydrogen storage system (CHSS) temperature can be used by the station to optimize the fueling.	See 1
Does the protocol incorporate two-way communications?	LDV only uses one-way communications from the vehicle to the station. Two-way communications could allow the vehicle to determine the status of the station in order to determine the best way to fuel.	Yes
Does the fueling protocol have an approach that combines communications and non-communications	A fueling protocol that combines communications and non-communications into one methodology will need to make conservative assumptions that apply to both fueling. Separating the two will allow the communications to be used to optimize the fueling, while allowing for a more conservative approach where the vehicle parameters cannot be transferred.	No, but PRHYDE will make recommend-ations for non-comm.
Station Design		
Is fueling of a lower pressure rated dispenser into a higher pressure rated vehicle allowed?	This is currently allowed in LDV stations.	Yes
Is fueling of a higher pressure rated dispenser into a lower pressure rated vehicle allowed?	This would require significant protection in place to avoid the over-pressurization of the CHSS.	No
Is fueling of a small capacity station into a larger vehicle acceptable	This approach would provide a backup fueling option for large vehicles, but could deplete the smaller station.	Yes
Is fueling of a large capacity station into a smaller vehicle acceptable?	This would require protections in place to ensure the station that fuels the vehicle at the appropriate fueling rate.	Yes
Vehicle Condition		
Does the fueling protocol use a more conservative approach in order to account for fueling at a previous station with a different pressure class?	These guidelines take into account the history and condition of the CHSS. They can be addressed if the CHSS temperature can be used to determine the fueling rate. PRHYDE team assumes eventually, advanced communications would be able to provide the actual CHSS temperature, so a conservative approach is not needed.)	No
Does the fueling protocol use a more conservative approach in order to account for fueling at a previous station with a different precooling level?		No
Does the fueling protocol use a more conservative approach in order to account for of a CHSS with a temperature which is different than the ambient temperature?		No

Fueling Approach		
Does the vehicle have any responsibility in determining fueling rate?	The vehicle can provide information that can assist in the determination of the fueling rate, or provide a target rate.	Yes
Is the station or the vehicle responsible for final selection of fueling rate?	Ultimately, the vehicle or station will need to determine the actual fueling rate and provide commands to start and stop the fueling.	See 2
Does the protocol consider the current status of the station?	The real time station capacity or the pre-cooled gas temperature could impact the ability of the station to provide a fueling at the fastest rate possible.	Yes
Does the protocol have minimum performance standards based upon vehicle and station size?	Performance standards would allow the buyers and users of the station to estimate how fast a vehicle can be fueled.	Yes
Hardware		
Does the fueling protocol need to be compatible with existing LDV Nozzles? Communications? CHSS?	No high flow nozzles and advanced communications are available, so the fueling protocol need to be designed to use these LDV components?	See 3
Does the protocol allow for adoption of future technology?	A flexible fueling protocol could take into account future designs, such as different CHSS liners and shapes.	Yes

1) The signals from current Infrared Data Association (IrDA) based communications used for LDV fueling are not Automotive Safety Integrity Level/Safety Integrity Level classified to any standard and therefore, are not used for safety critical decisions. The PRHYDE team determined that different approaches may be necessary and that further investigation was necessary, especially as part of the risk assessment, to determine the impact of using static and dynamic signals on the vehicle, station and fueling protocols.

2) The PRHYDE team did not come to consensus on whether the vehicle or station should determine the fueling rate and which should have final control and command over the fueling. However, there was discussion on increasing the responsibility the vehicle has in the decision-making process and that different approaches should be considered as part of the protocol development process. This topic is discussed later.

3)The PRHYDE team considered the use of existing nozzle, communications and CHSS technology. Due to the potential long lead time of developing HDV hardware, the team agreed that the use of the existing hardware should be considered, but would not limit the performance of the fueling protocol. For example, the team would assume that all CHSS meet UN Global Technical Regulation (GTR) No. 13 [2] requirements, but the protocol would allow for different tank designs and technologies.

3 FUELING CONCEPTS

The PRHYDE team is primarily focusing on fueling concepts based upon advanced versions of the MC Formula framework developed by Honda and published in SAE J2601. The team is not considering a non-communication approach because of the limitations of such an approach and the difficulty of defining the respective boundary conditions and assumptions. The team determined this work would be more appropriately done through a standards development organization such as (International Organization for Standardization) ISO or SAE, due to the broader industry participation. Nevertheless, the concepts will be compatible with the possibility to include back up non-communication fueling in case of unavailability of advanced com on HRS or loss of communications during the fueling.

