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

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SAE International

Presentation Outline

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

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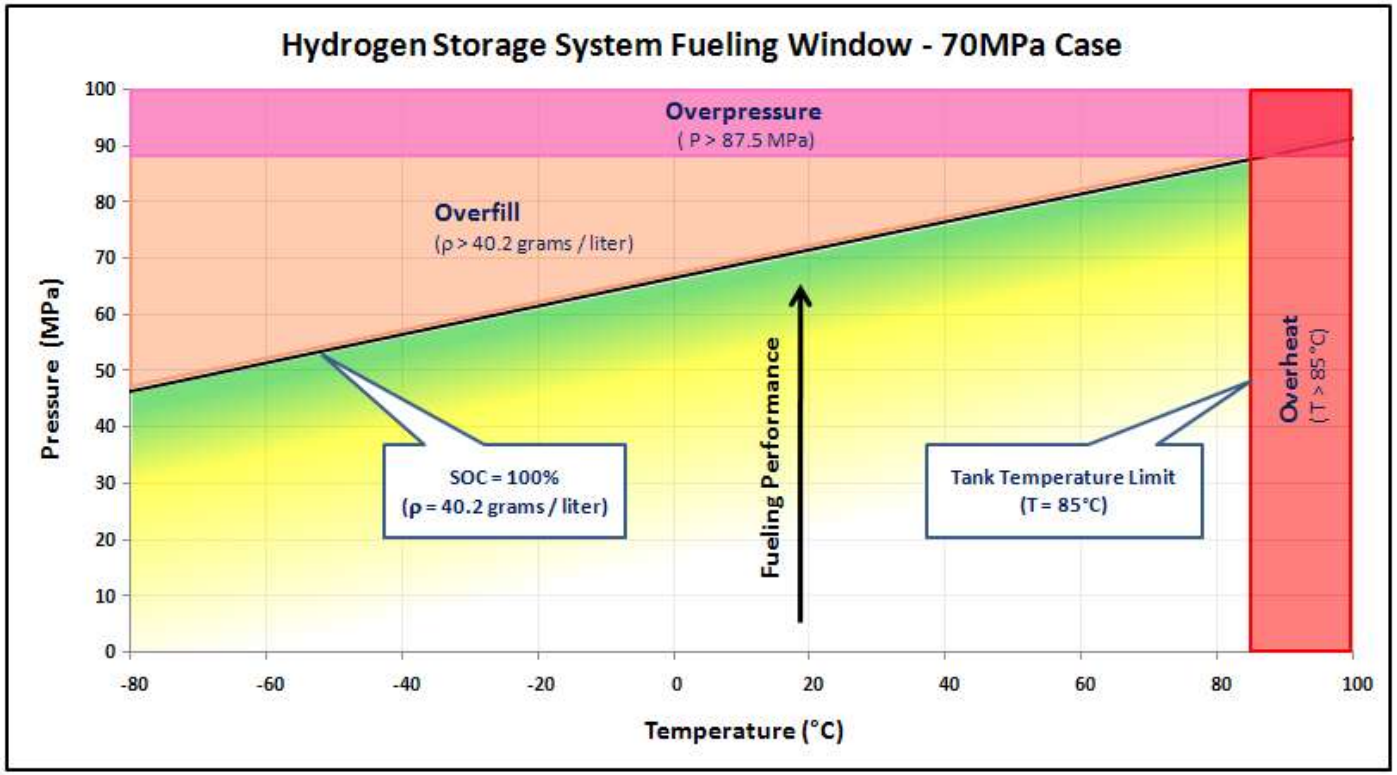
Fueling Fundamentals

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)



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What is SAE J2601?

