

SAE J2601- Worldwide Hydrogen Fueling Protocol: Status, Standardization & Implementation

Jesse Schneider,
SAE Fuel Cell Interface Group Chair

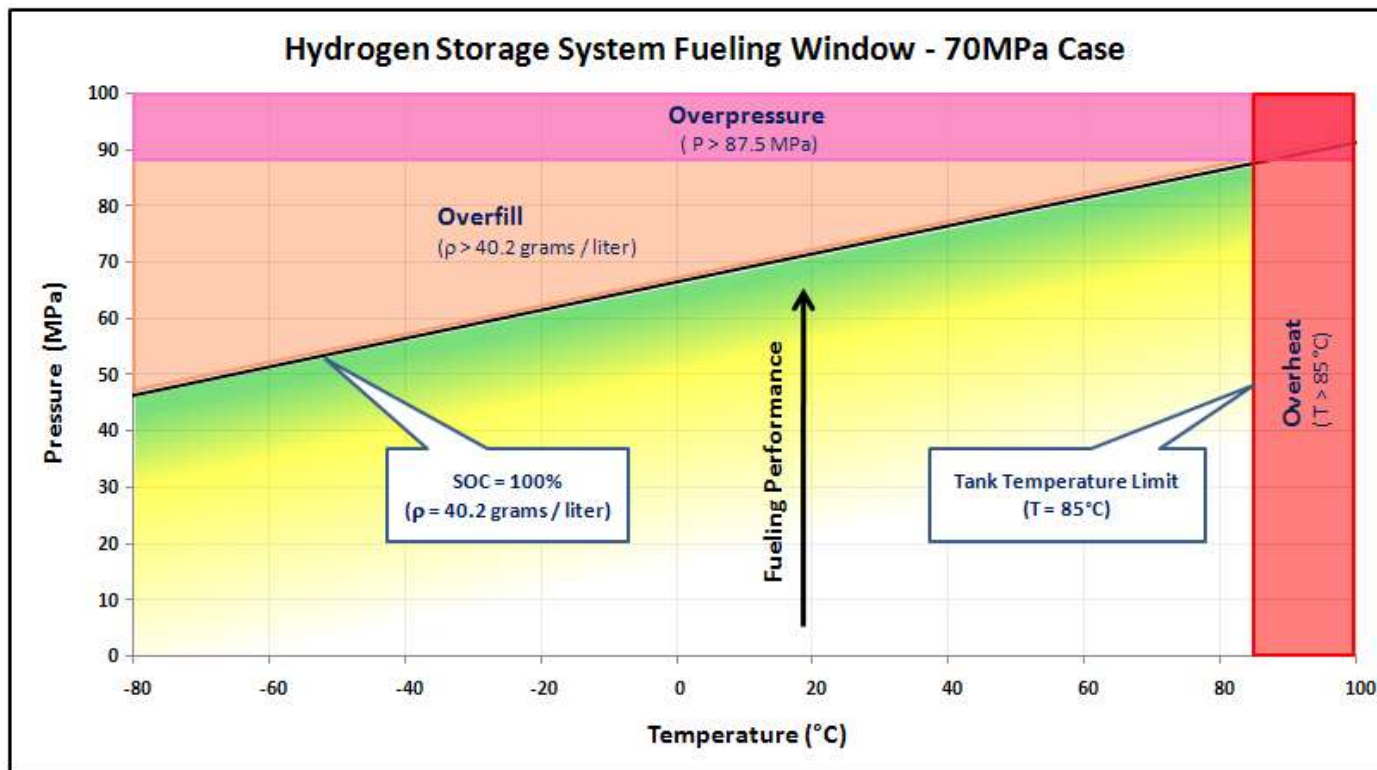
Presentation Outline

- ▶ What is J2601?
- ▶ In-field TIR J2601 Experience
- ▶ SAE J2601 Standard Overview
- ▶ Data Confirmation Plan

Fueling Fundamentals

An optimal fueling protocol will ...

- ▶ fuel all hydrogen storage systems quickly to a high state of charge (SOC)
- ▶ never violate the storage system operating limits of 85°C internal tank temperature (don't overheat) or 100% SOC (don't overfill)



What is SAE J2601?

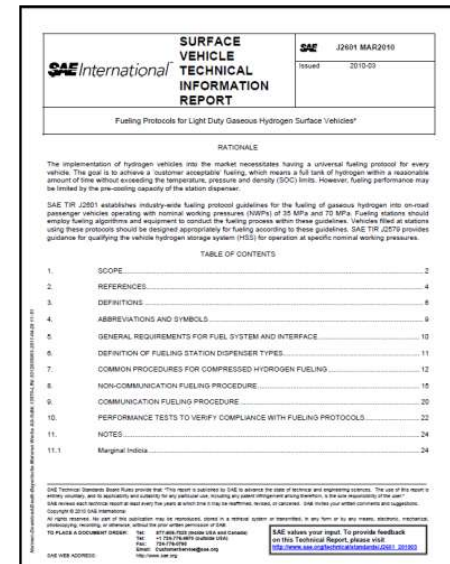
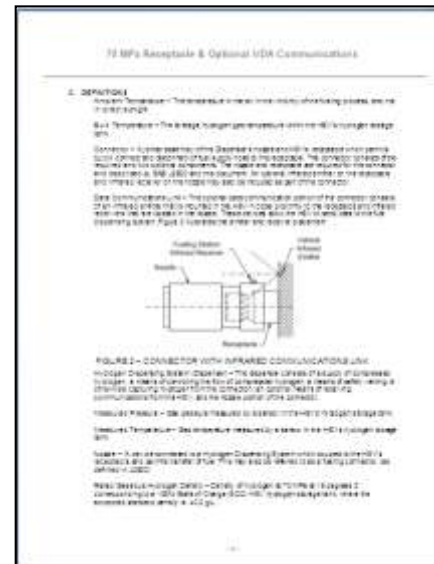
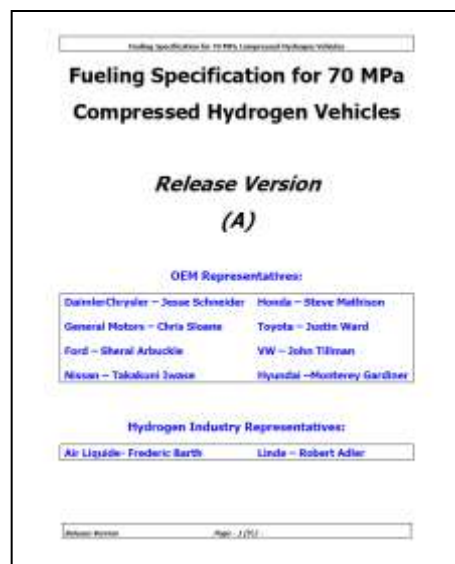
Hydrogen Fueling Protocol History and Path Forward