3.1 WHAT IS THE MC FORMULA FRAMEWORK?

The MC Formula Framework is described in detail in SAE J2601. To recap, the fueling control is determined by a Pressure Ramp Rate (PRR), which can change during the fill, namely by the estimated "time required to fill from P_{min} to P_{final}" (defined as t_{final}).

$$PRR = \frac{P_{final} - P_{ramp}}{t_{final} \times \left(\frac{P_{final} - P_{initial}}{P_{final} - P_{min}}\right) - t}$$ (Eq. 1)

Where t_{final} is defined as

$$t_{final} = a \times MAT^3 + b \times MAT^2 + c \times MAT + d$$ (Eq.. 2)

P_{final} is the final pressure used in the derivation of the t_{final} equation,
P_{min} is the initial pressure used in the derivation of the t_{final} equation,
$P_{initial}$ is the initial pressure in the CHSS prior to fueling (different than P_{min}), and
P_{ramp} is the pressure the dispenser is targeting for each time step during the fill.

P_{ramp} is also used to define the upper pressure corridor limit, which is a pressure limit which cannot be exceeded during the fill. More details on P_{final}, P_{min}, $P_{initial}$ and P_{ramp} can be found SAE J2601.

The coefficients to the t_{final} equation (*a*,*b*,*c*,*d*) are fueling parameters determined from the initial conditions (CHSS Volume, T_{amb}, P_{min}, Cold Dispenser flag). t_{final} changes with the mass average fuel delivery temperature (MAT). If the fuel delivery temperature is increasing, MAT increases and t_{final} also increases, which causes the PRR to decrease. If the fuel delivery temperature is decreasing, MAT decreases and t_{final} also decreases, which causes the PRR to increase. The current version of the MC Formula protocol in SAE J2601 utilizes tables of t_{final} equation coefficients (i.e., a, b, c, d). As a reference, tables of t_{final} values versus MAT at various ambient temperatures are provided. The tables are based upon worst case vehicle and station assumptions, and the same tables are used by every station.

3.2 HOW CAN FUELING PROTOCOLS BE IMPROVED?

There are margins which are rooted in the SAE J2601 worst case assumptions:

- Vehicle tank soak temperature
  (the temperature of the tank prior to fueling which may be different than ambient temperature)
- Station side pressure drop (breakaway to nozzle)
- Station side thermal mass
- Vehicle side pressure drop (receptacle to vehicle tank)
- Vehicle side thermal mass
- CHSS thermophysical assumptions (Type IV has a low thermal conductivity)
- Single vessel vehicle tank
- Fueling history is assumed (t_{final} based on a minimum pressure P_{min})

However, real world fueling has shown that the combination of these assumptions is too conservative. Therefore, improvements can be achieved by changing the philosophy of fueling, utilizing new approaches which allow vehicle specific information to be communicated to the station and incorporated into the fueling protocol to eliminate some of the conservative assumptions. Although the benefits are potentially high, there are some trade-offs that need to be considered.

In the following sections, several fueling concepts are derived from the MC Formula framework by making incremental improvements or changing philosophy of the fueling. The fueling concepts are categorized based on their underlying philosophy (i.e., what vehicle information is utilized for safety critical control functions), whether the station calculates the control parameters, or the vehicle calculates the control parameters and then communicates these to the station (in both cases, the station physically controls the fill), and whether they are prescriptive or performance-based.

In regards to the protocol philosophy, a Type 1 protocol uses no information from the vehicle for safety critical control functions, a Type 2 protocol uses static data from the vehicle (data that does not change intra-fill) for safety critical control functions, and a Type 3 protocol uses both static and dynamic data from the vehicle for safety critical control functions. Table 2 illustrates the Type 1, 2, and 3 protocol philosophies, and highlights the implications for each.

Table 2: Fueling protocol types and properties

Protocol Type	Vehicle CHSS Information Used	Implications
1	None	▪ SAE J2601 philosophy ▪ Conservative assumptions utilized for most parameters ▪ Fueling history is assumed ▪ Station is fully responsible
2	Static Data	▪ CHSS assumptions eliminated or reduced ▪ Conservative assumptions still utilized for some parameters ▪ Fueling history is assumed ▪ Station and vehicle share responsibility although most is still on station side
3	Dynamic Data	▪ Fewer assumptions need to be made ▪ The CHSS gas temperature can be used in different ways ▪ Screen for fueling history or use of actual temperature ▪ Station and vehicle share responsibility

The distinction between station control vs. vehicle control, is primarily based on the entity making the calculations to determine the control parameters. Most of the fueling concepts described herein utilize station control, however, the vehicle still communicates information to the station that is utilized in the control calculations. So, although these concepts are defined as station control, safety critical information from the vehicle is utilized as inputs to the station control calculations. Fueling concepts which are defined as vehicle control are those where the protocol control parameters are calculated by the vehicle and communicated as commands to the station, whereby the station implements these commands to control the fill. Table 3 illustrates the control options, and highlights the advantages and disadvantages of each.