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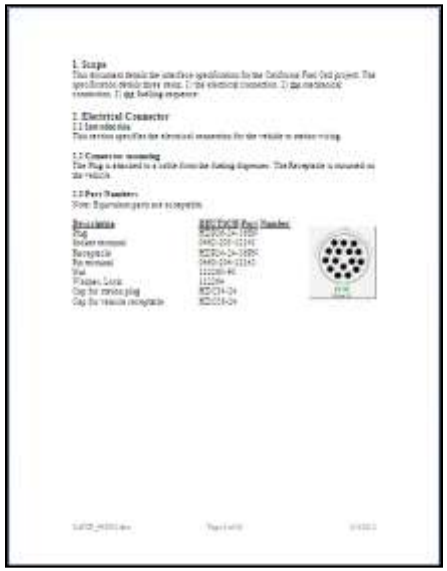
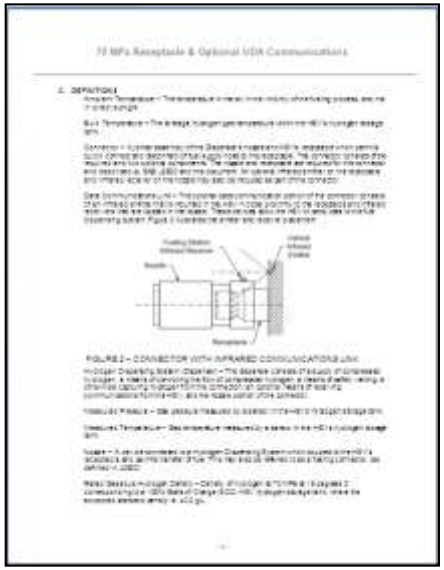
Hydrogen Fueling Protocol History and Path Forward

CaFCP I/O Guideline 2002

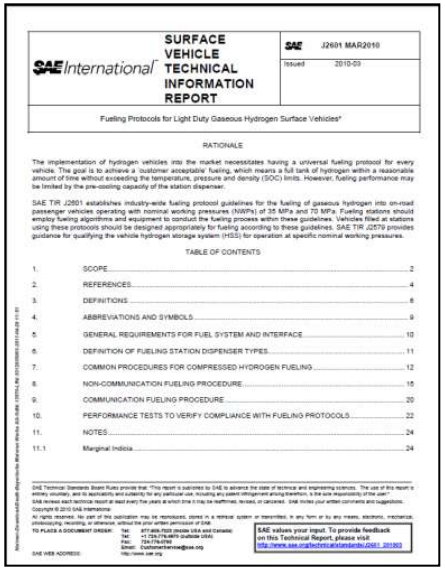


OEM Fueling „Rev A“ 2007

SAE J2799 „70MPa Coupling & IrDA“ 2007



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



SAE J2601 Light Duty H2 Fueling and Communications Standard 2013

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

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SAE TIR J2601
Light Duty

SAE International

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 H_2 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

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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)

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J2601 Fueling Tables: 70MPa with ≤ 7kg 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 25MPa 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	5	4	3	2	1	0	no fueling
45	5	4	4	4	3	3	2	1	1	0	no fueling
40	4	3	3	3	3	2	2	1	1	0	no fueling
35	3	3	3	2	2	2	1	1	0	0	no fueling
30	3	3	2	2	2	2	1	1	0	0	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	0	0	no fueling	no fueling
-10	2	2	2	2	2	1	1	0	no fueling	no fueling	no fueling
-20	2	2	2	2	2	1	1	0	no fueling	no fueling	no fueling
-30	2	2	2	2	2	1	1	0	no fueling	no fueling	no fueling
-40	2	2	2	2	2	1	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 3 Min.

B-70 1-7kg

Actual Fueling Duration (min)

Add intermediate leak check times: up to 10 sec after every 25MPa 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	5	4	3	2	1	no fueling	no fueling
0	5	5	4	4	4	3	2	1	1	0	no fueling
-10	5	5	4	4	4	3	2	1	1	0	no fueling
-20	5	5	4	4	4	3	2	1	1	no fueling	no fueling
-30	5	5	4	4	4	3	2	1	0	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)

