Impact of hydrogen SAE J2601 fueling methods on fueling time of light-duty fuel cell electric vehicles

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Abstract

Hydrogen fuel cell electric vehicles (HFCEVs) are zero-emission vehicles (ZEVs) that can provide drivers a similar experience to conventional internal combustion engine vehicles (ICEVs), in terms of fueling time and performance (i.e. power and driving range). The Society of Automotive Engineers (SAE) developed fueling protocol J2601 for light-duty HFCEVs to ensure safe vehicle fills while maximizing fueling performance. This study employs a physical model that simulates and compares the fueling performance of two fueling methods, known as the "lookup table" method and the "MC formula" method, within the SAE J2601 protocol. Both the fueling methods provide fast fueling of HFCEVs within minutes, but the MC formula method takes advantage of active measurement of precooling temperature to dynamically control the fueling process, and thereby provides faster vehicle fills. The MC formula method greatly reduces fueling time compared to the lookup table method at higher ambient temperatures, as well as when the precooling temperature falls on the colder side of the expected temperature window for all station types. Although the SAE J2601 lookup table method is the currently implemented standard for refueling hydrogen fuel cell vehicles, the MC formula method provides significant fueling time advantages in certain conditions; these warrant its implementation in future hydrogen refueling stations for better customer satisfaction with fueling experience of HFCEVs.

Keywords: Hydrogen fueling protocol; SAE J2601; Fueling time; Light-duty fuel cell electric vehicle; MC formula method.

1. Introduction

Hydrogen powered fuel cell electric vehicles (HFCEVs) have many advantages over the traditional internal combustion engine vehicles (ICEVs) including, high energy conversion efficiency, zero tail pipe emissions, and reduced greenhouse gas emissions [1]. Additionally, unlike petroleum-based fuels, hydrogen can be produced from a variety of domestic feedstock or renewable sources, thereby providing energy security and grid balancing benefits. HFCEVs provides drivers a similar experience to ICEVs, including a comparable fueling time and driving range.

The driving range of currently available ICEVs varies from about 275 to 600 miles for light-duty vehicles, with a median of 400 miles [2]. Hence, FCEVs require a minimum driving range of about 300 miles to achieve comparable consumer experience. Though the energy content of 1kg of hydrogen is approximately equivalent to about 1 gallon of gasoline, the higher efficiency of HFCEVs facilitates a driving range of more than 300 miles with only about 5–7 kg of hydrogen storage (tank) and a 60 mi/kg fuel economy [3]. The low volumetric energy density of hydrogen necessitates a nominal working pressure (NWP) of about 70MPa to store the required 5–7 kgs onboard the vehicle. Hydrogen is stored in type IV pressure vessels, comprised of a non-load-bearing polymer liner wrapped with load-bearing high-strength carbon fiber composite, due to its light weight and high strength in comparison to other pressure vessel types.

To provide a customer experience similar to that of gasoline ICEVs, SAE J2601 was developed to enable stations to fill HFCEVs with 5-7 kg of hydrogen within 3-5 minutes [4,5]. Fast refueling of hydrogen is constrained by the thermodynamic properties of hydrogen under compression and the material properties of the type IV tanks used to store hydrogen onboard HFCEVs. The operating temperature of Type IV storage tanks must stay between -40^{o}C and 85^{o}C to prevent degradation of the tank liner [4,5]. At a fueling station, hydrogen in bulk storage is approximately at ambient temperature. However, fast dispensing increases the temperature of both the hydrogen and the tank liner, such that the hydrogen must be cooled to -40^{O}C before it is dispensed to keep the FCEV tank from exceeding its operating temperature.

Computational fluid dynamics (CFD) models [6, 7, 8, 9, 10], and analytical thermodynamics models [11, 12, 13, 14, 15, 16, 17, 18] have been used to study the evolution of the hydrogen temperature and pressure in the vehicle's onboard tank during fast filling. The CFD models have been further used to study the effect of initial tank temperature [9, 8], tank properties [10], inlet temperature [8], on the fueling process parameters including the state of charge, final temperature, final pressure and cooling demand, etc. Similarly, the analytical thermodynamics models have also been used to estimate, the evolution of temperature and pressure [15, 16, 17, 18], the end of fill temperature and pressure [19, 20] using pre-cooling temperature and other fueling parameters including the, mass flow rate, inlet temperature and pressure, etc. Models were also used to estimate the required pre-cooling [21] with known ambient temperature, initial temperature, initial pressure mass flow rate, desired final temperature, and desired filling time etc. Elaborate models [15, 16, 22, 23, 24] of refueling station components have also been developed and used to simulate the operation of the refueling station, which were later used to optimize the station compression and storage [16, 22, 24] and vehicle fill time [23].

In order to ensure hydrogen fueling safety the SAE fuel cell standards committee interface working group has worked with experts from gas companies, fuel suppliers and the automotive industry to develop the SAE J2601 standard [4,5], which includes two fueling protocols for light-duty FCEVs: (1) lookup table method, and (2) MC formula method. Hydrogen fueling protocols have been developed based on computational modeling [6] and experimental data. Fueling protocols, such as J2601, are implemented at stations to keep the fueling process within specific temperatures and pressures to ensure that vehicles can be safely filled within a given time frame (e.g. 3-5 minutes). Another attempt to develop a new hydrogen refueling protocol [25] by optimizing the fueling time, precooling demand, and energy consumption through improved understanding of the fueling process and involved components is currently underway. The performance of the SAE J2601 lookup table method and MC formula method in different forms of development have been compared [19, 26, 27, 28] for different fill conditions through experimental data for particular tank characteristics. The experimental data of SAE J2601 lookup table method was also used to study the effect of mass flow rate and inlet temperature on the final state of charge of the fill [29].

The performance of the SAE J2601 fueling protocols have been compared previously but only through actual vehicle tank fills using a dispenser programmed with the two fueling methods [26,28]. No effort has been reported in literature that modeled and simulated the two fueling methods to systematically evaluate the impact of the various refueling methods on the fueling time at different boundary conditions. The motivation for the present study is to address this gap in the literature through careful modeling of the transient condition of the vehicle's tank by examining the SAE J2601 fueling methods at various permutations of possible initial and boundary conditions (e.g., ambient temperature, initial tank conditions, precooling transient temperature profiles, etc.). We employed the Hydrogen Station Cost Optimization and Performance Evaluation Model (H2SCOPE), developed by Argonne National Laboratory, to conduct the systematic evaluation of the SAE J2601 fueling methods. In this paper, we present an overview of both the SAE J2601 fueling methods and compare their performance at different fueling conditions, using the results from a simulation model. The two fueling methods lookup table and MC formula method have been incorporating in the model to study and compare their performance in terms of state of charge and filling time. In the following section, a summary of the SAE J2601 hydrogen refueling protocol methods is explained, followed by presentation of the H2SCOPE model used to simulate the performance of these fueling methods. Later, the results of the simulations for different boundary conditions are presented and conclusions are derived.

2. SAE J2601 refueling protocols

The fueling protocol determines the rate at which a dispenser should fill a vehicle (i.e. "ramp rate") to ensure a safe, fast fill. The fueling protocol thus requires the station to be equipped with the necessary equipment to control the fueling process. The fueling pressure ramp rate at the dispenser depends on the hydrogen precooling temperature at the dispenser, the vehicle tank's volume and initial pressure, and the ambient temperature. The dispenser is typically connected to a high-pressure hydrogen source that enables the required maximum pressure ramp rate, which is controlled via a variable area control device within the dispenser.

The SAE J2601 protocol establishes and maintains the fueling process limits to ensure process safety and performance. The safety limits of the vehicle storage system (tank) are shown in Table 1:

Table 1: SAE J2601 performance and safety limits for hydrogen vehicle tank fueling

Parameter	Limit
Minimum gas temperature	-40°C
Maximum gas temperature	85°C
Minimum dispenser pressure	0.5 MPa
Maximum dispenser pressure (70 MPa NWP)	87.5 MPa
Maximum flow rate	60 g/sec

The desired performance attributes used to develop the SAE J2601 fueling protocol ensure consumer convenience by enabling a fueling time of 3 minutes for a 70 MPa FCEV at a T40 station (i.e., capable of precooling to -40°C) achieving a state of charge of 90% to 100% of the rated capacity of the vehicle storage (defined at nominal working pressure and 15°C).

The SAE J2601 fueling protocol considers the available vehicle-station interface options and station control parameters to manage fueling events. The station interface strategies include:

- Communication (Comm) fueling: the vehicle provides tank parameters such as pressure and temperature through an electrical/communication interface during the fueling event
- Non-communication (Non-Comm) fueling: the vehicle provides tank pressure only during the fueling event

2.0.1 Protocol limits

The SAE J2601 protocol [4,5] defines specific assumptions of fueling conditions that must be met for the protocol to be used. The HFCEV's storage capacity should be between 2 to 10 kg if its NWP is 70 MPa. The ambient temperature must be between -40°C and 50°C. The hydrogen fuel delivery temperature (at the dispenser breakaway) cannot be less than -40°C or greater than -17.5°C at any time during the fueling process. The vehicle pressure at the beginning of a fill must be between 0.5 MPa and the nominal working pressure of the vehicle (35 MPa or 70 MPa). Finally, the hydrogen flow rate cannot be allowed to exceed 60 g/sec at any time during the fueling process.