Table 3: Fueling protocol control options

Control	Advantages	Disadvantages
Station (Type 1, 2, or 3)	▪ Some fueling concepts may not require advanced bi-directional communications (lower cost) ▪ 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

A prescriptive fueling protocol is a protocol that is defined explicitly, such that there is no ambiguity in its application. SAE J2601 is an example of a prescriptive fueling protocol. A performance-based protocol is a protocol that is not explicitly defined, although in the context of the fueling concepts described herein, a performance-based protocol operates within the Advanced MC Formula framework and utilizes common control parameters, but the manner in which these control parameters are calculated is left open. Again, in the context of the fueling concepts described herein, a performance-based protocol must also be a protocol which utilizes vehicle control. Table 4 below highlights the advantages and disadvantages of prescriptive vs performance-based protocols.

Table 4: Prescriptive vs. performance based fueling protocols

Protocol Description	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
Performance -based	▪ More room for innovation ▪ Allows for competition ▪ Can optimize fueling cost	▪ Development costs ▪ Less fair for small companies (must spend on development) ▪ Allows companies to corner the market through IP

The fueling concepts described are given names, identified by their philosophy (type), prescriptive (PR) or performance-based (PB), and station control (S) or vehicle control (V):

- Type 1 — Non-Comm
- Type 2-PR-S — Static Data
- Type 3-PR-S — Dynamic Data – T_{gas} Initial
- Type 3-PR-S — Dynamic Data – T_{gas} Initial+
- Type 3-PR-S — Dynamic Data – T_{gas} Throttle
- Type 3-PB-V — Advanced MC
- Type 3-PB-V — Original Equipment Manufacturer (OEM) Proprietary

All of these concepts can be utilized within the same Advanced MC Formula control framework. This means that a vehicle can choose which fueling concept to utilize and the station can implement the MC Formula control logic under this unified framework. This is illustrated in Figure 1. Each of these concepts have advantages and disadvantages, so by providing a variety of concepts, a vehicle OEM can utilize the concept that best meets their objectives. Of course, all of the concepts listed will not be developed within PRHYDE as a down-select process will be implemented to select a couple of these concepts. However, there is the intention to develop more than just a single concept in order to facilitate choices by the vehicle OEM.

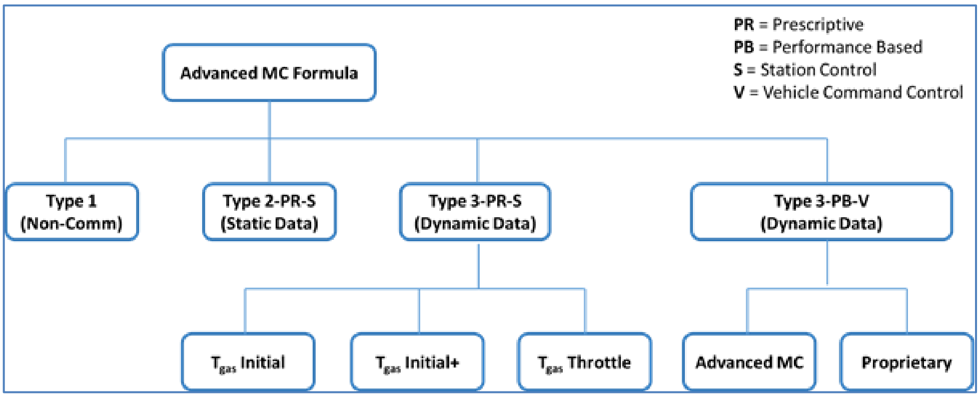


Figure 1: Fueling protocol concepts

4 ADVANCED MC FORMULA FRAMEWORK FUELING CONCEPTS

All of the Advanced MC Formula fueling concepts described herein (except for Type 1 and Type 3 PB-V Proprietary) utilize the same approach to derive the t_{final} values used in the protocol. The OEM is responsible for the derivation of the values based on a fueling model.

The fueling model used must be able to reflect accurately the CHSS design of the considered vehicle (individual tank sizes, fueling line diameters and wall thicknesses, lengths, junctions, manifolds, valves, etc) and thermophysical properties. This fueling model must also be able to reflect the dispenser fueling component design and thermophysical properties (based on consensus assumptions, to be defined in a fueling protocol standard).

The fueling model is then run over a range of input conditions where the fuel delivery temperature (T_{fuel}), ambient temperature (T_{amb}), minimum CHSS pressure (P_{min}), and initial CHSS soak temperature (T_{soak}) are varied over a defined range of values. The output from each of these simulations is a t_{final} value. These t_{final} values are then arranged in a set of tables (delineated by T_{amb} and MAT) which are stored in the vehicle electronic control unit (ECU), and called upon during each fueling event. Figure 2 illustrates how the derivation of the t_{final} tables is conducted. The specific range of inputs is explained in more detail for each fueling concept.