CaFCP I/O Guideline
2002

OEM Fueling „Rev A“
2007

SAE J2799 „70MPa
Coupling & IrDA“
2007

SAE TIR „L.D. H2
Fueling“ Guideline
2010



SAE J2601 Light Duty H2 Fueling
and Communications Standard
2013

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J2601 Fueling and Intellectual Property

- ▶ Prior Art existed on hydrogen fueling with communications and density targeted fueling, for example. This was documented in an NHA paper “Optimizing Hydrogen Vehicle Fueling” in 2005 from Daimler/Ford/GM/Honda/Hyundai/Toyota/Linde/Hydrogenics/HCI/ GTI/ NAC (J. Schneider, F. Lynch, J. Ward, S. Mathison, et al)
- ▶ The *table-based* approach utilized in SAE TIR J2601 uses “Look up tables which stop the fueling at a set target pressure (for non- and with communications). This is ***not*** patentable as it originated from TIR J2601 document in 2010.



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J2601-Editions & Timeline

- ▶ J2601 Light Duty Vehicle Fueling Protocols, Communications Currently Released (TIR) Guideline/ 2013 Standard
- ▶ J2601-2 (HD) hydrogen vehicle fueling guideline for 350 bar bus and heavy duty vehicles (>10kg): 2013 Guideline
- ▶ J2601-3 (FL) hydrogen vehicle fueling standard for 250 and 350 bar forklifts with small fuel tanks : 2013 Standard
 - J2601 Chair: Jesse.Schneider@bmw.de
 - J2601-2 Sponsor: NBouwkamp@cafcp.org
 - J2601-3 Sponsor: Boyd.Hydrogen@gmail.com

SAE TIR J2601

Light Duty

J2601 LD Fueling Protocol

Technical Goals for Compressed Hydrogen Fueling

- [Maintain the safety limits of storage system.](#)
 - Max. Temperature: 85° C / Max. Pressure: 87.5 MPa (70 MPa NWP)
- [Achieve target desired customer attributes.](#)
 - [Fueling Time:](#) 3-5 minutes Ramp Rate (Type A Station, longer for other types)
 - [Typical State of Charge Range :](#) 90% to 100% (density based on NWP at 15° C)

Options for Compressed Hydrogen Fueling Protocol

- Vehicle to station interface strategies
 - [Communication:](#) vehicle transmits tank parameters through wireless interface
 - [Non-communication:](#) vehicle provides tank pressure only
- Station key control factors
 - [Pre-cooling of hydrogen:](#) station conditions H₂ temperature prior to dispensing
 - [Hydrogen delivery rate:](#) station provides fill rate per mass or pressure vs. time
 - [Fill termination:](#) station determines end pressure and/or density that meets goals

SAE TIR J2601 LD Summary

After 8 years, the [guideline](#) TIR J2601 was released in March 2010

What is SAE TIR J2601?

- ▶ First World-Wide Light Duty Hydrogen Vehicle Fueling Protocol 35 & 70MPa: [Created by Math Modeling, Confirmed by Real OEM System Testing](#)

What does it cover?

- ▶ [Light Duty Hydrogen Vehicle Fueling](#) (1-10kg@70MPa, 1-7kg@35MPa)
Dispenser Protocol for with & without communications
- ▶ Defines Safety Limits and Performance Targets.
- ▶ Table-Based Approach
- ▶ Enables “Same as Today” fueling, [< 300 mile range in 3 minutes fueling time](#) with Type ‘A’ Dispenser, < 7 kg hydrogen

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LD Fueling Dispenser Types

TIR J2601 defines fueling station dispenser type by capability to dispense hydrogen fuel at a specific nozzle “pre-cooled temperature”. Note: There is a direct relation between pre-cooling and fueling speed.

- Type “A”- Dispenser has -40 ° C pre-cooling (70 & 35 MPa)
- Type “B”- Dispenser has -20 ° C pre-cooling (70 & 35 MPa)
- Type “C”- Dispenser has 0 ° C pre-cooling (35 MPa only)
- Type “D”- Dispenser has **no** pre-cooling (35 MPa only)

J2601 Fueling Tables: 70MPa with $\leq 7\text{kg}$ Storage Capacity*

Type A (-40°C)

Type B (-20°C)

Estimated Fueling Time
In Minutes

A-70 1-7kg		Actual Fueling Duration (min)											
		Add Intermediate leak check times: up to 10 sec after every 20MPa increase in fueling pressure											
		Initial Tank Pressure, P_0 (MPa)											
Ambient Temperature, T_{amb} (°C)		2	5	10	15	20	30	40	50	60	70	> 70	
		> 50	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling
		50	6	6	6	5	4	3	2	1	0	no fueling	no fueling
		45	5	4	4	4	3	3	2	1	0	no fueling	no fueling
		40	4	3	3	3	3	2	2	1	0	no fueling	no fueling
		35	3	3	3	2	2	2	1	1	0	no fueling	no fueling
		30	3	3	2	2	2	2	1	1	0	no fueling	no fueling
		25	3	2	2	2	2	1	1	1	0	no fueling	no fueling
		20	3	2	2	2	2	1	1	1	0	no fueling	no fueling
		10	2	2	2	2	2	1	1	1	0	no fueling	no fueling
		0	2	2	2	2	2	1	1	1	0	no fueling	no fueling
		-10	2	2	2	2	2	1	1	1	0	no fueling	no fueling
		-20	2	2	2	2	2	1	1	1	0	no fueling	no fueling
		-30	2	2	2	2	2	1	1	1	0	no fueling	no fueling
		-40	2	2	2	2	2	1	1	1	0	no fueling	no fueling
		< -40	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling

Typical
3 Min.