Irrespective of the type of fueling, communication or non-communication, the station monitors the communications interface with the vehicle. For communication fueling, the vehicle temperature and pressure are monitored throughout the fueling to control the fueling process such that the vehicle tank does not exceed preset upper limits. If the temperature of the tank reaches the maximum compressed hydrogen storage system (CHSS) operating temperature or if the pressure exceeds 1.25 times the tank's nominal working pressure, the fueling is aborted.

2.1 SAE J2601 lookup table method

The "lookup table" method controls the rate at which the pressure of hydrogen fueling increases during a fill (i.e. "pressure ramp rate") based on temperatures and pressures at the station and the FCEV tank. The method is based on 44 individual tables that specify pressure ramp rates for given combinations of HFCEV onboard storage capacities (2–4kg, 4–7kg and 7–10kg), station types/fuel delivery temperature (T40, T30 and T20), station/hose delivery pressure (H70 for 70 MPa and H35 for 35 MPa), type of vehicle-dispenser interface (communication and non-communication) and temperature at the dispenser outlet.

These tables were developed by thermodynamic simulations that have been validated using HFCEV fueling data from real world refueling stations, along with environment controlled laboratory testing.

In the lookup table method, the ambient temperature defines the average pressure ramp rate, and thus the speed of fueling, while the combination of ambient temperature and initial pressure together define the target pressure at which the fueling is terminated. For non-communication fueling, the protocol maintains a constant average pressure ramp rate (APRR) throughout the fill and terminates the fill once the end pressure is reached, for all initial pressures greater than 0.5 MPa (see Figure 1). For communication fueling, the protocol adopts a similar approach as the non-communication fueling for initial pressures greater than 5 MPa. However, communication fills with initial pressures below 5 MPa and greater than 0.5 MPa, at ambient temperature greater than $0^{O}C$, the protocol adopts a different approach called top-off fueling. The top-off fueling starts the fueling at the same APRR as the non-communications fueling for the same boundary conditions up to an intermediate pressure, after which the APRR is reduced until it reaches the top-off target pressure. The top-off APRR and end pressure values are shown at the top left corner of the communications tables, an example of which is shown in Figure 1.

Ambient Temperature, T_{amb} [°C]	*APRR [MPa/min]*	Top-Off Fueling Parameters: Target Pressure P_{target} [MPa]	Top-Off Fueling Parameters: Target Pressure Top-Off [MPa]	Top-Off Fueling Parameters: *Top-Off APRR [MPa/min]*	Target Pressure, Ptarget [MPa]											
		Initial Tank Pressure, P_o [MPa]														
		0.5-5 (no interpolation)			0.5	2	5	10	15	20	30	40	50	60	70	>70
>50	No Fueling															
50	*5.1*	78.2	87.5	*2.6*	Top-Off Fueling		80.8	85.7	86.8	86.5	85.8	85.0	84.0	82.7	81.1	No Fueling
45	*8.1*	76.3	87.5	*4.0*	Top-Off Fueling		81.1	86.9	86.6	86.2	85.3	84.3	83.0	81.6	79.7	No Fueling
40	*11.5*	73.2	87.5	*5.4*	Top-Off Fueling		81.1	86.9	86.4	85.9	84.7	83.5	82.0	80.3	78.3	No Fueling
35	*12.4*	72.9	87.5	*5.6*	Top-Off Fueling		81.2	86.9	86.4	85.9	84.7	83.4	81.9	80.2	78.2	No Fueling
30	*15.3*	70.6	87.5	*6.6*	Top-Off Fueling		81.0	86.8	86.3	85.6	84.3	82.8	81.2	79.4	77.2	No Fueling
25	*18.5*	69.0	87.4	*7.2*	Top-Off Fueling		81.0	86.8	86.1	85.4	83.8	82.2	80.4	78.5	76.1	No Fueling
20	*21.8*	67.9	87.4	*7.6*	Top-Off Fueling		81.2	86.8	85.9	85.1	83.3	81.5	79.6	77.5	75.1	No Fueling
10	*28.0*	66.3	87.4	*9.0*	Top-Off Fueling		81.2	86.8	85.7	84.7	82.6	80.5	78.3	76.1	73.4	No Fueling
0	*28.5*	No Top-Off Fueling			78.4	84.6	86.8	85.6	84.4	83.1	80.6	78.1	75.6	73.1	No Fueling	
-10	*28.5*	No Top-Off Fueling			82.2	87.1	86.4	85.2	84.0	82.8	80.4	77.9	75.4	72.9	No Fueling	
-20	*28.5*	No Top-Off Fueling			86.0	86.8	86.1	84.9	83.7	82.4	80.0	77.6	75.1	72.7	No Fueling	
-30	*28.5*	No Top-Off Fueling			86.8	86.5	85.7	84.5	83.3	82.1	79.6	77.2	74.9	72.5	No Fueling	
-40	*28.5*	No Top-Off Fueling			86.5	86.2	85.4	84.2	83.0	81.8	79.3	77.0	74.6	72.3	No Fueling	
<-40	No Fueling															

Figure 1: Lookup table [4, 5] for communications fueling at T40 station with H70 hose for a 4-7kg capacity HFCEV (the APRR of the fill at 25°C ambient temperature and 5 MPa initial tank pressure is highlighted).

The SAE J2601 fueling protocols consists of three main phases: (i) startup, (ii) control, and (iii) termination. During the startup phase the integrity of the connections between the dispenser nozzle and vehicle receptacle is verified and the capacity of the HFCEV is established. In the control phase, the fuel flow is controlled by APRR at the dispenser to ensure that all the parameters are consistent with the protocol. During the termination phase, the flow is stopped and the receptacle is disconnected from the dispenser nozzle.

2.1.1 Fueling using SAE J2601 lookup table method details

2.1.1.1 Startup phase:

The startup phase ensures a safe connection between the nozzle and vehicle receptacle. The dispenser sends a startup connection pulse after verifying the coupling between the receptacle and the nozzle. The initial vehicle tank pressure is detected with an initial pressure pulse. A second pressure pulse is used to estimate the volume of the vehicle tank, and to detect any leaks. The vehicle tank volume and initial pressure should be estimated to at least ±15% accuracy. No more than 200 grams of hydrogen is allowed to flow into the HFCEV tank during this phase.

In addition, during the startup period the dispenser considers the ambient temperature, initial vehicle tank pressure, the station type/pre-cooling temperature, and dispenser condition (warm vs. cold) to select the appropriate lookup table APRR consistent with the available measured data. On selecting the appropriate table, the data from the table is linearly interpolated to calculate the APRR and target pressure for the measured ambient temperature and vehicle initial pressure.

The startup phase of fueling ends when the fuel starts flowing through the hose to the vehicle tank system, after the dispenser successfully checks for leaks, and calculates the APRR corresponding to the initial pressure, ambient temperature, station type and HFCEV tank capacity.

2.1.1.2 Main fueling phase

This phase begins with the flow of hydrogen from the station hose to the vehicle tank. During this phase the pre-cooling temperature and communication signals from the vehicle, if any, are monitored. The fueling continues at the calculated APRR from the startup phase. The fueling parameters monitored by the dispenser are used to control the fueling process by adjusting APRR depending on the pre-cooling temperature after the initial 30 seconds in this phase.

2.1.1.2.1 Pre-cooling temperature effect:

The temperature of the hydrogen being dispensed (i.e. pre-cooling temperature) is an important parameter to ensure the fueling process safety, so it is monitored throughout the fill. The rolling average and total mass average fuel delivery temperature is calculated and used to terminate the fueling, to prevent vehicle tank over-heating, in the event of equipment failure. The station should achieve the pre-cooling temperature consistent with the station type within the first 30 seconds of fueling. For example, for a T40 station with an H70 hose, if the pre-cooling temperature falls within the expected range (window) at the end of 30 seconds, the fueling continues as expected by maintaining the calculated APRR at the dispenser.

If the pre-cooling temperature does not fall within the designated station type precooling temperature window, the station shall terminate the fueling if there is no valid communication signal from the vehicle. In the presence of a valid communication signal from the vehicle a fallback procedure is initiated and a new lower pressure ramp rate is calculated, which is defined by following equation:

$$Fallback\ Pressure\ Ramp\ Rate, FPRR_{\text{target}} = \frac{(P_{\text{end target}} - P_1)}{[\frac{1}{APRR_{\text{final}}} \times (P_{\text{end target}} - P_0) - t_{\text{station fallback}}]} \quad (1)$$

where,

$APRR_{final}$ is the APRR from fallback lookup table;

$P_{end\ target}$ is the dispenser fueling end target pressure at a warmer precooling temperature category;

P_1 is the vehicle tank pressure at fallback point;

P_0 is the initial vehicle tank pressure measured during fueling startup; and

$t_{station\ fallback}$ is the main fueling time at the fallback point

The protocol allows a fallback APRR calculation procedure only once and does not allow roll back to the original ramp rate if the pre-cooling temperature later reaches a value consistent with the station type.