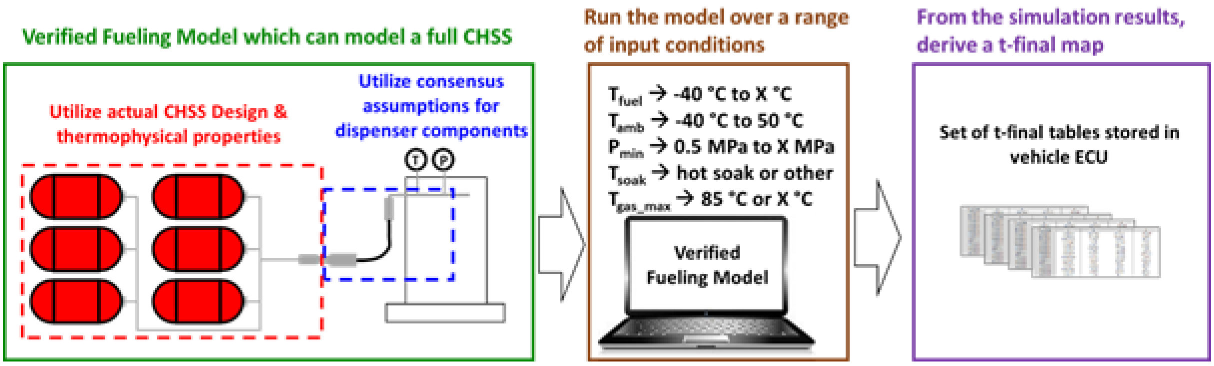


Figure 2: Deriviation of t_{final} values

The advantage of this approach is that many of the vehicle CHSS assumptions can be eliminated, while other assumptions can be more precise. This allows the optimization of fueling performance to the characteristics and capabilities of the CHSS, which should result in significantly improved performance when compared to a Type 1 approach which utilizes worst case assumptions.

Table 5 illustrates the formatting of a t_{final} table. The values are stored at T_{amb} increments of 5 °C and MAT increments of 2 °C, as MM.M, which is in minutes to the tenth of a minute. This provides a t_{final} resolution of 6 seconds, which is deemed acceptable.

Table 5: Example t_{final} table.

MAT (°C) → T_{amb} (°C) ↓	-40	-38	-36	-34	→
50	MM.M	MM.M	MM.M	MM.M	MM.M
45	MM.M	MM.M	MM.M	MM.M	MM.M
40	MM.M	MM.M	MM.M	MM.M	MM.M
35	MM.M	MM.M	MM.M	MM.M	MM.M
↓	↓	↓	↓	↓	↓

4.1 TYPE 1 – NON-COMMUNICATIONS

Type 1 resembles the MC Formula in its present form in SAE J2601. Although SAE J2601 facilitates communications, a Type 1 protocol does not utilize any communicated data from the vehicle for safety critical control functions (e.g., pressure ramp rate control). A Type 1 protocol will not be developed within the PRHYDE project. However, it is used as a benchmark for comparison with new fueling concepts.

4.2 TYPE 2-PR-S – STATIC DATA

This fueling concept is characterized by using the static data from communications to optimize the fueling parameters accounting for vehicle CHSS characteristics such as the CHSS design and thermophysical properties. The Static Data fueling concept uses up to four sets of t_{final} tables – one set of two tables for dispenser fueling components that are warm (i.e., warm dispenser), and the other set of two tables for dispenser fueling components that are cold (i.e., cold dispenser). As in SAE J2601, t_{final} tables are developed for two different P_{min} values: 0.5 and 5 MPa. The former is used for all fueling starting with $P_{initial}$ below 5 MPa, and the latter for all $P_{initial}$ above 5 MPa. This fueling concept must assume the vehicle was just recently fueled (i.e., fueling history), which can cause the gas temperature in the CHSS to be significantly higher than assumed In SAE J2601 because it cannot use the CHSS gas temperature to determine this. That is why even if $P_{initial}$ = 20 MPa (for example), the minimum pressure P_{min} used in the derivation of t_{final} is 5 MPa. This approach prevents overheat risk if there has been fueling history.

4.3 TYPE 3-PR-S (T_{GAS} INITIAL)

This fueling concept is characterized by using dynamic data from communications to optimize the fueling parameters accounting for vehicle CHSS characteristics such as the CHSS design and thermophysical properties, and fueling history / initial tank soak.