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	89%	89%	89%	89%	88%	89%	89%	89%	90%	91%	no fueling
45	89%	89%	89%	89%	89%	89%	89%	90%	90%	92%	no fueling
40	89%	89%	89%	89%	89%	90%	90%	90%	91%	92%	no fueling
35	90%	89%	89%	89%	90%	90%	91%	91%	92%	93%	no fueling
30	89%	89%						1%	92%	94%	no fueling
25	89%	89%						1%	92%	no fueling	no fueling
20	89%	89%						1%	92%	no fueling	no fueling
10	88%	88%						1%	92%	no fueling	no fueling
0	88%	88%						1%	92%	no fueling	no fueling
-10	87%	87%						9%	no fueling	no fueling	no fueling
-20	86%	85%						6%	no fueling	no fueling	no fueling
-30	85%	84%						4%	no fueling	no fueling	no fueling
-40	84%	84%						84%	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)

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	91%	91%	90%	90%	90%	90%	90%	90%	90%	91%	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%						%	93%	no fueling	no fueling
25	89%	89%						%	93%	no fueling	no fueling
20	88%	88%						%	93%	no fueling	no fueling
10	88%	88%						%	93%	no fueling	no fueling
0	87%	87%						%	93%	no fueling	no fueling
-10	86%	86%						%	91%	no fueling	no fueling
-20	85%	85%						%	no fueling	no fueling	no fueling
-30	84%	84%						%	no fueling	no fueling	no fueling
-40	84%	83%							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

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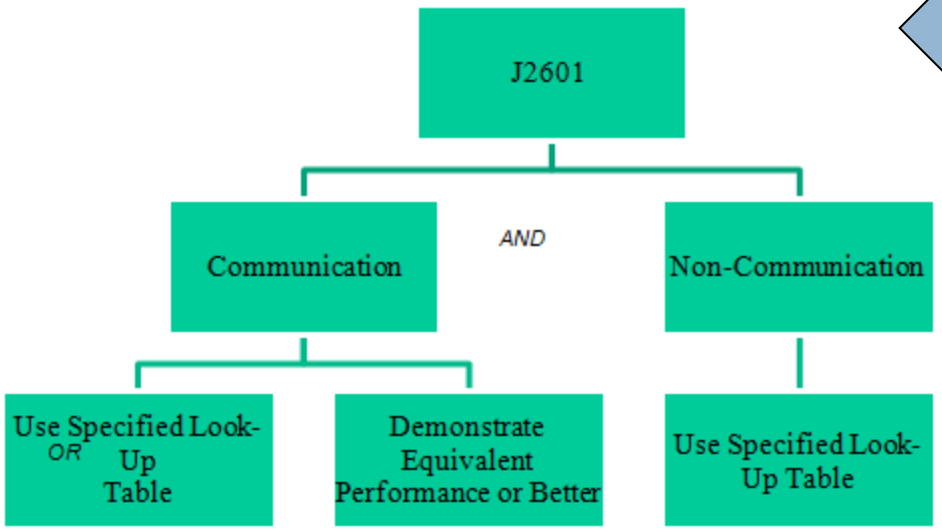
L.D.V. H2 Limits & Targets

- Non-Communication
- Communications



CSA 4.3 (or equivalent)

H_2 Dispenser Fueling Test

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

*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

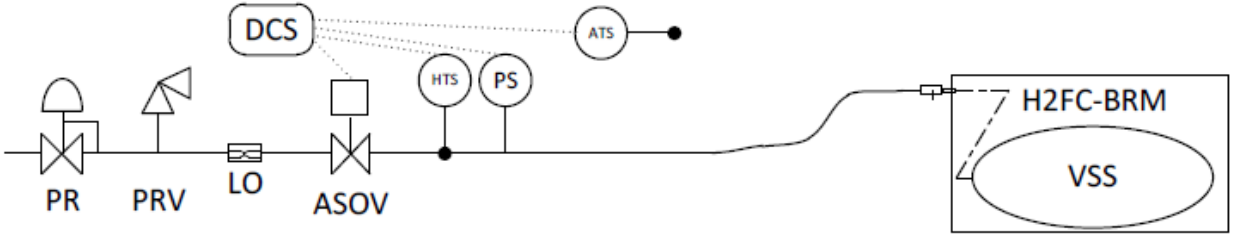
<Heavy Duty Vehicle / Track>

J2601-3 Fork Lift Fueling

Draft

Option 1: Fill to Service Pressure

Option 2: Fill to Target Pressure



In-field TIR J2601 LD Experience

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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 tolerences on ramp rate, temperatures
- „Too-strict“: Potential for shutdown with out-of-tolerence
- No Station met 100% of requirements (closest in EU)