2.1.1.2.2 Fueling process control:

The station controls the pressure at the dispenser to maintain the desired pressure ramp rate. The resulting pressure ramp rate is expected to fall within an allowed range, defined by the initial pressure, target pressure and fueling time elapsed. If the dispenser-pressure ramp rate falls outside the expected range after the first 5 seconds of fueling, the fueling event is aborted.

The fueling continues at a constant APRR. In the case of non-communication fueling or communication fueling with an initial pressure greater than 5MPa, the main fueling phase ends upon reaching the target pressure calculated during the startup phase. For communication fueling with initial vehicle pressure between 0.5 and 5 MPa, and an ambient temperature greater than 0^oC, fueling is carried out in two phases. An APRR consistent with non-communications fueling is used until a target pressure is reached, and then fueling continues (to gain a higher state of charge) at lower top-off pressure ramp rate until the top-off target pressure is reached.

2.1.1.3 Fueling termination

Termination starts when the target pressure at the dispenser is reached, or any of the fueling parameter safety limits have been exceeded. The parameter safety limits include vehicle tank pressure and temperature, and dispenser target pressure. Termination is also forced when the station cannot meet fueling goals (e.g., the station may not have enough storage to maintain the desired pressure ramp rate at the dispenser).

2.2 Fueling using SAE J2601 MC formula method:

The MC method is an analytical method that uses thermodynamic properties of the FCEV tank to dynamically determine the APRR that controls fueling speed. The MC formula method [5, 27, 28] or MC default fill method [4] is a version of Honda's MC method [19, 20, 26], which is aligned to the boundary conditions of the SAE J2601 protocol. The MC formula method has been verified by simulation model [6] results and confirmed by testing. Although the MC formula method uses the same set of empirical equations to calculate the APRR for both communication and non-communication fueling, it uses separate set of parameters to determine the target end pressures for both communications and non-communications fueling.

The MC formula method does not divide fueling stations into categories based on their precooling temperatures; instead, it employs an adaptive dynamic control strategy by which it varies the APRR in accordance with the measured temperature at dispenser outlet. Unlike the lookup table method, the MC formula method uses the same approach (implying same APRR under same conditions for communications and non-communications fueling) for calculating the APRR over the entire precooling window of -17.5^{O}C to -40^{O}C for a given vehicle tank capacity, and ambient temperature. The MC formula method [4, 5, 27, 28] uses a set of formulae along with empirical coefficients, which are determined by the initial vehicle tank pressure, ambient temperature and tank capacity to calculate the pressure ramp rate at any given time during the fueling event. The same boundary conditions, and vehicle tank capacities and properties of the lookup table method are used in developing the empirical formulae used in MC formula method.

2.2.1 SAE J2601 MC formula method details:

2.2.1.1 Startup phase:

The startup phase of the MC formula method is the same as that of the lookup table method including measurement of the vehicle tank initial pressure and volume, and the station ambient temperature. However, unlike the lookup table method, which uses fixed control parameters, the MC formula method dynamically calculates and adjusts the fueling control parameters throughout the fill based on active measurements of precooling temperature and mass flow rate.

2.2.1.2 Main fueling phase

2.2.1.2.1 Pre-cooling temperature

The MC formula method actively measures and uses the pre-cooling temperature at the dispenser to calculate the mass average temperature (MAT) and the mass average enthalpy of hydrogen at the dispenser, which is further used to decide the APRR and target pressure during the fueling. The MC formula method allows 30 seconds before using the pre-cooling temperature to actively control the fueling. During the initial 30 seconds, the APRR and target pressure are calculated using an expected MAT (-36^{o}C for 70 MPa fueling) which is consistent with the stations' refrigeration unit capacity to control the process (i.e., independent of the actual precooling temperature in the first 30 seconds). Thirty seconds into the fueling, the MC formula method uses a calculated MAT [4, 5, 28] based on actual measured precooling temperature, starting from the end of the 30th second (MAT30) to control the process. Later upon reaching a preset transition pressure (e.g., 50 MPa for a 70 MPa fueling), the MC formula method uses a weighted average MAT based on the actual precooling temperature measured at the start of the fueling phase (MAT0) and MAT30 to control the fueling. In summary, the MC formula method uses three MATs to control the fueling in different phases, $MAT_{expected}$ for the first 30 seconds of the fueling, MAT30 beyond the first 30 seconds until the transition pressure is reached, and transitional weighted average [4, 5] of MAT0 and MAT30 until the end of the fueling after the dispenser, pressure equals the preset transition pressure. The mass average temperature and average enthalpy (*h*) are calculated using the following equations, where i is the time step and *m* and *T* are readings of the mass flow rate sensor and the pre-cooled hydrogen temperature sensor, respectively:

$$MAT_{(i)} = \frac{\sum_1^i (m_{(i)} - m_{(i-1)}) \times 0.5 (T_{(i)} + T_{(i-1)})}{\sum_1^i (m_{(i)} - m_{(i-1)})} \quad (2)$$

$$h_{ave(i)} = \frac{\sum_1^i (m_{(i)} - m_{(i-1)}) \times 0.5 (h_{(i)} + h_{(i-1)})}{\sum_1^i (m_{(i)} - m_{(i-1)})} \quad (3)$$

2.2.1.2.2 Fueling process control:

The fueling process is controlled by two parameters: APRR and target pressure. The APRR is calculated based on the mass flow rate and pre-cooling temperature measured at the dispenser. As stated earlier, the MC formula method measures the actual pre-cooling temperature at the dispenser and calculates the time, t_{final}, defined as the total time taken to fill the vehicle tank from a minimum pressure to a maximum pressure. If the actual pre-cooling temperature stays constant at -33$^{\text{O}}$C during the main fueling phase, the ramp rate calculated would be the same as the value provided in the corresponding lookup tables.

The t_{final} is dynamically calculated using MAT0 or MAT30 (depending on the dispenser and main fueling time) to define the MATC in the following formula:

$$t_{final\,(T_{amb})} = a_{(T_{amb})} \times MATC^3 + b_{(T_{amb})} \times MATC^2 + c_{(T_{amb})} \times MATC + d_{(T_{amb})} \quad (4)$$

Where,

a, b, c and d are coefficients defined in tables (or "maps" e.g. as shown in Figure 2) for combinations of HFCEV tanks sizes (2, 4, 7, and 10 kg), initial tank pressures (≥5MPa and <5MPa) and ambient temperatures (T_{amb}). The values of the coefficients are selected from different tables (e.g., from 4 and 7 kg for a vehicle tank capacity of 5 kg) and are linearly interpolated to calculate the coefficients for a specific tank size and ambient temperature.

		t_{final} formula coefficients			
		a	b	c	d
Ambient Temperature, T_{amb}[°C]	50	0.940495	-677.562	162773.99	-13038656.4
	45	0.041616	-28.224	6406.944	-486772.772
	40	0.000857	0.670	-436.366	54608.289
	35	-0.001205	2.096	-767.206	80352.877
	30	0.000443	0.614	-347.657	42214.769
	25	0.002606	-1.165	127.143	755.724
	20	0.001359	-0.366	-44.804	13224.692
	15	0.003471	-2.034	389.029	-24028.418
	10	0.004391	-2.796	594.358	-42132.709
	5	-0.007808	6.282	-1661.040	144902.046
	0	0.004085	-2.780	636.372	-48976.220
	-10	-0.000877	0.956	-302.221	29691.844
	-20	0.000562	-0.160	-15.167	5153.359
	-30	0.000591	-0.199	-1.922	3825.408
	-40	0.000634	-0.240	9.623	2816.027

Figure 2: Example of the table of coefficients used to calculate the t_{final} for 4kg tank, and initial vehicle tank pressure greater than 5MPa [28].

The MATC is the mass average temperature used to control the fueling process, defined by the calculated fueling time and the dispenser pressure.