The T_{gas} Initial fueling concept uses multiple sets of t_{final} tables – one set of multiple tables for dispenser fueling components that are warm (warm dispenser), and another set of multiple tables for dispenser fueling components that are cold (cold dispenser). The T_{gas} Initial fueling concept differs from the Static Data fueling concept in that it has tables for many different P_{min} values. Whereas the Static Data fueling concept uses two P_{min} values, 0.5 MPa, and 5 MPa, the T_{gas} Initial fueling concept can utilize P_{min} values of 0.5, 5, 10, 15, 20 MPa, etc. There is no limit to the number of P_{min} values, or to the spacing of these values – this is left up to the vehicle OEM to decide. The benefit of being able to utilize higher P_{min} values is that the t_{final} values become progressively shorter as P_{min} increases, and thus fueling times can be significantly reduced. The reason that the T_{gas} Initial fueling concept can utilize higher P_{min} values is that this fueling concept uses the initial CHSS gas temperature T_{gas} to screen for fueling history. If $T_{gas} \le T_{soak}$ (the hot soak temperature utilized in SAE J2601), then the t_{final} table with the highest P_{min} value which is less than the initial CHSS pressure $P_{initial}$ can be utilized. As an example, if the initial CHSS pressure is measured to be 18 MPa and $T_{gas} \le T_{soak}$, then the t_{final} table corresponding to a P_{min} value of 15 MPa can be utilized. Using this same example, if $T_{gas} > T_{soak}$, then the t_{final} table corresponding to a P_{min} value of 0.5 or 5 MPa (to be determined based on additional analysis) must be utilized, because in this case, fueling history is likely to have occurred, meaning that the vehicle may have recently been fuelled with a much lower initial pressure. By utilizing this approach, fueling performance can be greatly improved under typical conditions, and in those rare instances where fueling history is present, this concept utilizes conservative t_{final} values to prevent overheating from occurring.

4.4 TYPE 3-PR-S (T_{GAS} INITIAL+)

This fueling concept is characterized by using dynamic data from communications to optimize the fueling parameters accounting for vehicle CHSS characteristics such as the CHSS design and thermophysical properties, and eliminates the initial CHSS soak temperature assumptions._ A key difference of the T_{gas} Initial+ concept vs the T_{gas} Initial concept is the initial CHSS gas temperature T_{gas} is used to both screen for fueling history and to determine the initial CHSS soak temperature assumption to use.

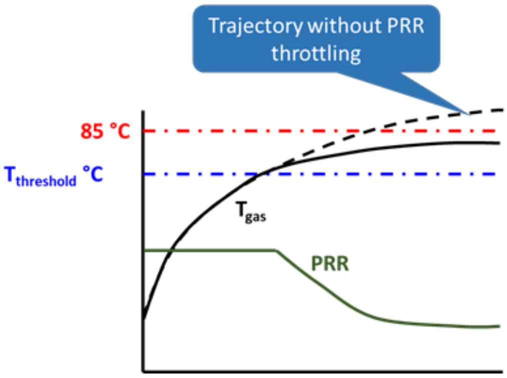
4.5 TYPE 3-PR-S (T_{GAS} THROTTLE)

This fueling concept is characterized by using both static and dynamic data from the communications to optimize the fueling parameters accounting for vehicle CHSS characteristics such as the CHSS design and thermophysical properties and to actively monitor the T_{gas} temperature and reduce the pressure ramp rate once the T_{gas} temperature rises above a threshold temperature.

With this approach, a table is derived but only using a P_{min} value of 0.5 MPa. This approach is simple as there is only a single t_{final} table for warm dispenser and cold dispenser. It is possible to use additional t_{final} tables with higher P_{min} values, but it is not likely to significantly improve the fueling performance. In regards to the table derivation, the key difference is in the peak CHSS gas temperature limit utilized in the fueling simulations. In the T_{gas} Initial and Tgas Initial+ approaches, the maximum CHSS gas temperature utilized in the simulations for the derivation of the t_{final} values is 85 °C, which is the current limit for fueling protocols, such as SAE J2601, due to the CHSS qualification standards and regulations and GTR No. 13. In the Tgas Throttle fueling concept, the maximum CHSS gas temperature utilized in the fueling simulations during derivation of the t_{final} tables is chosen by the OEM. It could be 90 °C, 95 °C, 100 °C, or even some higher value. The higher the value chosen, the shorter the t_{final} table values will be. However, there is a "throttling" control function in the implementation of this protocol approach which prevents the CHSS gas temperature from exceeding 85 °C. Therefore, the higher the maximum gas temperature utilized in the t_{final} table derivation, the more often this throttling function will activate, and fueling times increase when throttling is activated. There should be a balance sought – choose a high enough maximum CHSS gas temperature in the derivation of the t_{final} tables to achieve excellent fueling performance without throttling under most conditions, resulting in throttling under a relatively small percentage of conditions, e.g., 10-20% of the time.

The advantage of the approach is that the t_{final} values are relatively short for all fills, regardless of initial conditions. This means that the fueling performance will be excellent over a wide range of initial conditions. An additional advantage of this approach is that in the event that the CHSS gas temperature is incorrect, whether that be through a fault in the temperature sensor(s), or a fault in the communication of the gas temperature measurement, the overheat probability is limited – it cannot exceed the maximum temperature used in the derivation of the t_{final} tables (e.g., 95 °C). This feature may allow for lower functional safety requirements on the vehicle. For example, if the CHSS were qualified to the maximum CHSS gas temperature used in the derivation of the t_{final} tables, then it is possible that no additional functional safety requirements would be needed on the vehicle to prevent an overheat event.