B-70 1-7kg		Actual Fueling Duration (min)											
		Add Intermediate leak check times: up to 10 sec after every 20MPa increase in fueling pressure											
		Initial Tank Pressure, P_0 (MPa)											
Ambient Temperature, T_{amb} (°C)		2	5	10	15	20	30	40	50	60	70	> 70	
		> 50	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling
		50	41	39	36	33	30	24	18	13	7	1	no fueling
		45	29	28	25	23	21	17	13	9	5	1	no fueling
		40	21	20	19	17	16	13	10	7	4	1	no fueling
		35	16	16	14	13	12	10	7	5	3	1	no fueling
		30	13	12	11	10	10	8	6	4	2	no fueling	no fueling
		25	11	10	9	9	8	6	5	3	1	no fueling	no fueling
		20	9	8	8	7	6	5	4	2	1	no fueling	no fueling
		10	7	6	6	5	4	3	2	1	no fueling	no fueling	no fueling
		0	5	5	4	4	3	2	1	0	no fueling	no fueling	no fueling
		-10	5	5	4	4	3	2	1	0	no fueling	no fueling	no fueling
		-20	5	5	4	4	3	2	1	0	no fueling	no fueling	no fueling
		-30	5	5	4	4	3	2	1	0	no fueling	no fueling	no fueling
		-40	5	5	4	4	3	2	1	0	no fueling	no fueling	no fueling
		< -40	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling

Typical
15 Min

Lower SOC Limits
Without Communication

A-70 1-7kg		Hot Case Final State of Charge, SOC (Hot Soak - No History)											
		Initial Tank Pressure, P_0 (MPa)											
		2	5	10	15	20	30	40	50	60	70	> 70	
Ambient Temperature, T_{amb} (°C)		> 50	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling
		50	89%	89%	89%	89%	89%	89%	89%	90%	91%	no fueling	no fueling
		45	89%	89%	89%	89%	89%	89%	89%	90%	92%	no fueling	no fueling
		40	89%	89%	89%	89%	89%	90%	90%	91%	92%	no fueling	no fueling
		35	90%	89%	89%	89%	90%	90%	91%	91%	92%	93%	no fueling
		30	89%	89%					91%	92%	94%	no fueling	no fueling
		25	89%	89%					91%	92%	no fueling	no fueling	no fueling
		20	89%	89%					91%	92%	no fueling	no fueling	no fueling
		10	88%	88%					91%	92%	no fueling	no fueling	no fueling
		0	88%	88%					91%	92%	no fueling	no fueling	no fueling
		-10	87%	87%					90%	91%	no fueling	no fueling	no fueling
		-20	86%	86%					89%	90%	no fueling	no fueling	no fueling
		-30	85%	84%					88%	89%	no fueling	no fueling	no fueling
		-40	84%	84%					87%	88%	no fueling	no fueling	no fueling
		< -40	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling

90% non-com
98%+ comm.

B-70 1-7kg		Hot Case Final State of Charge, SOC (Hot Soak - No History)											
		Initial Tank Pressure, P_0 (MPa)											
		2	5	10	15	20	30	40	50	60	70	> 70	
Ambient Temperature, T_{amb} (°C)		> 50	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling
		50	91%	91%	90%	90%	90%	90%	90%	90%	91%	no fueling	no fueling
		45	90%	90%	90%	89%	89%	89%	90%	90%	91%	92%	no fueling
		40	90%	90%	89%	89%	89%	90%	90%	91%	92%	93%	no fueling
		35	90%	89%	89%	89%	90%	90%	91%	92%	93%	94%	no fueling
		30	89%	89%					91%	92%	93%	no fueling	no fueling
		25	89%	89%					91%	92%	no fueling	no fueling	no fueling
		20	88%	88%					91%	92%	no fueling	no fueling	no fueling
		10	88%	88%					91%	92%	no fueling	no fueling	no fueling
		0	87%	87%					91%	92%	no fueling	no fueling	no fueling
		-10	86%	86%					91%	91%	no fueling	no fueling	no fueling
		-20	85%	85%					90%	90%	no fueling	no fueling	no fueling
		-30	84%	84%					89%	89%	no fueling	no fueling	no fueling
		-40	84%	83%					88%	88%	no fueling	no fueling	no fueling
		< -40	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling

90% non-com
98%+ comm.

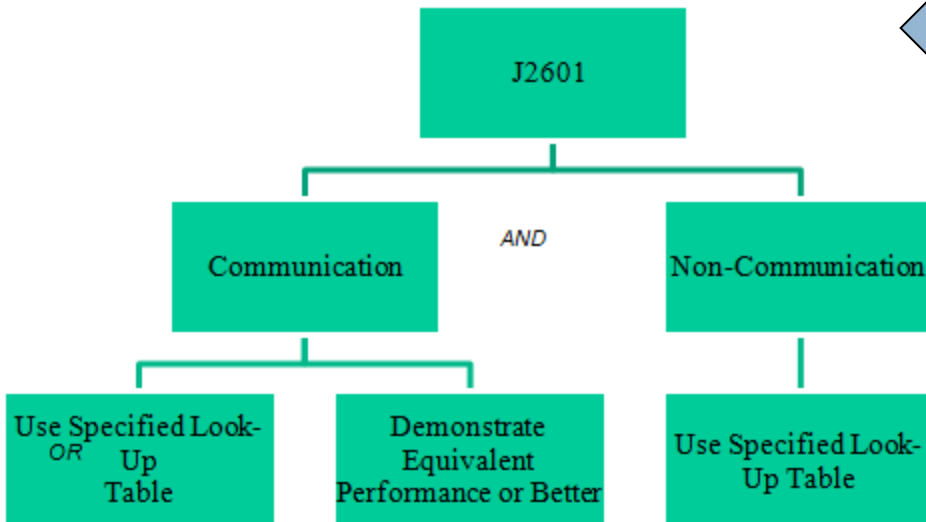
*Note: Cool Down Times may add a minute

Hydrogen Dispenser Validation

SAE J2601

L.D.V. H₂ Limits & Targets

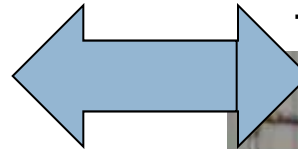
- Non-Communication
- Communications



CSA 4.3 (or equivalent)

H₂ Dispenser Fueling Test

- Test Procedure
- Testing Device (H.D.T.A.)