When current fill duration, t(i) ≤ 30 seconds,

$$MATC(\mathrm{i}) = MAT_{\mathrm{expected}} \quad (5)$$

When current fill duration, t(i) ≥ 30 seconds, and current control pressure at dispenser $P_{\mathrm{Control(i)}} \leq P_{\mathrm{trans}}$

$$MATC(\mathrm{i}) = MAT30(\mathrm{i}) \quad (6)$$

When current fill duration, t(i) ≥ 30 seconds, and current control pressure at dispenser $P_{\mathrm{Control(i)}} > P_{\mathrm{trans}}$

$$MATC_{(\mathrm{i})} = MAT30_{(\mathrm{i})}\left(\frac{P_{final}-P_{control(\mathrm{i})}}{P_{final}-P_{trans}}\right) + MAT0_{(\mathrm{i})}\left(1-\frac{P_{final}-P_{control(\mathrm{i})}}{P_{final}-P_{trans}}\right) \quad (7)$$

The pressure ramp rate (PRR) is then calculated by using the equation below where *i* is the current time step.

$$PRR_{(\mathrm{i})} = \frac{P_{final}-P_{control(\mathrm{i})}}{t_{final}\left(\frac{P_{final}-P_{initial}}{P_{final}-P_{min}}\right)-t_{(\mathrm{i})}} \quad (8)$$

$$P_{(\mathrm{i+1})} = P_{(\mathrm{i})} + PRR_{(\mathrm{i})} \times (t_{(\mathrm{i+1})} - t_{(\mathrm{i})}) \quad (9)$$

where,

P_{final}, is the maximum dispenser fueling pressure, typically 83.5MPa for 70 MPa fueling;

P_{initial}, is the initial vehicle tank pressure measured at the beginning of the fill;

P_{min}, is the minimum pressure used to calculate pressure ramp rate (assumes the value of 0.5 for $P_{\mathrm{initial}} < 5$ MPa and 5 for $P_{\mathrm{initial}} \geq 5$ MPa);

$P_{\mathrm{Control(i)}}$, is the current control pressure at the dispenser;

P_{trans}, is the transition pressure, typically 50MPa for 70MPa fueling;

$P_{(\mathrm{i})}$, is the current pressure at the dispenser;

$P_{(\mathrm{i+1})}$, is the target control pressure at the dispenser for the next time step;

$t_{(\mathrm{i})}$, is the current fill duration time step; and

$t_{(\mathrm{i+1})}$, is the next fill duration time step.

2.2.1.2.3 Target pressure control:

The MC formula method calculates the final temperature T_{final} using equation 10 and 11. The adiabatic internal energy $U_{\mathrm{adiabatic}}$ in equation 11 is calculated by using equation 12. The mass average enthalpy, h_{ave} in equation 12 is a function of the temperature, pressure, mass of the hydrogen at the dispenser as shown in equation 3. The estimated final or end temperature, T_{final} is later used to calculate the target pressure based on the target density. The MC method uses different target densities for communications and non-communication fueling.

$$Final\ End\ Temperature, T_{final} = \frac{m_{cv}C_vT_{adiabatic}+MCT_{initial}}{MC+m_{cv}C_v} \quad (10)$$

Where, MC is a function of fueling conditions and time.

$$MC = A + B\ln\left(\frac{U_{adiabatic}}{U_{initial}}\right)^{1/2} + g\left(1 - e^{-k\Delta t}\right)^{j} \quad (11)$$

$$Adiabatic\ Internal\ Energy, U_{adiabatic} = U_{initial} + m_{add}\ h_{ave} \quad (12)$$

where,

m_{cv}, is the mass in the vehicle tank at the end of the fill;

C_v, is the specific heat capacity of hydrogen at constant volume;

$T_{adiabatic}$, is the adiabatic vehicle tank temperature calculated from the equation of state with pressure and specific internal energy of hydrogen;

$T_{initial}$, is the initial measured or assumed vehicle tank temperature at the start of the fill;

A, B, g, k and j are coefficients defined for 1kg type 3 vehicle tanks at cold case boundary conditions;

$U_{initial}$, is the internal energy of hydrogen (in the vehicle tank) at the start of the fill; and

m_{add}, is the calculated mass to be added to the tank to achieve a 100% state of charge (SOC) fill.

2.2.1.3 Fueling termination:

Similar to the fueling termination criteria in the lookup table method, termination starts when the target pressure at the dispenser is reached or any of the fueling parameters safety limits have been exceeded. The parameter safety limits include vehicle tank pressure and temperature, and dispenser target pressure. Termination is also forced when the station cannot meet fueling goals (e.g., the station may not have enough storage to maintain the desired pressure ramp rate at the dispenser). Table 2 provides a comparison overview of the SAE J2601 lookup table and MC formula methods

Table 2: Comparison overview of the SAE J2601 lookup table and MC formula methods

	Lookup Table	MC Formula
Common Features	Same boundary conditions.	
	Both use information from the station and do not require on information from vehicle to safely complete the fill	
Differences	Assumes the warmest temperature in the pre-cooling temperature window for the given station type to determine the control parameters of the fill	Considers the actual pre-cooling temperature at the dispenser to determine the control parameters of the fill
	Fixed pressure ramp rate based on the initial and boundary conditions.	Fixed pressure ramp rate based on the initial and boundary conditions in the first 30 seconds of the fill; thereafter varying pressure ramp rate based on the actual

		pre-cooling temperature and other conditions.
	The target pressure is determined at the start of the fill based on the initial and boundary conditions and remains constant for the duration of the fill unless there is a fallback.	The target pressure is dynamically calculated throughout the fill based on actual conditions.
	Leak checks add time to the actual fueling time (when fuel flows into the vehicle tank), since APRR is kept constant.	The ramp rate is increased (immediately after the leak checks) to recover most of the time lost during leak checks.
	The fallback procedure for lag in pre-cooling exists only for communication fills.	Fuels the vehicle for any temperatures between -17.5°C and -40°C for both communication and non-communication fills
	Accuracy of the mass flow meter is not critical to the implementation of the lookup table method.	Accuracy of the mass flow is critical to the implementation of the MC formula method.

Both the fueling methods described in Table 2 provide fast fueling of HFCEVS within minutes, but the MC formula method takes advantage of active measurement of the precooling temperature to dynamically control the fueling process, and thereby provides faster vehicle fills with most initial and boundary conditions.

3. Simulation setup

The Hydrogen Station Cost Optimization and Performance Evaluation Model (H2SCOPE), developed by Argonne National Laboratory, was used to simulate the evolution of the vehicle tank parameters and the APRR using various fueling protocols. The validation and verification of the H2SCOPE model is detailed in a previous research paper [16]. The model calculations were verified by ensuring mass and energy balance at the component and system levels. The model results were also validated against published experimental data using vehicle tank geometry and material properties, as well as initial and boundary conditions provided by Immel and Gardner (2011) [30]. The transient vehicle tank temperature and pressure variation predicted by the model were in excellent agreement with the measured values reported by Immel and Gardner [30]. The model was further validated against propriety measured pressure and temperature data for other vehicle tanks, providing additional confidence in the model predictions.

A 129 L type IV [30] tank with a capacity of 5.2 kg of hydrogen at 40.2 kg/m^3 mass density has been used as the HFCEV CHSS. The thermal properties of the HFCEV CHSS used to simulate the performance of the fueling protocols are provided in Table 3. The HFCEV tank is assumed to be at 5 MPa at the start of the fill with no pre-soak, meaning the hydrogen inside is at ambient temperature (assumed to be 25°C) at the beginning of the fill.

Table 3: Vehicle tank thermal properties

Vehicle Tank (Type IV) Thermal Properties		
	Composite layer	**Polyethylene Liner**
Temperature Range	(-100°C to 140°C)	(-100°C to 140°C)
Density (kg/m³)	1550	975
Specific Heat (J/kg-K)	500–1500*	1000–3000*
Thermal Conductivity (W/m-K)	0.3–0.8*	
Thermal Diffusivity (cm²/sec)	0.001– 0.009*	

*The range of properties is consistent with a low and high temperatures of -100°C and 140°C, respectively

The temperature increase from the dispenser breakaway to the vehicle receptacle has been modelled and used to estimate the vehicle tank parameters. Figure 3 shows the components between the dispenser breakaway and the vehicle tank. Figure 4 shows the temperature increase from the dispenser breakaway to the vehicle receptacle, for T40 fill of a 5 kg tank at 25°C ambient. The H2SCOPE model fill duration results for both the lookup table method and MC formula based methods have been verified. The constant ramp rate, and end pressure from the lookup table, along with leak check duration has been used to calculate the total fill duration; the MC formula method fill duration has been verified using the MC Default fill fueling time calculator version 1.12 [31]. All the time duration results from the H2SCOPE model are within 3% of the estimates from the MC Default fill fueling time calculator [31] for all boundary conditions.