SAE J2601 LD Standardization

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SAE J2601 Standard Timeline

2012 | 2013 | 2014

J2601 TIR

J2601 Guideline For Demo Station Build-up

SAE J2601 Standard

- Realistic Tolerances and Sensor Locations
- New Precooling Catagories
- Updated Validated Tables
- Relaxed Tolerences
- IrDA Comm
- Optional Alternative Fueling

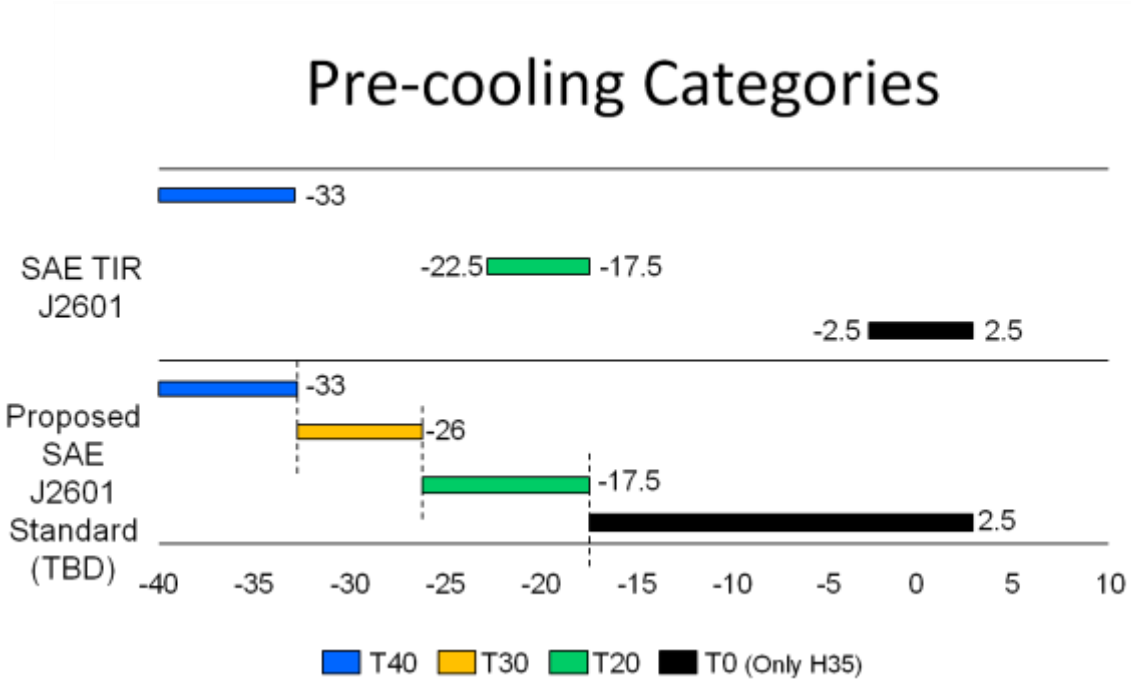
J2601 Standard for „Initial-Phase“ Commercialization Station Build-up

Input & Coordination w/Organizations (CEP, HySuT, CaFCP)