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*Shown CaFCP Station Test Apparatus



SAE J2601 HD & FL Guideline Drafts

J2601-2 HD Bus Fueling

HD fueling assumptions (draft)

- Total vehicle tank capacity: >10kg
- 35 MPa
- Performance based
- Maximum fueling rate
 - Option A: up to 3.6 kg/min (60g/s)
 - Option B: up to 7 kg/min (120g/s)
- Communication between vehicle and station suppliers
- LD vehicles cannot fill at “Option B” HD dispenser

<Heavy Duty Vehicle / Track>



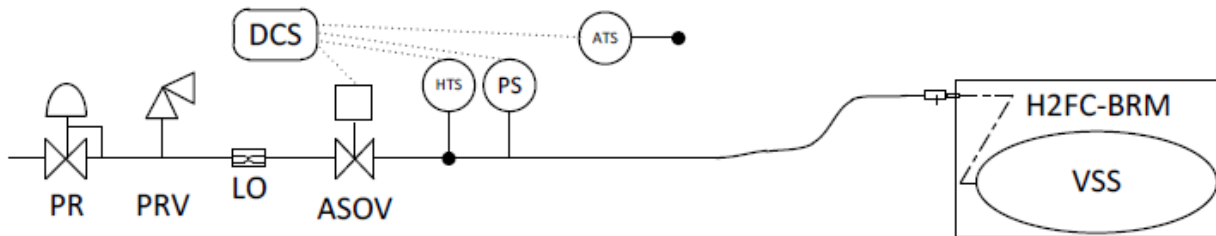
J2601-3 Fork Lift Fueling

Draft

Option 1: Fill to Service Pressure



Option 2: Fill to Target Pressure



In-field TIR J2601 LD Experience

TIR J2601 LD Experience

Positive:

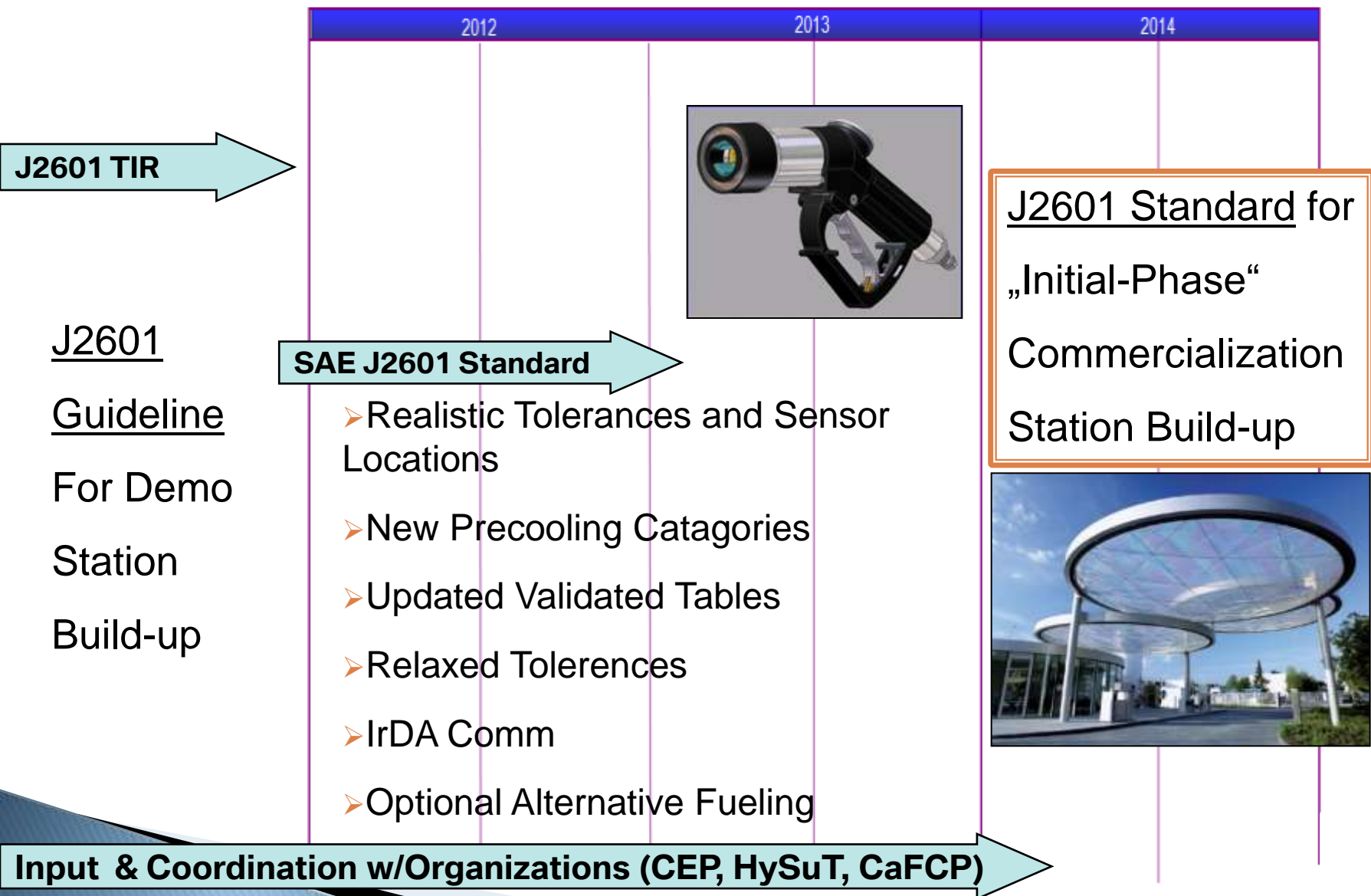
- ▶ Safe Fueling (no overheating with correct tables)
- ▶ Communications Fueling very robust, repeatable (high SOC)
- ▶ Good performance with proper pre-cooling
- ▶ World Wide Acceptance of Guideline

„Room for Improvement“

- ▶ Pre-cooling Issue to meet „cool down window“(15s)
- ▶ Issue to meet tolerances on ramp rate, temperatures
- ▶ „Too-strict“: Potential for shutdown with out-of-tolerance
- ▶ No Station met 100% of requirements (closest in EU)