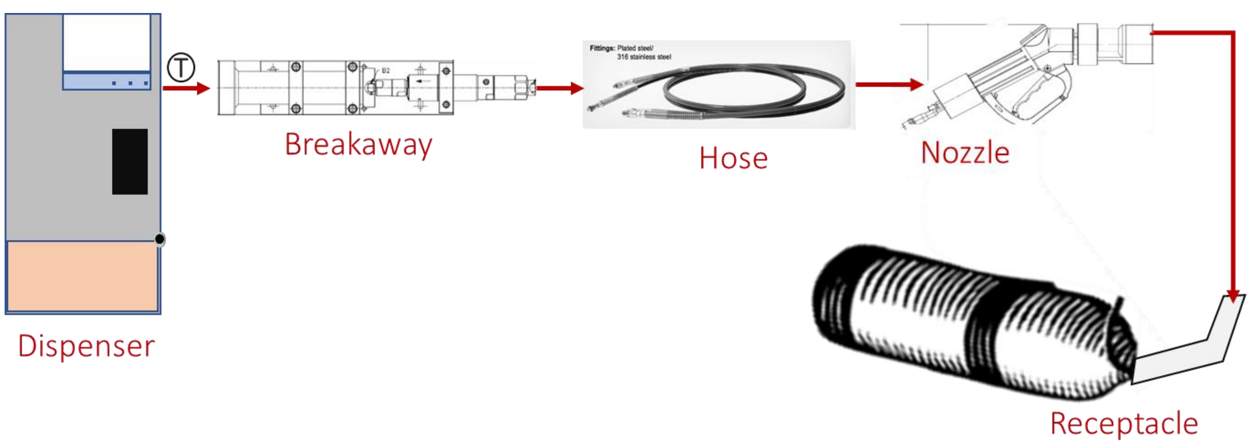

Figure 3: Schematic of the components between the dispenser breakaway and vehicle tank

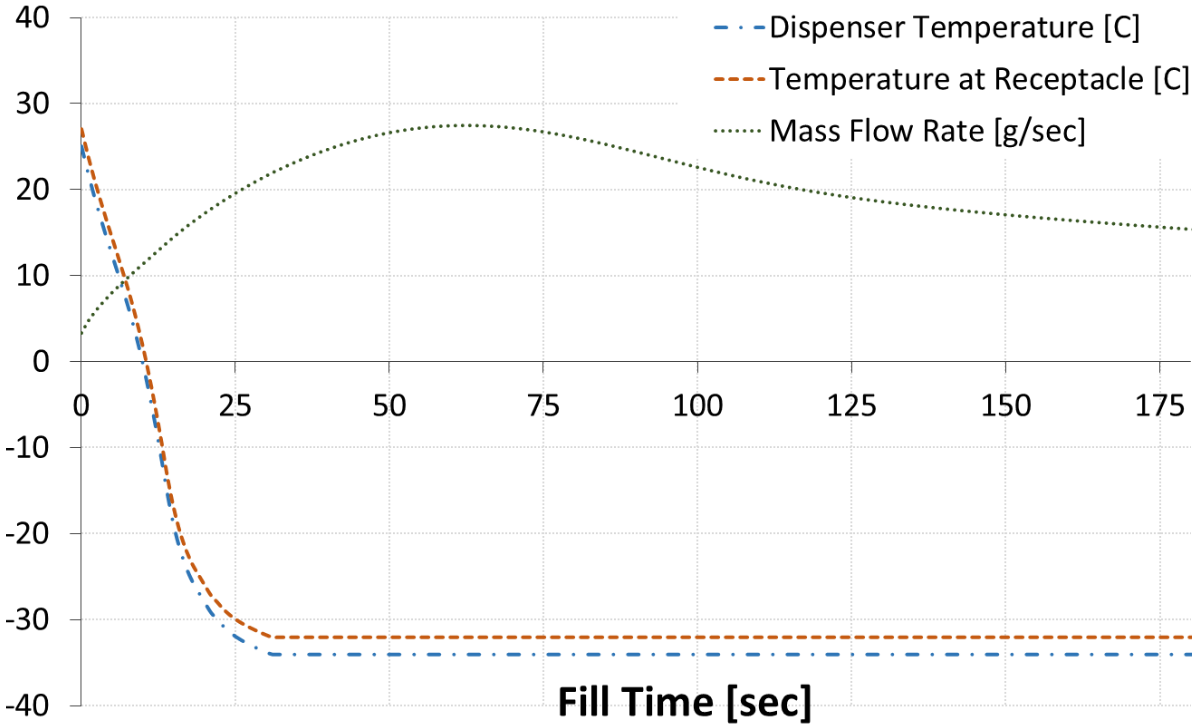

Figure 4: Example of the temperature rise estimated from the dispenser outlet to the vehicle tank from ambient temperature

4. Results

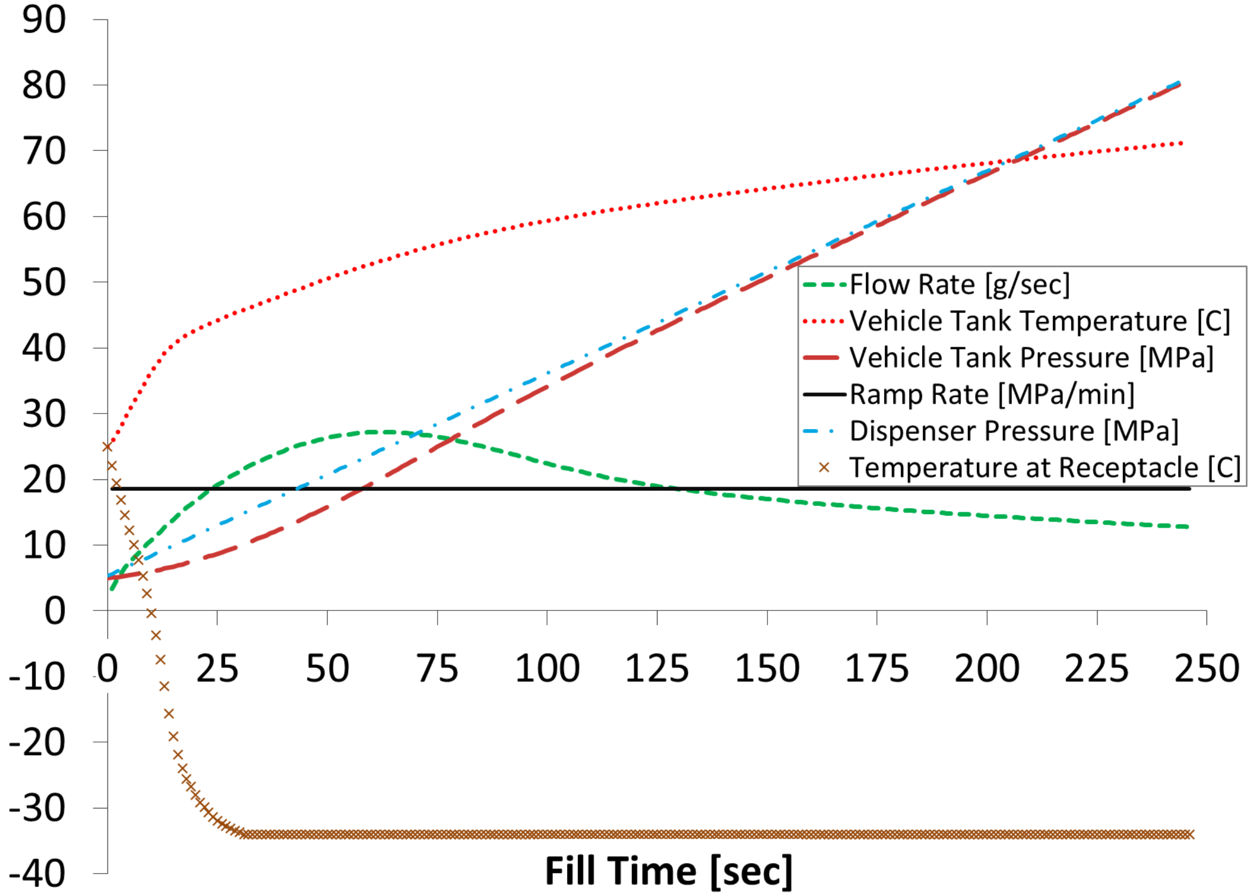

Figure 5: Vehicle and station parameters during a communication fill using lookup table method

Figures 5 and 6 show the typical fueling parameters during a fueling event, using lookup table and MC formula fueling protocol methods, respectively, using an H70 dispenser at a T40 refueling station. The precooling temperature and pressure ramp rate (at dispenser) are the boundary conditions used to determine the fueling parameters while the flow rate, vehicle tank temperature and pressure are calculated based on the fueling parameters. During the initial portion of fueling, the pressure drop between the dispenser and vehicle tank increases so does the flowrate. In the later portion of fueling, the pressure difference between the dispenser and the vehicle tank decreases and the flowrate follows the same trend.

In the fills modeled in Figures 5 and 6, the lookup table method (Figure 5) maintains a constant APRR of 18.5 MPa/min throughout the fill event while the MC formula method (Figure 6) changes the APRR by adapting to the dispenser temperature as the fueling progresses. The MC formula method applies an APRR of 26 MPa/min during the initial 30 second, after which the APRR is adjusted to 22MPa/min consistent with the pre-cooling temperature, which is assumed to remain constant, ensuing an almost constant APRR until a preset transition pressure is reached. Upon reaching the transition pressure of 50MPa at the dispenser, the APRR is reduced gradually (based on the precooling temperature in the first 30 seconds) until the target pressure is reached. Note that the fueling time in Figures 5 and 6 does not include the additional time for leak checks, which will be higher with the lookup table method than with the MC formula method as mentioned in Table 2. The impact of leak checks on the total refueling time is apparent in Figures 8, 9 and 11 below. In simulating the refueling events with lookup table and MC formula methods, leak checks were assumed to be 10 seconds for every 20 MPa pressure increase at the dispenser. The time for each leak check varies in real refueling events.