Figure 3 visually illustrates how the throttling approach works. When the CHSS gas temperature T_{gas} reaches a threshold temperature $T_{threshold}$, the pressure ramp rate *PRR* is reduced to prevent the gas temperature from exceeding 85 °C. The reduction in *PRR* is a function of the *PRR* at $T_{threshold}$ (referred to as $PRR_{threshold}$) and T_{gas}. As T_{gas} continues to rise above $T_{threshold}$, the *PRR* is gradually reduced using Equation 3.



$$IF\ T_{gas} \geq T_{threshold}$$

$$PRR = \frac{(85 - T_{gas})PRR_{threshold}}{(85 - T_{threshold})}$$

Figure 3: Throttle approach *Eq. 3*

Where,

PRR = the pressure ramp rate
T_{gas} = the CHSS gas temperature (highest value in a multi-tank system)
$T_{threshold}$ = the CHSS gas temperature at which the throttling equation is activated
$PRR_{threshold}$ = the PRR when $T_{gas} = T_{threshold}$

The $T_{threshold}$ value is determined by the vehicle OEM and is communicated to the station during fueling. The higher the $T_{threshold}$ value utilized, the less frequent the throttling equation will be activated; however, this also narrows the throttling range and makes the pressure ramp rate adjustments more sensitive, so there is trade-off. Thus, the highest $T_{threshold}$ value should be utilized which still facilitates sufficient pressure ramp rate control (this may need to be determined through testing, resulting in further guidance on what values are practical).

4.6 TYPE 3-PB-V - DYNAMIC DATA

This fueling concept is characterized by using dynamic data to directly communicate a set of control parameters from the vehicle to the station via communications. This performance-based approach may use one of the three Type 3-PR-S fueling concepts described above, or it may use an OEM proprietary method. Because this fueling concept is intended to function within the Advanced MC Formula framework, which facilitates any of the fueling concepts described in this document, the primary control parameter which is communicated should the same (i.e., P_{ramp}). To facilitate this approach, the station also needs to communicate dynamic data to the vehicle, as the vehicle is responsible for calculating and communicating back to the station the control parameter. The data communication from the station to the vehicle may include the fuel delivery temperature, the mass dispensed, the expected end of fill MAT, the ambient temperature, hot or cold dispenser, and the station pressure. The PRHYDE team, to date, has only had high level discussions of this approach, and which parameters need to be communicated. This approach needs additional consideration of which parameters are needed and the order of communication.

4.7 COMMAND AND CONTROL

The fueling concepts described above (except for the Type 1 – Non-communications) are intended to utilize bi-directional wireless communications which facilitate the station communicating information to the vehicle and the vehicle communicating information to the station. The use of bi-directional communication opens up many new fueling approaches that could not be considered using the existing IrDA-based unidirectional communications. Although such bi-directional communications do not exist today, there are development efforts ongoing and standardization work has started within the ISO TC/197 Hydrogen Technologies Technical Committee. Therefore, the PRHYDE team is developing fueling concepts which leverage this bi-directional wireless communication capability with the expectation that it will be available in the near future.

The PRHYDE team does not intend to precisely define the data formatting, or the communication of data not directly related to the fueling protocol control. And to date, the team has not discussed exactly which parameters are communicated from the station to the vehicle, and from the vehicle to the station, as well as the order of transmission, for each of the fueling concepts described herein. However, at a high level, the options for communication of parameters and the manner in which they are used, are described below.

The static data and dynamic data fueling concepts using station control (i.e., Type 2-PR-S and Type 3-PR-S) all operate on the same general principle. All fueling concepts operate on the principle that the vehicle stores a set of t_{final} tables in the vehicle ECU. The station and vehicle use the following steps to implement the fueling protocol:

1 Vehicle/Station handshake and initialization
2 Station initiates a connection pulse to measure the initial pressure ($P_{initial}$)
3 Station transmits the ambient temperature (T_{amb}), the initial pressure ($P_{initial}$), and whether the dispenser fueling components are warm or cold (this is still to be defined)
4 Based upon the values received from the station as well as its own measurement of these parameters, the vehicle selects the appropriate t_{final} table
5 The vehicle then interpolates t_{final} based on T_{amb} for every MAT value
6 The vehicle then transmits the t_{final} values for the range of MAT values at the ambient temperature
7 The station receives these t_{final} values and stores them in local memory accessible to the PLC.
8 Once the fueling begins, the station calls upon these stored values and precisely calculates the t_{final} used in the pressure ramp rate equation based on its calculation of the MAT. It does this continuously throughout the fill.

There is another option that may be considered by the PRHYDE team, and that is for the vehicle to communicate the full set of t_{final} tables stored in the vehicle to the station after the handshake/initiation step. The difficulty with this approach is that each fueling concept uses a different number of tables, and the manner in which these tables are selected is also different.