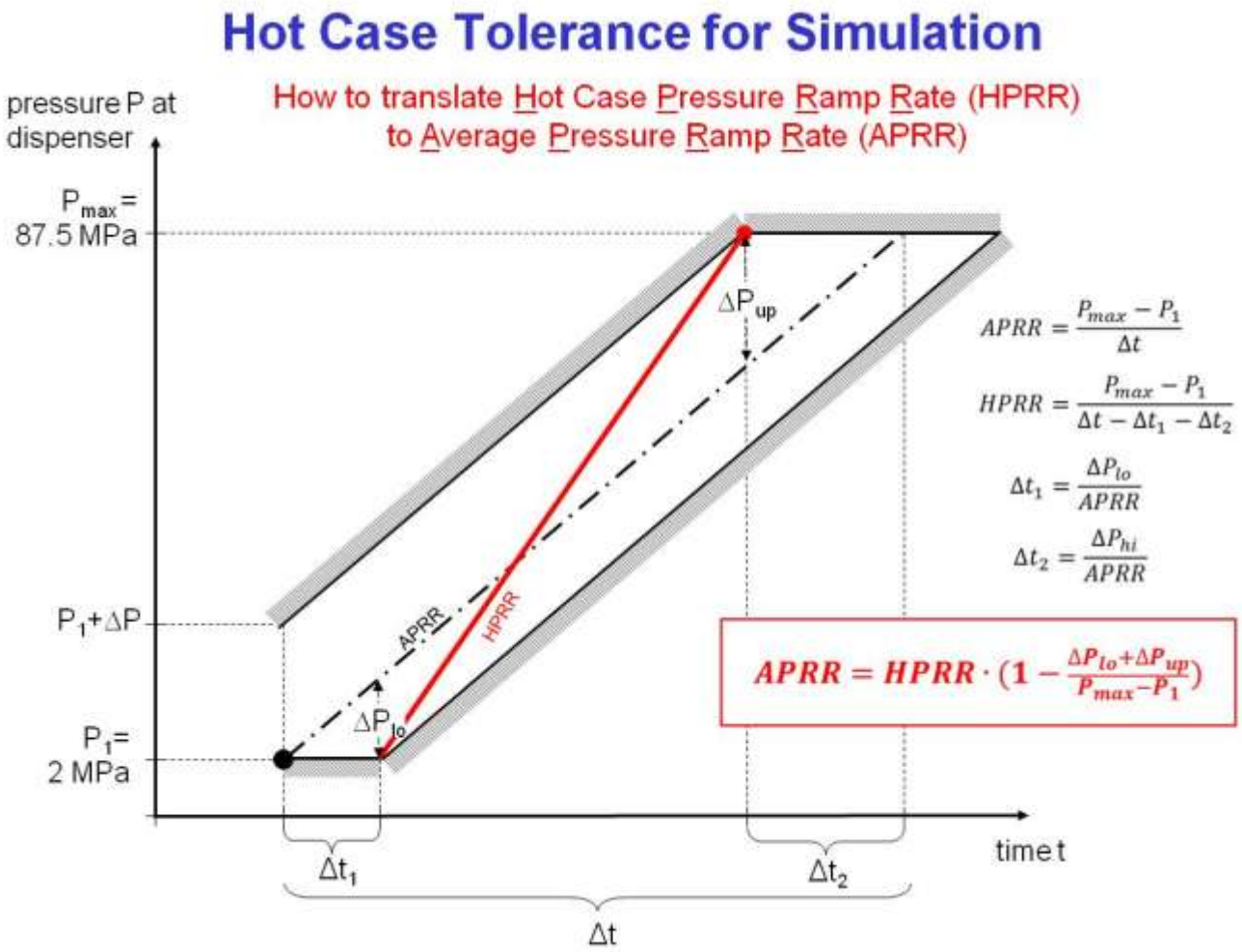
Fueling Dispenser Types

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.