SAE J2601 LD Standardization

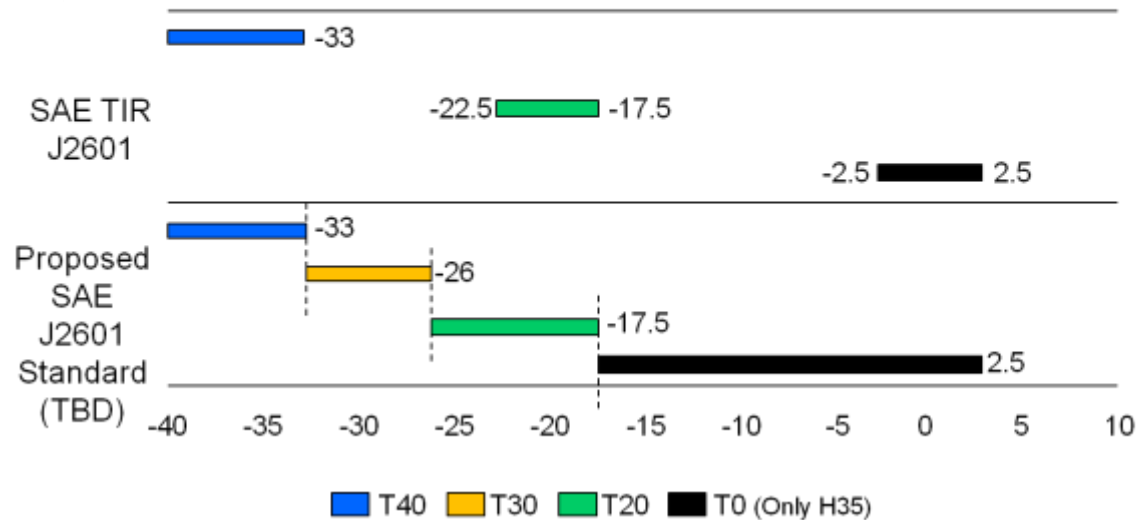
SAE J2601 Standard Timeline



Fueling Dispenser Types

J2601 Standard defines fueling station dispenser type by capability to dispense hydrogen fuel at a specific nozzle “pre-cooled temperature”. Note: There is a direct relation between pre-cooling and fueling speed.

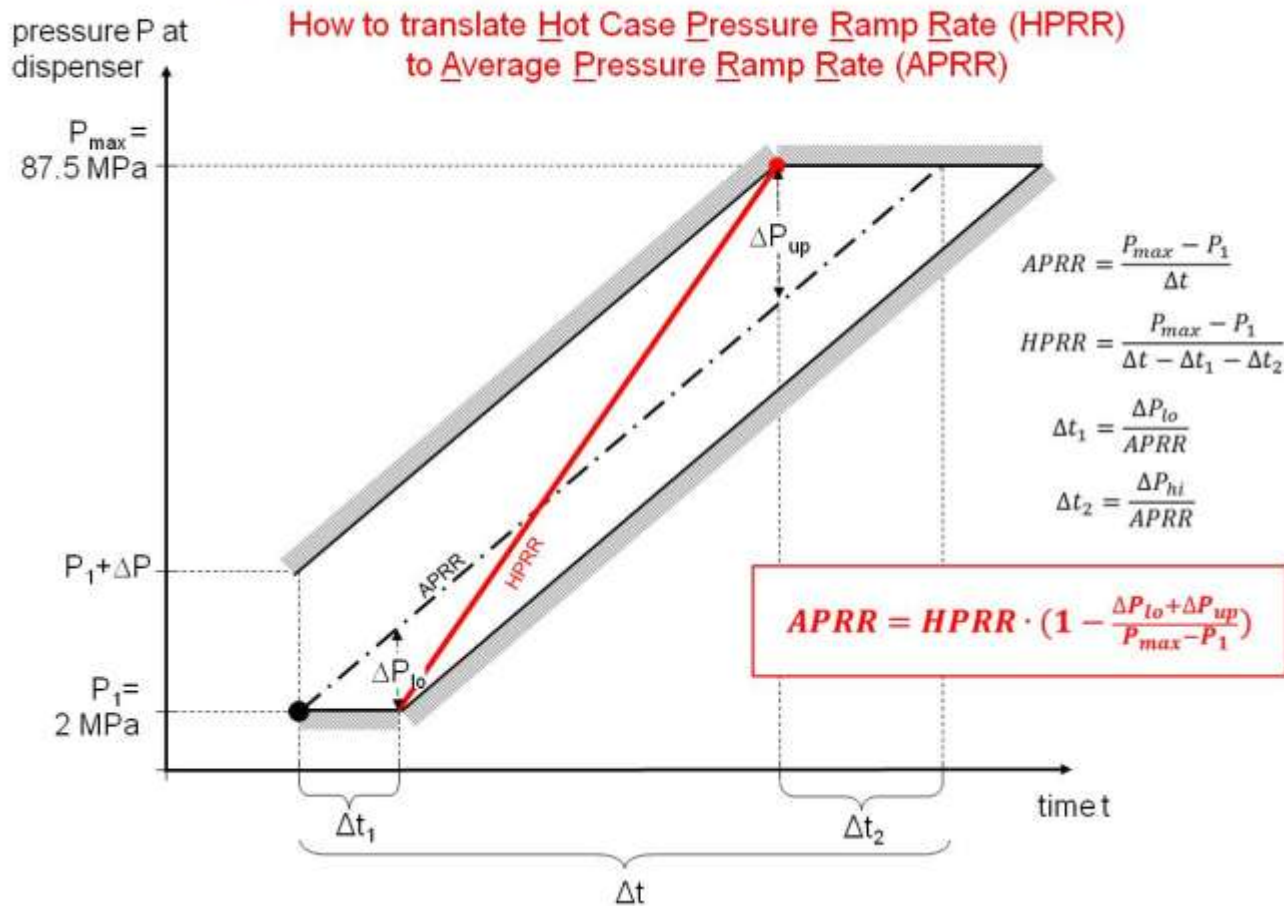
Pre-cooling Categories



JARI
Proposal:

Pressure Corridore Tolerances*

Hot Case Tolerance for Simulation



Proposed Tolerances

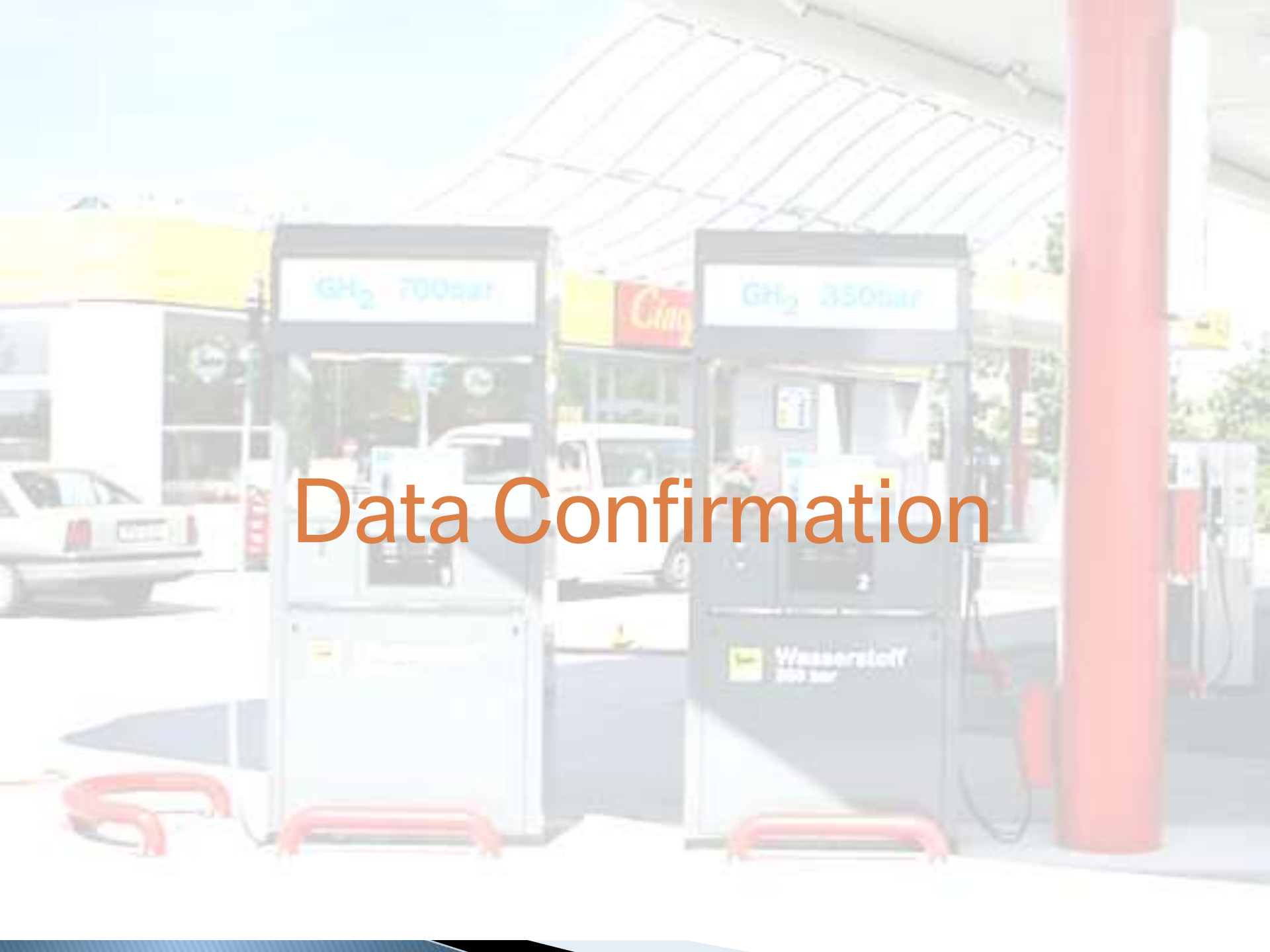
$dP_{\text{lower}} = 2.5 \text{ Mpa}$

$dP_{\text{upper}} = 7.0 \text{ Mpa}$

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*Proposal is based on input from JARI/ Opel Presentations

Data Confirmation



Confirmation of Look-Up Tables

SAE J2601 Validation Testing

Purpose:

- Experimentally confirm the 35 and 70 MPa fueling targets included in the SAE J2601 look-up tables
- Experimentally confirm the tests utilize representative fueling storage

Scope of Work examines three distinct areas of interest:

1. Confirm Real World Experience to meet Original Tables from TIR
2. Over-temperature fueling
 - Testing with hot-soak conditions on Type 4 tanks
3. Over-density fueling
 - Testing with cold-soak and cooling from driving on Type 3 tanks
4. Target SoC fueling
 - Testing with “normal” conditions on all tanks to confirm non-communication SoC
5. Optional MC Fueling Confirmation

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4. Target SoC fueling
 - Testing with “normal” conditions on all tanks to confirm non-communication SoC
5. Optional MC Fueling Confirmation

Conclusion

- J2601 L.D. to be published in 2013 based on simulation and validation data
 - *“Field Data Lessons Learned” tolerances to be used in updated fueling tables to allow for a commercial infrastructure*

Additional Features to J2601: for fueling:

- *IrDA Data Communications (from J2799)*
- *Optional Alternative Methods*

- J2601-2 HD Guideline publishing in 2013 (Standard 2014)
- J2601-3 FL Standard publishing in 2013

Questions ?