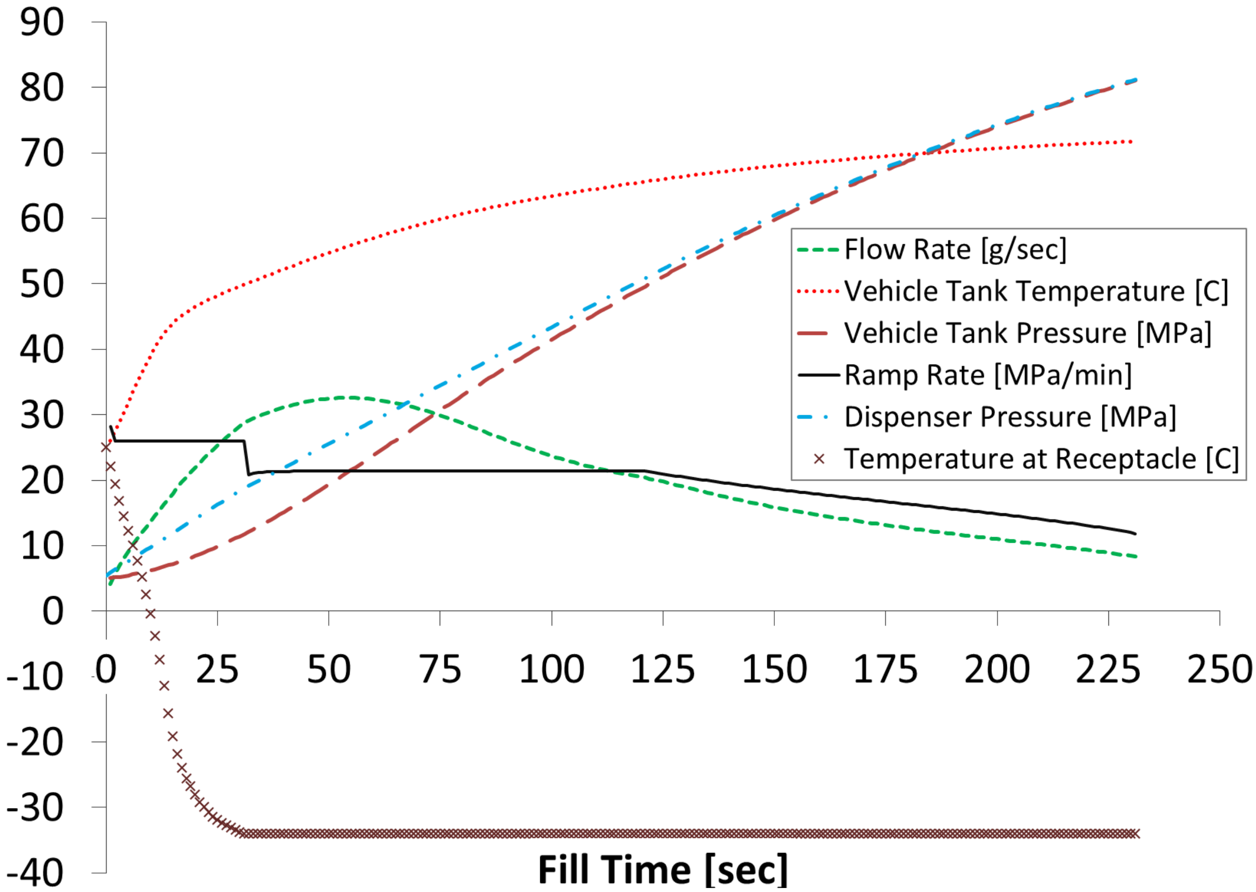

Figure 6: Vehicle and station parameters during a communication fill using MC formula method

The pre-cooling temperature measured at the dispenser plays an important role in determining the APRR, and thus the total fueling time. The lookup table method and the MC formula method utilize the pre-cooling temperature differently during fueling. While the lookup table method assumes a constant pre-cooling temperature based on the station type, the MC formula method uses measurements of pre-cooling temperature throughout the fill to dynamically control the speed of fueling by repeatedly calculating and adjusting the APRR and target pressure. In this context, it is important to consider the time-dependent pre-cooling profile while comparing the performance of the two methods. Figure 7 shows the different pre-cooling profiles used to assess the performance of the two SAE J2601 fueling methods. Each pre-cooling curve starts at an ambient temperature of 25°C, reaches a set temperature at the end of the initial 30 seconds of the fill event, and stays constant for the rest of the fill duration. The temperatures selected, as shown in Figure 7, represent the precooling temperature ranges possible for T40, T30 and T20 station types.

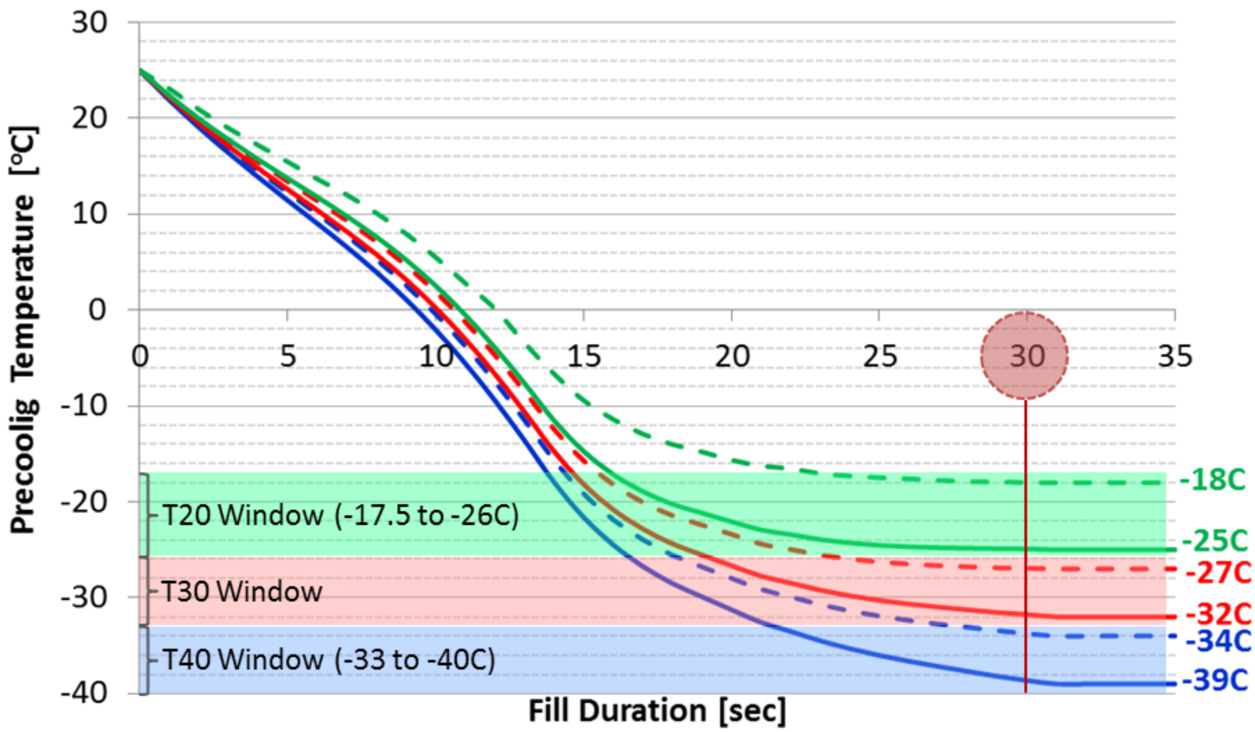

Figure 7: The precooling temperature profiles used for simulations of fueling events with lookup table and MC formula methods