JARI Proposal:



Pressure Coridore Tolerences*



Proposed Tolerences

dP_{lower} = 2.5 Mpa

dP_{upper}= 7.0 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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Confirmation of Look-Up Tables

SAE J2601 Validation Testing

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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

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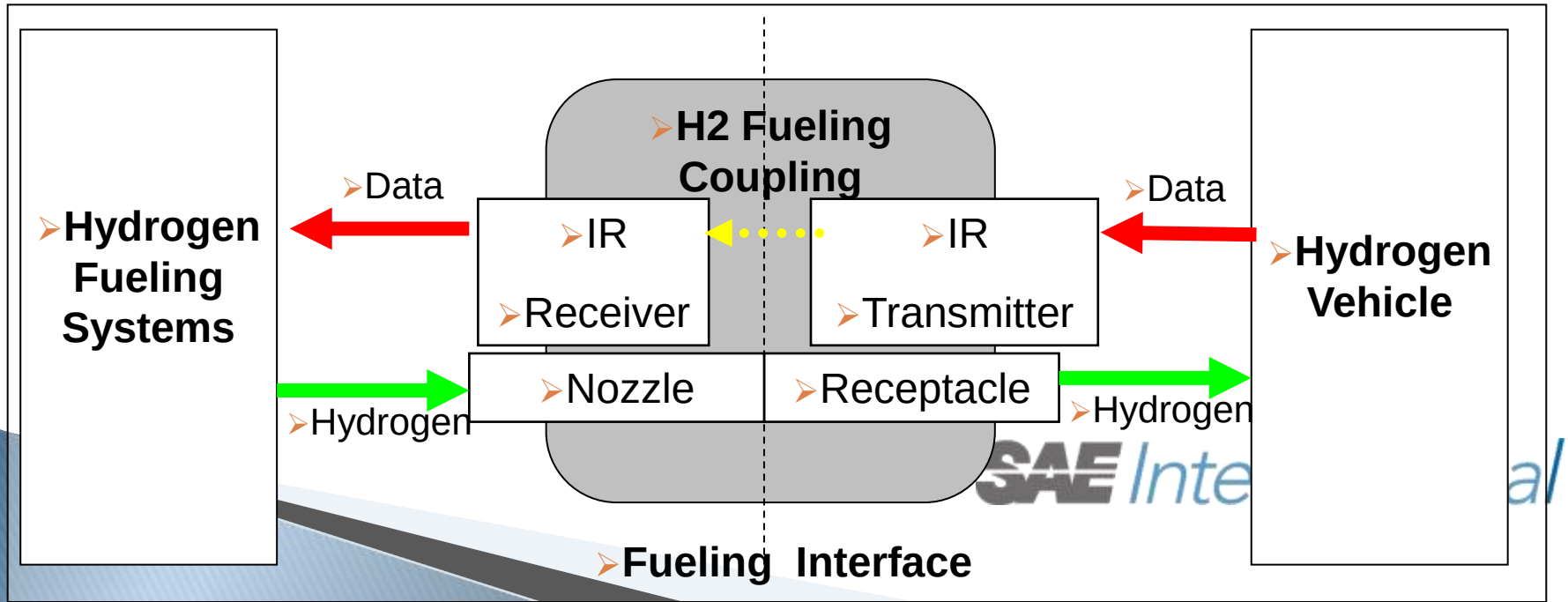
Questions ?