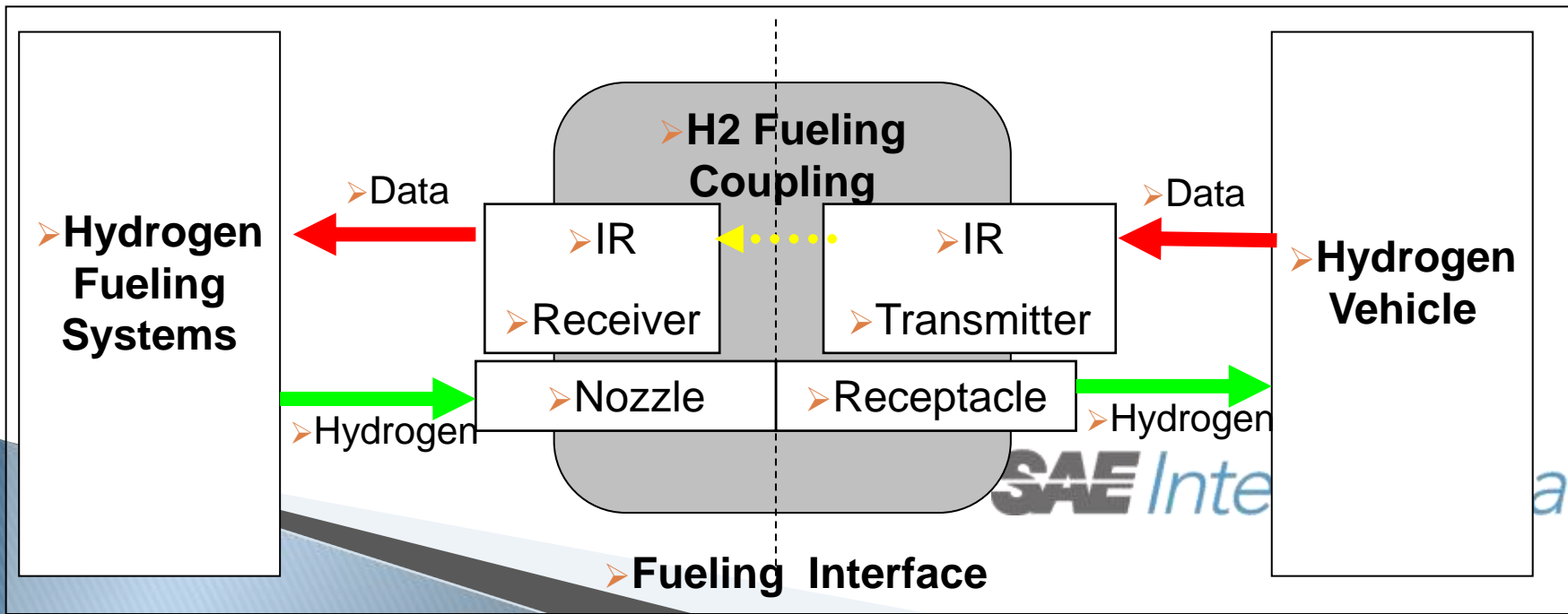


Contact: Jesse.Schneider@web.de

IrDA Communications

Infrared Data

- ▶ Available Technology
- ▶ Transparent to customer
- ▶ Vehicle tank info for Temp. Comp.
- ▶ 10%+ Better Fueling Density
- ▶ IrDA is being taken from J2799



SAE TIR J2601 LD

- Published Guideline :
Technical Information Report
(TIR): Light Duty Vehicle H2
Fueling for 35 & 70MPa
- Fueling protocol created from
fueling **actual OEM tanks** tested
under extreme conditions
- Provides guidance for hydrogen
fueling within reasonable time
without exceeding temperature
and pressure limits
- Provides pressure targets to
achieve a reasonable state of
charge (SOC) under diverse
ambient temperature(s)
- Validated with CSA 4.3 device

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SURFACE VEHICLE TECHNICAL INFORMATION REPORT

Fueling Protocols for Light Duty Gasoline Vehicles

RATIONALE

The implementation of hydrogen vehicles into the market vehicle. The goal is to achieve a customer acceptable fueling amount of time without exceeding the temperature, pressure, or flow rate limits of the pre-cooling capacity of the station dispenser.

SAE JIR J2601 establishes industry-wide fueling protocol for passenger vehicles operating with nominal working pressure employ fueling algorithms and equipment to conduct the fueling using these protocols should be designed appropriately for fueling guidance for qualifying the vehicle hydrogen storage system.)

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SAE values your input. To provide feedback on this Technical Report, please visit http://www.sae.org/technicalstandards/j2601_201003

J2601 Fueling Tables: 35MPa Non-Communication

Type A (-40°C)

A-35		Actual Fueling Duration (min)							
		Add intermediate leak check time: up to 10 sec after 25MPa increase in fueling pressure							
		Initial Tank Pressure, P_0 (MPa)							
Ambient Temperature, T_{amb} (°C)		2	5	10	15	20	30	35	> 35
	> 50	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling
	50	2	2	2	1	1	0	0	no fueling
	45	2	2	2	1	1	0	0	no fueling
	40	2	2	2	1	1	0	0	no fueling
	35	2	2	2	1	1	0	0	no fueling
	30	2	2	2	1	1	0	0	no fueling
	25	2	2	2	1	1	0	0	no fueling
	20	2	2	2	1	1	0	0	no fueling
	10	2	2	2	1	1	0	0	no fueling
	0	2	2	2	1	1	0	0	no fueling
	-10	2	2	2	1	1	0	0	no fueling
	-20	2	2	2	1	1	0	0	no fueling
	-30	2	2	1	1	1	no fueling	no fueling	no fueling
	-40	2	2	1	1	1	no fueling	no fueling	no fueling
	< -40	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling

Typical
2 Min.

Type B (-20°C)

B-35		Actual Fueling Duration (min)							
		Add intermediate leak check time: up to 10 sec after 25MPa increase in fueling pressure							
		Initial Tank Pressure, P_0 (MPa)							
Ambient Temperature, T_{amb} (°C)		2	5	10	15	20	30	35	> 35
	> 50	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling
	50	8	7	6	5	4	1	0	no fueling
	45	6	5	4	4	3	1	0	no fueling
	40	4	4	3	3	2	1	0	no fueling
	35	4	3	3	2	2	1	0	no fueling
	30	3	3	2	2	1	0	0	no fueling
	25	3	2	2	2	1	0	no fueling	no fueling
	20	2	2	2	2	1	0	no fueling	no fueling
	10	2	2	2	2	1	0	no fueling	no fueling
	0	2	2	2	2	1	0	no fueling	no fueling
	-10	2	2	2	2	1	0	no fueling	no fueling
	-20	2	2	2	1	1	1	no fueling	no fueling
	-30	2	2	1	1	1	1	no fueling	no fueling
	-40	2	2	1	1	1	1	no fueling	no fueling
	< -40	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling

Typical
3 Min.