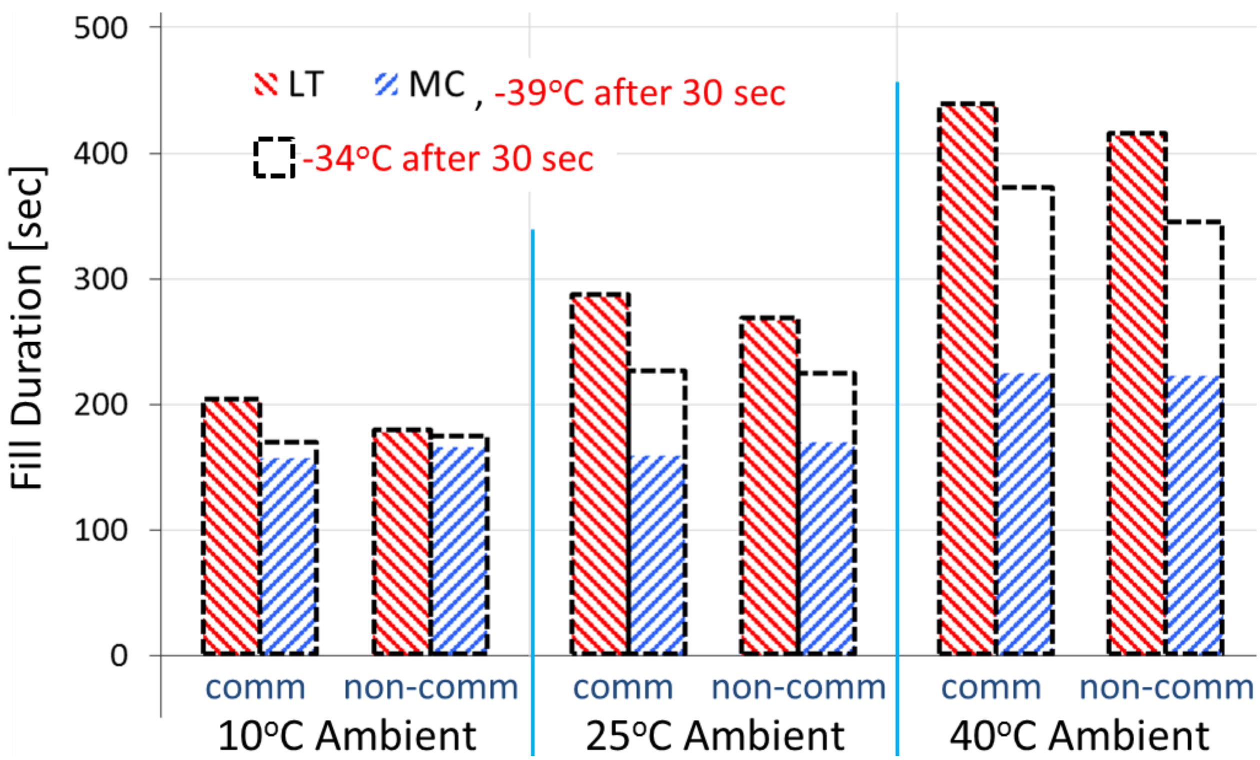

Figure 8: Performance of the lookup table and MC formula method at different ambient temperatures

Figure 8 shows the performance of the two SAE J2601 fueling methods for a T40 Station at different ambient temperatures, with communication (comm) and non-communication (non-comm) fills. Two temperature profiles one at the warmer side (-34°C) of the T40 station precooling temperature window and the other at the colder side (-39°C) of the window have been considered to study the performance of the SAE J2601 fueling methods. The hatched bars represent the total fueling time at the colder temperature and the dashed columns represent the total fueling time at the warmer temperature of the window. It can be seen that MC formula method (MC) provides faster fills compared to the lookup table method (LT), especially at the colder precooling temperature within a station type window, as well as at higher ambient temperatures. Significant reduction in fueling time has been observed during actual vehicle fills with MC formula method compared to lookup table method [28]. Although both methods of the SAE J2601 adopt the same APRR calculation for communication and non-communication fueling, the communication fills usually take longer time to provide higher state of charge at the end of the fill. While non-communication fills are more conservative [29], resulting in a lower SOC at the end of the fill, communication fills calculate higher target pressures, thus allowing a higher state of charge at the end of the fill. Figure 8 shows the filling durations at ambient temperature of 25°C for the two extreme cold and warm precooling inlet temperatures with different station designs (i.e., T40, T30 and T20). For intermediate precooling inlet temperatures, the filling time can be approximated through linear interpolation between the two extreme fill durations.

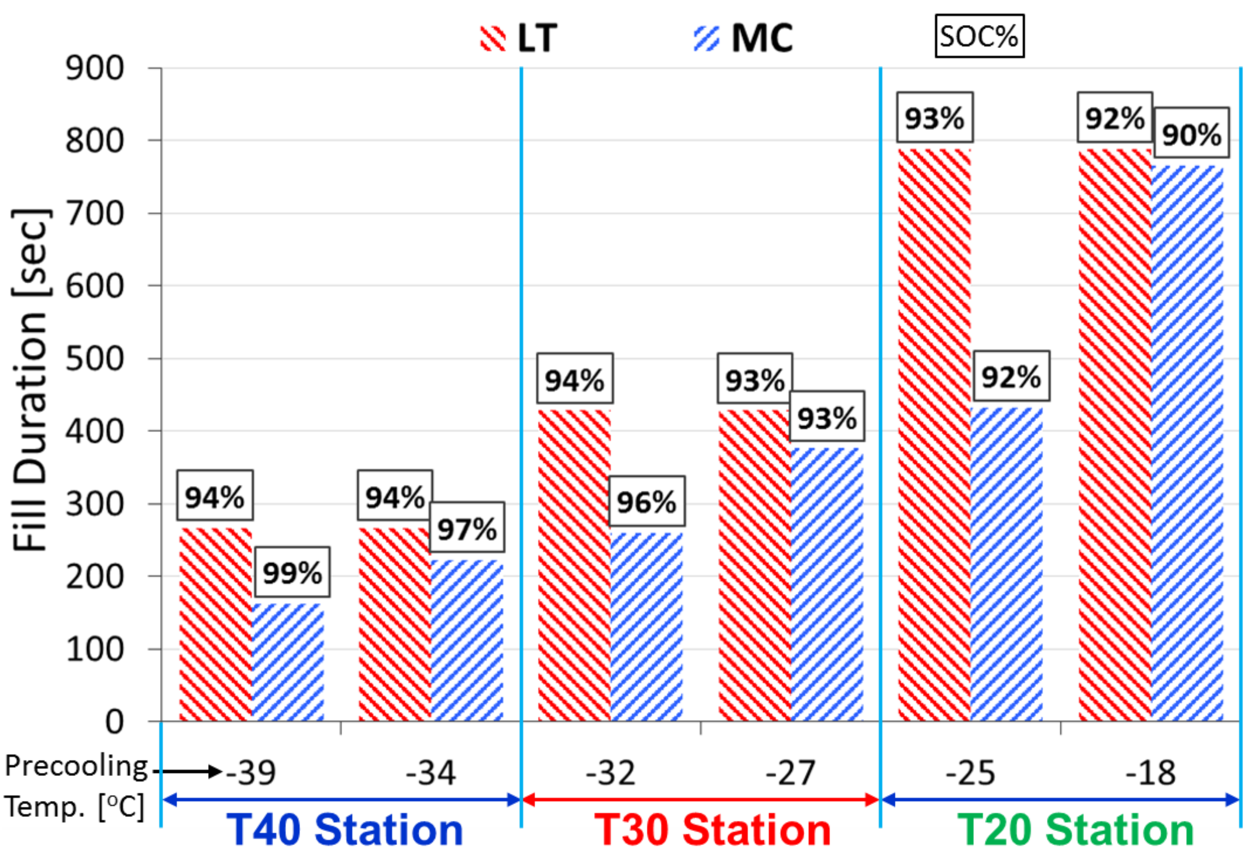

Figure 9: Performance of lookup table (LT) and MC formula (MC) methods at different pre-cooling temperatures and 25°C ambient temperature with non-communication fill (vehicle tank state of charge is shown at the top of each bar)

Since the lookup table method maintains an APRR at a constant value (irrespective of the pre-cooling temperature within the temperature window for the station type), the APRR in the lookup tables is conservatively estimated based on the worst case (i.e., the warmest temperature within the station type window). This explains why the lookup table method results in the same fueling time for both colder and warmer temperatures in each station type's window of acceptable pre-cooling temperatures (Figure 8 & 9). The MC formula method actively controls the fueling speed by adjusting the APRR (based on the measured pre-cooling temperature). Fills performed by the MC method can therefore take advantage of colder pre-cooling temperatures within each station type's pre-cooling temperature window. The MC formula method provides significantly faster fills at colder temperatures compared to warmer temperatures within a given precooling temperature window (see Figure 8 & 9), and compared to the lookup table method. Figure 8 shows that the savings in time via the MC method as opposed to the lookup table method are greater at higher ambient temperatures for all station types, as observed during actual vehicle fueling [28].