Contact: Jesse.Schneider@web.de

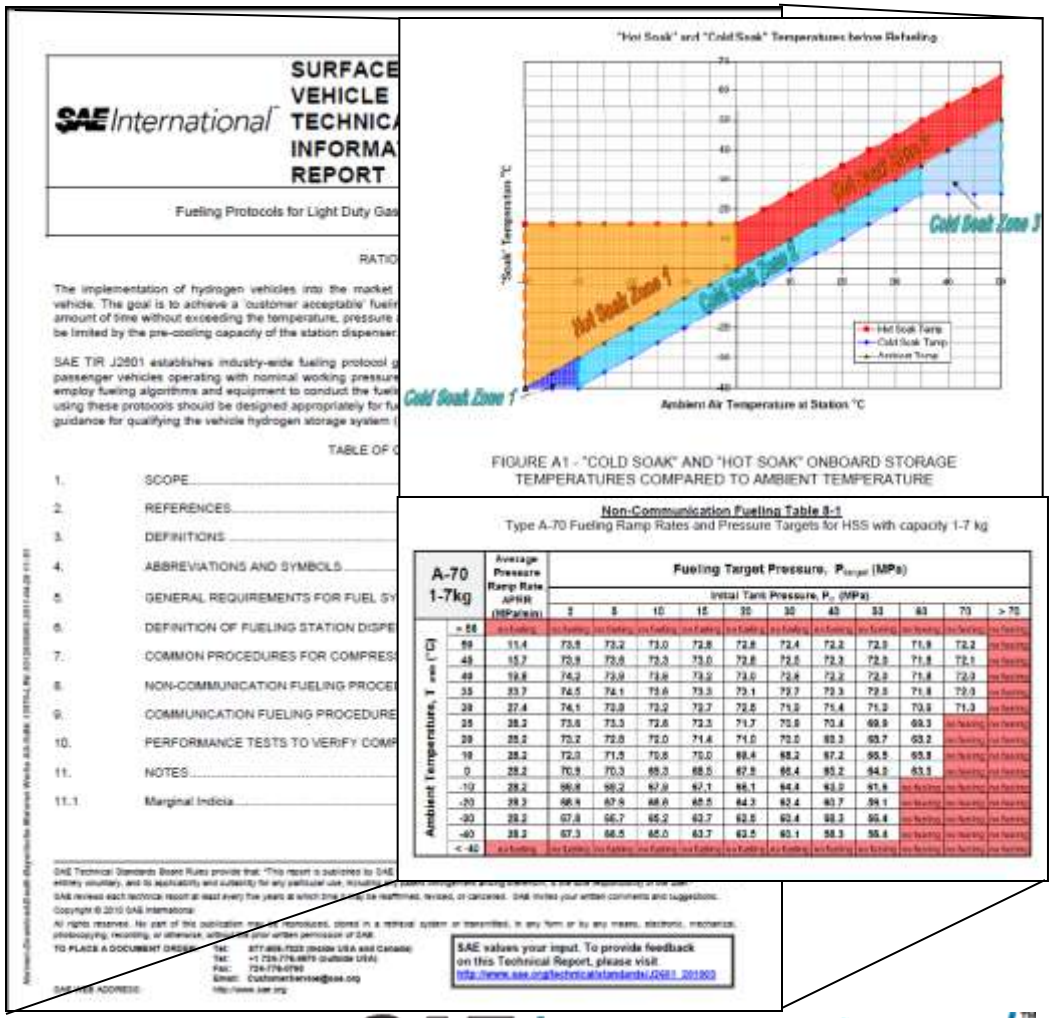
IrDA Communications Infrared Data

- 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



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							
Ambient Temperature, T_{amb} (°C)	Initial Tank Pressure, P_0 (MPa)							
	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	no fueling	no fueling
20	2	2				0	no fueling	no fueling
10	2	2				0	no fueling	no fueling
0	2	2				0	no fueling	no fueling
-10	2	2				0	no fueling	no fueling
-20	2	2				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 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							
Ambient Temperature, T_{amb} (°C)	Initial Tank Pressure, P_0 (MPa)							
	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				0	no fueling	no fueling
10	2	2				0	no fueling	no fueling
0	2	2				0	no fueling	no fueling
-10	2	2				0	no fueling	no fueling
-20	2	2				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 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							
Ambient Temperature, T_{amb} (°C)	Initial Tank Pressure, P_0 (MPa)							
	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				1	no fueling	no fueling
10	6	5				1	no fueling	no fueling
0	5	4				0	no fueling	no fueling
-10	5	4				0	no fueling	no fueling
-20	4	4				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