The performance based fueling concept Type 3-PB-V operates differently. The PRHYDE team has not yet determined all of the parameters required to be communicated by the station to the vehicle in this approach. However, the basic way this fueling concept functions is that the vehicle conducts all of the calculations required to determine the control parameter and communicates these to the station continuously throughout the fill. The control parameter is essentially P_{ramp}, which is used by the station as both a target pressure for each point in time during the fill, as well as a pressure limit (P_{ramp} + ΔP), which serve as a limit on pressure that the station pressure should not exceed.

5 COMPARISON OF SELECTED APPROACHES

With many fueling concepts comes a need to evaluate and short-list, so the protocol development efforts can be more focused on the concept(s) that brings the most value. Table 6 shows a relative comparison of the different fueling concepts under various topics.

Table 6: Comparison of fueling concepts

	Static	**T_{gas} Initial**	**T_{gas} Initial+**	**T_{gas}Throttle**	**Vehicle Control**
Fueling time	Slow	Fast	Faster	Fastest	UD
Sensor position accuracy requirement	Low	Low	Low	High	UD
Vehicle functional safety level	Low	High	High	Higher[1]	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	High	Higher	Highest
Impact of conservative assumptions on performance	High	Medium	Medium	Low	UD
UD = Undetermined due to flexibility of approach 1 Depends on design of T_{gas} Throttle approach					

6 QUALITATIVE COMPARISON OF SELECTED APPROACHES

An initial overall comparison was made for all fueling concepts. However, the comparison was limited to a qualitative assessment. At the time of publication, the PRHYDE team had just begun simulations and therefore had no data to support a quantitative performance comparison. In addition, the PRHYDE team needed to conduct a risk assessment to determine how each fueling concept impacts the station design or the vehicle. This comparison is shown in Appendix A.

7 NEXT STEPS

As described in this report, there are multiple fueling concepts which are being considered. The Advanced MC Formula Framework supports all of these fueling concepts, so they are all potentially viable fueling methodologies, and may be considered as candidates for eventual standardization. However, the PRHYDE project does not have sufficient time and resources to develop and validate all of these fueling concepts, and therefore, the immediate next step is to down select two or three fueling concepts which will then be developed and validated within PRHYDE.

7.1 RISK ASSESSMENT

The team will conduct a risk assessment of all the fueling concepts defined herein. A generic station and vehicle system will be defined and a bow-tie layer of protection analysis risk assessment will be conducted where layers or protection will be applied in order to achieve the desired residual risk. The risk assessment will limit the scope to failures of components and software which directly influence the fueling control as defined by the fueling protocol concept. The objective is to understand the protective layers required on the station and the vehicle for each fueling component. From this, the PRHYDE team can make a more informed choice of the fueling concepts to down select.

7.2 FUELING CONCEPT DEVELOPMENT

Once the fueling concepts have been determined through the down select process, the team will develop each fueling concept in detail. This will involve first defining a reference CHSS and station side fuel dispensing components and associated thermophysical properties to be utilized in the fueling model via a consensus process. Secondly, the fueling control for each fueling concept will be clearly defined (e.g., initial conditions utilized, how the fueling rate is established, how the fill is stopped, control related process limits, and considerations on fueling circumstances, i.e., intended non-fueling events, maximum start-up mass, etc). Thirdly, the team will determine the messages, data, and order of transmission to be utilized by the protocols via the communications link between vehicle and station.

7.3 MODELING

Once the CHSS and station fuel dispensing components have been defined and characterized, the PRHYDE modelling team will conduct fueling simulations to derive the appropriate t_{final} tables for each fueling concept. After the tables have been derived, team will define a matrix of scenarios (i.e., CHSS initial conditions, fuel dispending components initial conditions and thermophysical properties, ambient temperature, fuel delivery temperature, etc.) and will then determine the fueling performance of the fueling concepts under these scenarios.

7.4 TESTING

The PRHYDE testing team will conduct real world testing of the fueling concepts, likely to be conducted at several of the PRHYDE members test facilities and the National Renewable Energy Laboratory Innovative Hydrogen Station with a HD vehicle simulator. This testing will confirm the fueling performance previously modelled, provide real world "proof of concept" of the fueling protocols, and will be used to indicate if there are any real-world issues which were not previously accounted for and require adjustments or changes to the fueling concepts.

8 CONCLUSION

Based upon a core set of fueling protocol design questions, the PRHYDE team developed several different HD vehicle fueling protocol approaches based upon the type of data transmitted between the station and vehicle and the level of data used to optimize the fueling. The team also examined if the station or vehicle provides the command to fueling and controls the final determination of the fueling rate. The team qualitatively compared the approaches which showed distinct benefits and disadvantages for each. The next steps for the PRHYDE team are to conduct a risk analysis and model and test a select number of the fueling concepts presented in this paper.

9 REFERENCES

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10 APPENDIX A: QUALITATIVE COMPARISON OF FUELING PERFORMANCE

As a first step in comparing the fueling performance of the different fueling protocol options, a qualitative assessment was conducted based on a relative comparison of the fueling speed under a variety of different scenarios. These assessments are based on the structure and function of each protocol option.