Type C (0°C)

C-35		Actual Fueling Duration (min)							
		Add intermediate leak check time: up to 10 sec after 25MPa increase in fueling pressure							
		Initial Tank Pressure, P_0 (MPa)							
Ambient Temperature, T_{amb} (°C)		2	5	10	15	20	30	35	> 35
	> 50	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling
	50	35	32	27	22	16	6	1	no fueling
	45	25	23	19	15	12	5	1	no fueling
	40	19	17	14	11	9	3	1	no fueling
	35	15	13	11	9	7	3	0	no fueling
	30	12	11	9	7	5	2	0	no fueling
	25	10	9	7	6	4	1	no fueling	no fueling
	20	8	7	6	5	4	1	no fueling	no fueling
	10	6	5	4	3	2	1	no fueling	no fueling
	0	5	4	3	2	1	0	no fueling	no fueling
	-10	5	4	3	2	1	0	no fueling	no fueling
	-20	4	4	3	2	1	no fueling	no fueling	no fueling
	-30	4	4	3	2	1	no fueling	no fueling	no fueling
	-40	4	4	3	2	1	no fueling	no fueling	no fueling
	< -40	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling

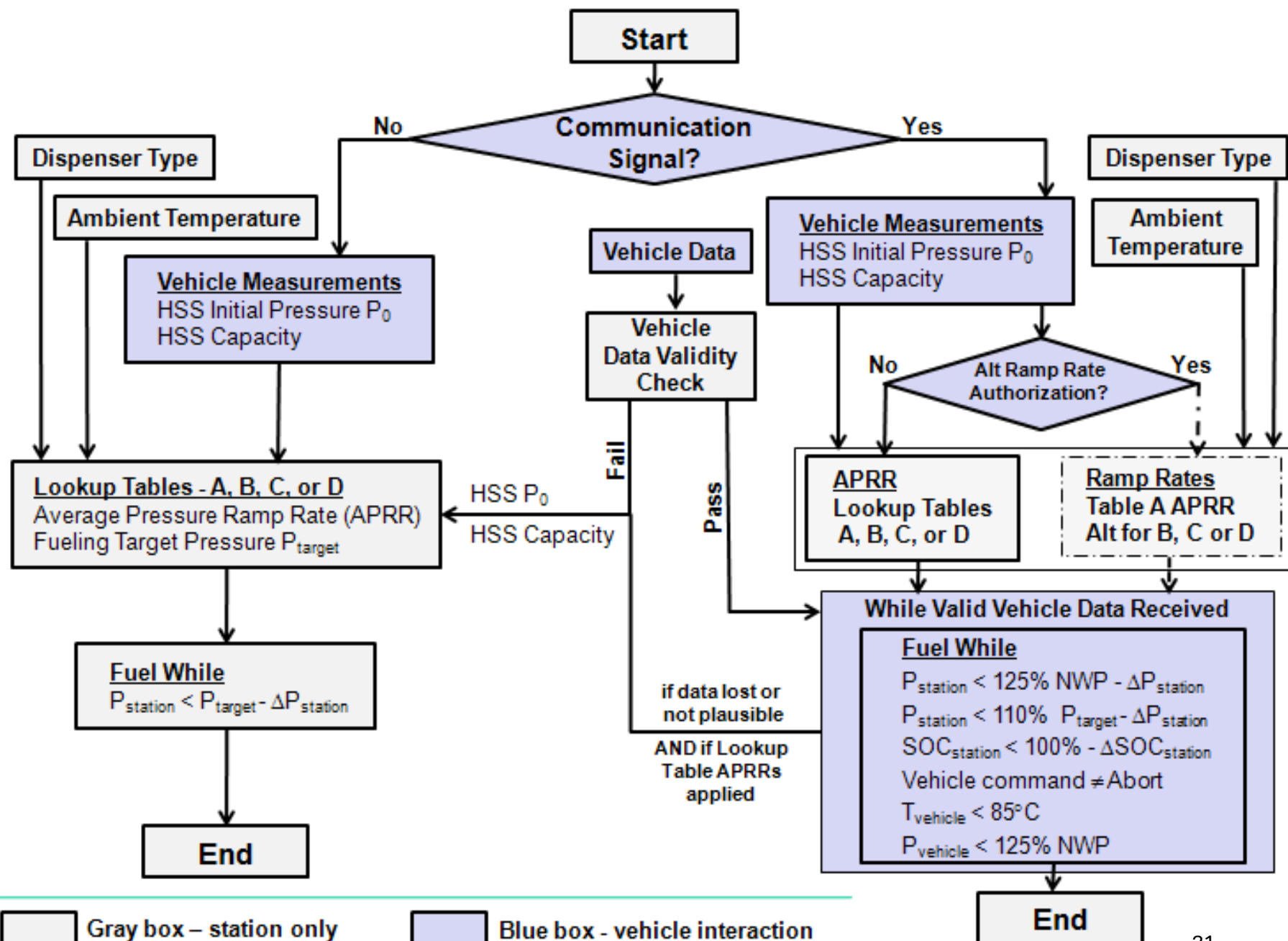
Typical
15Min.

Type D (no pre-cooling)

D-35		Actual Fueling Duration (min)							
		Add intermediate leak check time: up to 10 sec after 25MPa increase in fueling pressure							
		Initial Tank Pressure, P_0 (MPa)							
Ambient Temperature, T_{amb} (°C)		2	5	10	15	20	30	35	> 35
	> 50	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling
	50	156	142	120	97	74	29	6	no fueling
	45	112	102	85	69	53	20	4	no fueling
	40	79	72	60	48	37	14	3	no fueling
	35	56	50	42	34	26	10	2	no fueling
	30	39	35	29	23	18	6	1	no fueling
	25	27	25	20	16	12	4	no fueling	no fueling
	20	19	18	14	11	8	3	no fueling	no fueling
	10	10	9	7	5	4	1	no fueling	no fueling
	0	5	5	4	3	2	0	no fueling	no fueling
	-10	3	3	2	2	1	0	no fueling	no fueling
	-20	2	2	1	1	1	no fueling	no fueling	no fueling
	-30	2	2	1	1	1	no fueling	no fueling	no fueling
	-40	2	2	1	1	1	no fueling	no fueling	no fueling
	< -40	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling

Typical
45 Min.

Fueling Procedure Summary



SAE J2601 Standard Goals

- Realistic Tolerances and Sensor Locations
 - New Categories for Precooling
 - Define „fall back“ procedures for APRR
- New Type of Dispenser Pre-cooling
- IrDA Integration (potential for Alt-Fueling identification)
- Interpolation between tables
- Simulation Needed to update tables
- Optional „Alt“ Alternative Fueling with confirmation (TBC):
 - MC Method
 - Variable Pressure Ramp Rate