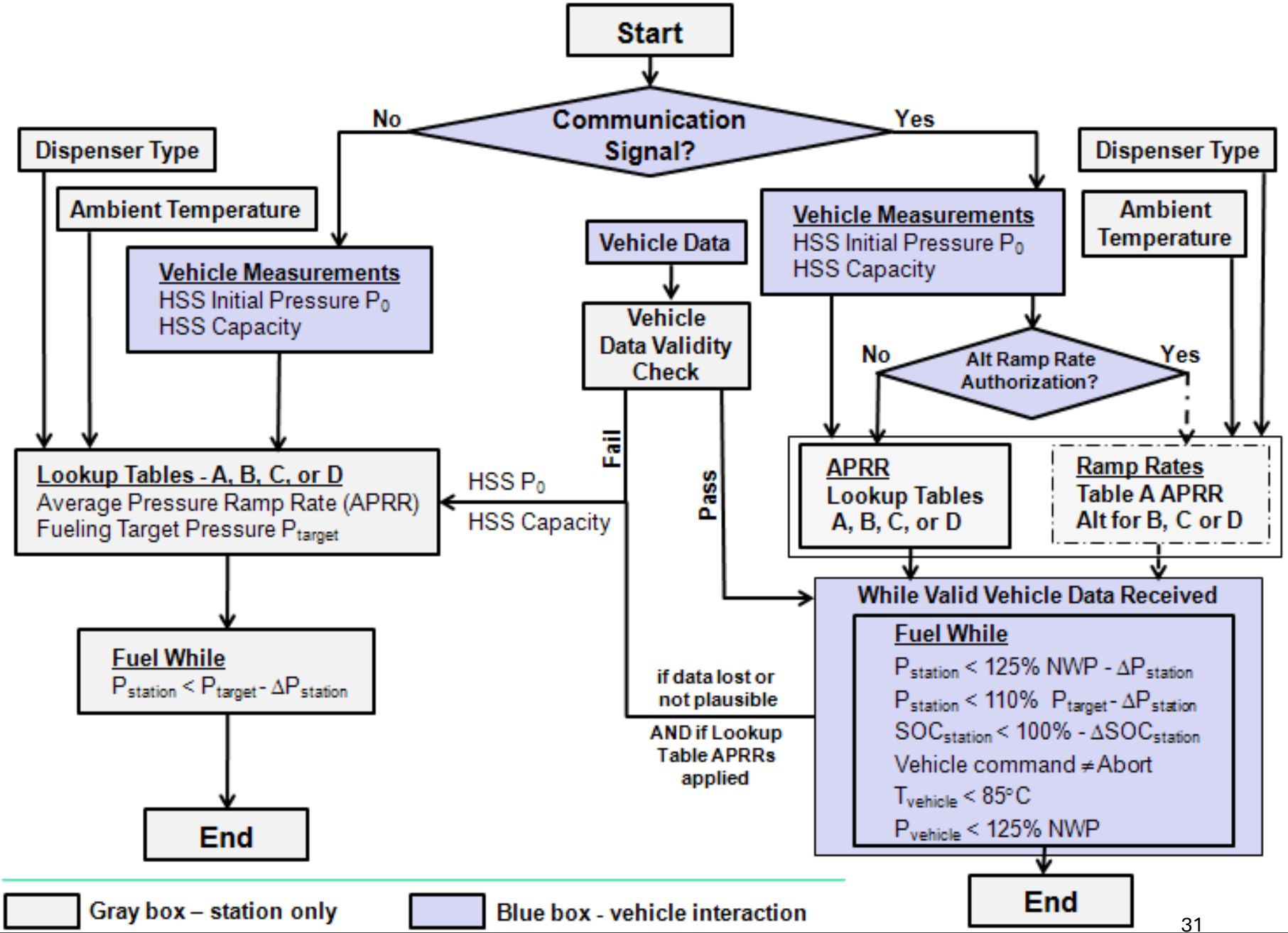
Typical 15Min.

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							
Ambient Temperature, T_{amb} (°C)	Initial Tank Pressure, P_0 (MPa)							
	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				3	no fueling	no fueling
10	10	9				1	no fueling	no fueling
0	5	5				0	no fueling	no fueling
-10	3	3				0	no fueling	no fueling
-20	2	2				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 Tolerences and Sensor Locations
  - New Catagories for Precooling
  - Define „fall back“procedures for APRR
- New Type of Dispenser Pre-cooling
- IrDA Integration (potential for Alt-Fueling identification)
- Interperolation between tables
- Simulation Needed to update tables

- Optional „Alt“ Alternative Fueling with confirmation (TBC):
  - MC Method
  - Variable Pressure Ramp Rate

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