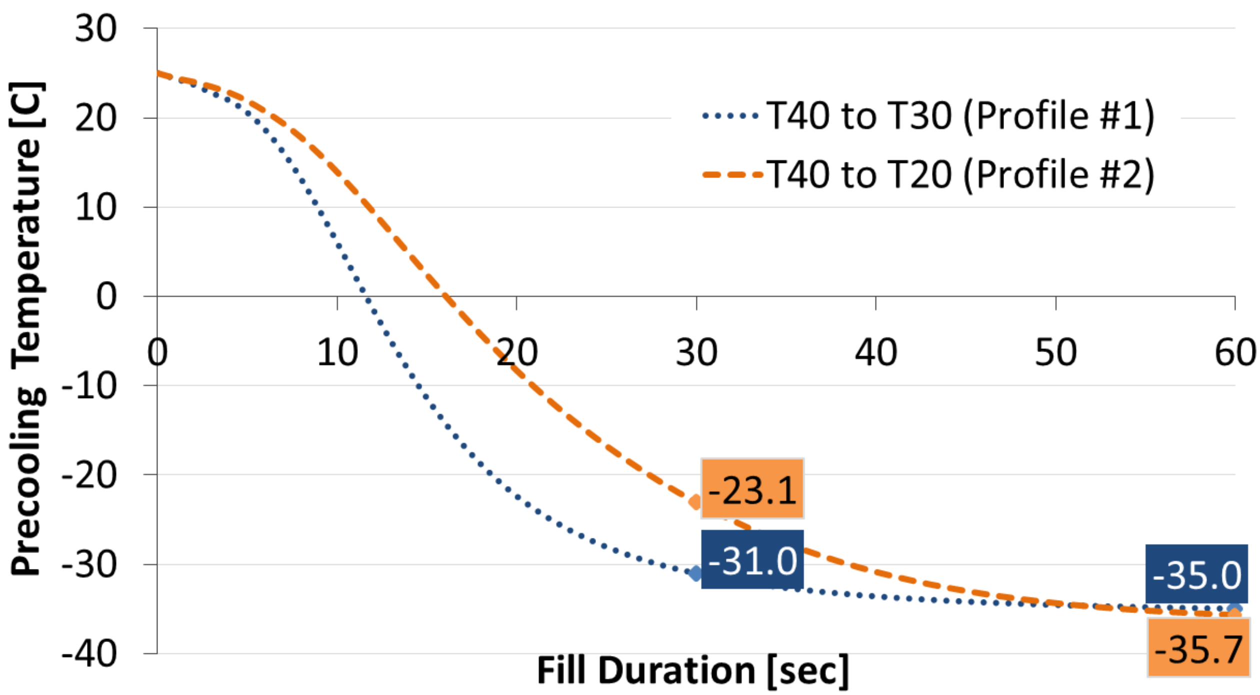

Figure 10: The pre-cooling profiles used to demonstrate the fallback procedure of lookup method

As stated earlier, the lookup table method requires the station to reach the required pre-cooling temperatures consistent with the station type within 30 seconds of the start of fueling. If the station pre-cooling temperature (as measured at the end of 30 seconds after the start of fueling, or thereafter) is warmer than the upper limit of the station type temperature window, the fueling is terminated for non-communication fueling, or forced to a fallback APRR for communication fueling [4]. To illustrate the impact of not achieving the required pre-cooling temperatures within the 30-second window, the two pre-cooling temperature profiles shown in Figure 10 have been examined. Both temperature profiles start at an ambient temperature of 25^{O}C and reach the target T40 station type pre-cooling temperature range at different times during the fueling. Such profiles may occur due to an undersized pre-cooling unit, a drop in performance of the refrigeration unit overtime, or unusually high ambient temperatures.

Figure 11 shows the total fueling time for the two precooling temperature profiles of Figure 10 for communication and non-communication fills, for the two fueling methods. For communication fill, since the required pre-cooling temperature for a T40 fill is not reached in 30 seconds in the profiles being simulated, the lookups table method will fallback to APRRs based on higher temperature station types. For communication fill, pre-cooling temperature profile #1 will result in APRR fallback to FPRR (see equation 1) based on a target pressure and APRR from the T30 station type lookup tables. A communication fill with the pre-cooling temperature profile #2 will use a fallback APRR calculated from the T20 station type lookup tables. As mentioned earlier, the MC formula method controls the fueling process dynamically (by adjusting APRR with MAT, i.e., without a need for a non-reversible fallback in APRR), thus resulting in significantly faster fill (see Figure 11). In addition to allowing faster fills, the MC method enables fills to occur where the lookup table would abort fills. For non-communications fill, the lookup table method terminates the fueling event if the precooling temperature is warmer than the upper limit of the station type temperature window (at the end of 30 seconds or thereafter), while the MC formula method fills the vehicle as long as the precooling temperature does not exceed -17.5°C as measured at the end of 30 seconds or afterwards.

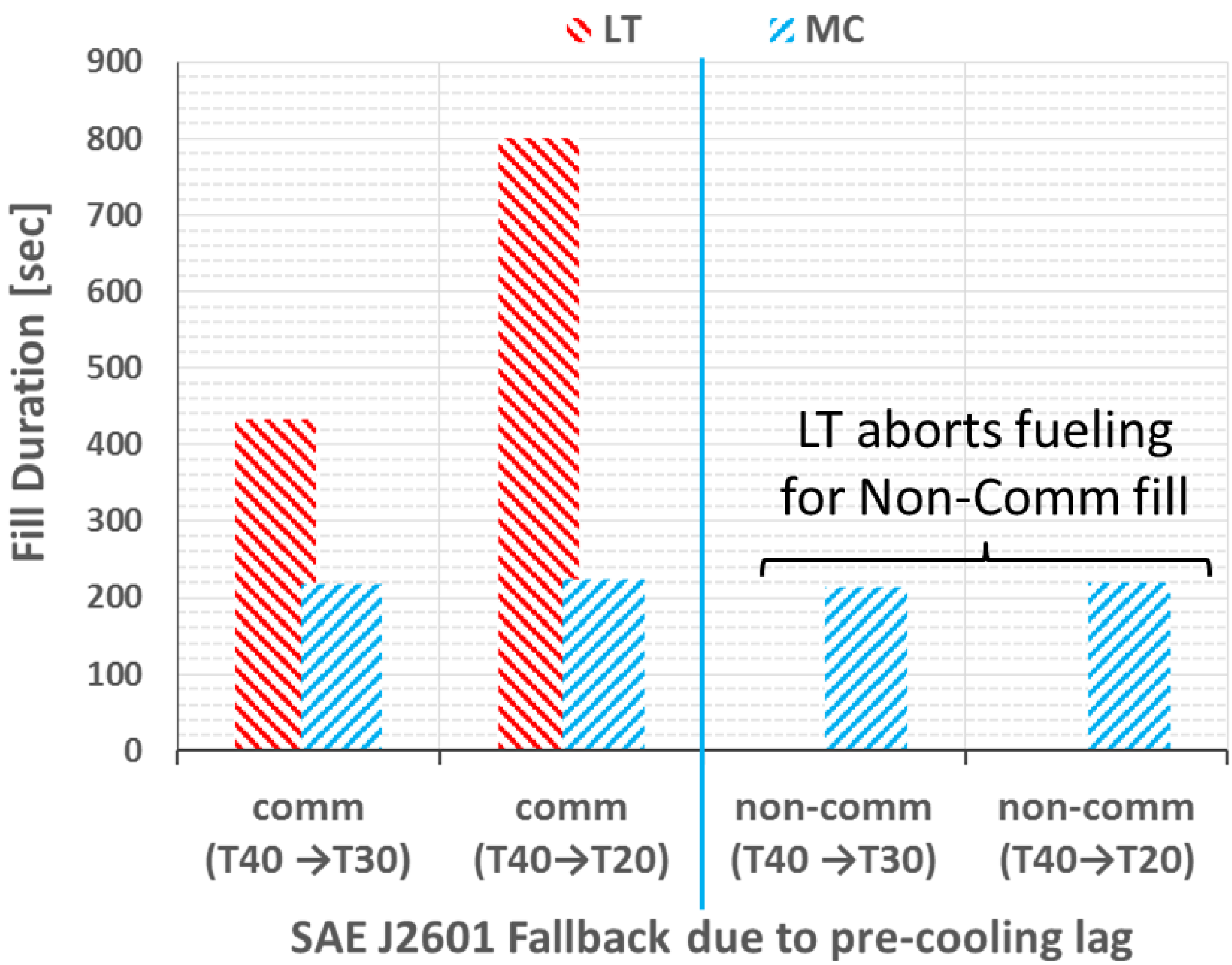

Figure 11: Performance of the lookup table (LT) method and MC formula (MC) method performance with pre-cooling curves shown in figure 7

5. Conclusions

This study evaluated the fueling performance of the lookup table fueling method and the MC formula fueling method from the SAE J2601 fueling protocol, with respect to fueling time of light-duty HFCEVs. The MC formula method embeds many of the features in the lookup table method, but relaxes some of its limitations, thus providing a more efficient fueling method to improve the vehicle's fueling time. The MC formula method actively controls the fueling speed by adjusting the average pressure ramp rate at the dispenser based on the measured pre-cooling temperature, thus taking advantage of precooling temperatures at the colder end of a given dispenser's temperature window to provide a faster fill. The MC formula method provides significantly faster fills than the lookup table method when the precooling temperature is at the colder end of a given dispenser's acceptable precooling temperature range, and at higher ambient conditions for all station types. While the SAE J2601 protocol includes both lookup table method and MC formula method, the MC formula method allows for significantly faster fills, and its implementation in future hydrogen refueling stations is warranted for better customer satisfaction with fueling of HFCEVs.

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