Four (Type 2-PR-S Static, Type 3-PR-S_T_{gas}_Initial, Type 3-PR-S_T_{gas}_Initial+, Type 3-PR-S_T_{gas}_Throttle) fueling concepts were compared in 3 scenarios as shown in Table 7 through Table 9. A base case station was qualitatively contrasted to stations with components that had a better thermal mass and/or Kv which resulted in improved fueling performance due to a higher heat transfer or lower pressure drop, respectively. The performance was evaluated at various gas temperatures and initial pressures.

Table 7: Qualitative Assessment of fueling protocol concepts Base Case

Station Thermal Mass = Base case Station Kv = Base case		**Static**	**Dynamic Data - Type 3-PR-S**		
T_{gas_0}	**P_0**	**Type 2-PR-S**	**T_{gas} Initial**	**T_{gas} Initial+**	**T_{gas} Throttle**
T_{gas} = hot soak	< 2 MPa	1	1	1	1
	~ 5 MPa	2	2	2	2
	~ 10 MPa	2	3	3	3
	~ 15 MPa	2	4	4	4
	~ 20 MPa	3	4	4	4
T_{gas} = T_{amb}	~ 5 MPa	2	2	3	2
	~ 10 MPa	2	3	4	3
	~ 15 MPa	2	4	4	4
	~ 20 MPa	3	4	5	4
T_{gas} = T_{amb} – 15 C	~ 5 MPa	2	2	4	4
	~ 10 MPa	2	3	4	4
	~ 15 MPa	2	4	5	4
	~ 20 MPa	3	4	5	4
T_{gas} > hot soak (fueling history)	~ 5 MPa	1	1	1	1
	~ 10 MPa	2	2	2	2
	~ 15 MPa	2	2	2	3
	~ 20 MPa	2	2	2	4
Assume Temperature Constrained Fills, i.e., Warm T_{amb} and T20 pre-cooling		1= Slowest 5 Fastest			

Table 8: Qualitative Assessment of fueling protocol concepts:
Station component thermal mass OR Station Kv better than base Case

Station Thermal Mass OR Station Kv better than base case		**Static**	**Dynamic Data - Type 3-PR-S**		
T_{gas_0}	P_0	**Type 2-PR-S**	T_{gas} **Initial**	T_{gas} **Initial+**	T_{gas} **Throttle**
T_{gas} = hot soak	< 2 MPa	1	1	1	2
	~ 5 MPa	2	2	2	3
	~ 10 MPa	2	3	3	4
	~ 15 MPa	2	4	4	4
	~ 20 MPa	3	4	4	4
T_{gas} = T_{amb}	~ 5 MPa	2	2	3	2
	~ 10 MPa	2	3	4	4
	~ 15 MPa	2	4	4	4
	~ 20 MPa	3	4	5	4
T_{gas} = T_{amb} – 15 C	~ 5 MPa	2	2	4	4
	~ 10 MPa	2	3	4	4
	~ 15 MPa	2	4	5	4
	~ 20 MPa	3	4	5	5
T_{gas} > hot soak (fueling history)	~ 5 MPa	1	1	1	1
	~ 10 MPa	2	2	2	2
	~ 15 MPa	2	2	2	4
	~ 20 MPa	2	2	2	4
Assume Temperature Constrained Fills, i.e., Warm T_{amb} and T20 pre-cooling		1= Slowest 5 Fastest			

Table 9: Qualitative Assessment of fueling protocol concepts:
Station component thermal mass AND Station Kv better than base Case

Scenarios Station Thermal Mass <u>AND</u> Station Kv better than base case		**Static**	**Dynamic Data - Type 3-PR-S**		
T_{gas_0}	P_0	**Type 2-PR-S**	T_{gas} **Initial**	T_{gas} **Initial+**	T_{gas} **Throttle**
T_{gas} = hot soak	< 2 MPa	1	1	1	3
	~ 5 MPa	2	2	2	4
	~ 10 MPa	2	3	3	4
	~ 15 MPa	2	4	4	4
	~ 20 MPa	3	4	4	5
T_{gas} = T_{amb}	~ 5 MPa	2	2	3	3
	~ 10 MPa	2	3	4	4
	~ 15 MPa	2	4	4	4
	~ 20 MPa	3	4	5	5
T_{gas} = T_{amb} – 15 C	~ 5 MPa	2	2	4	4
	~ 10 MPa	2	3	4	4
	~ 15 MPa	2	4	5	5
	~ 20 MPa	3	4	5	5
T_{gas} > hot soak (fueling history)	~ 5 MPa	1	1	1	3
	~ 10 MPa	2	2	2	4
	~ 15 MPa	2	2	2	4
	~ 20 MPa	2	2	2	5
Assume Temperature Constrained Fills, i.e., Warm T_{amb} and T20 pre-cooling		1= Slowest 5 Fastest			