Comparison of Refueling Methods for Hydrogen Rail Vehicles

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Agenda

1. The Heidekrautbahn-Project
2. Motivation: Refueling of Hydrogen Rail Vehicles
3. Methodology: Simulation of Hydrogen Refueling Processes
4. Results: Comparison of different Refueling Approaches
5. Conclusion

The Heidekrautbahn Project
Overview

Key Facts:

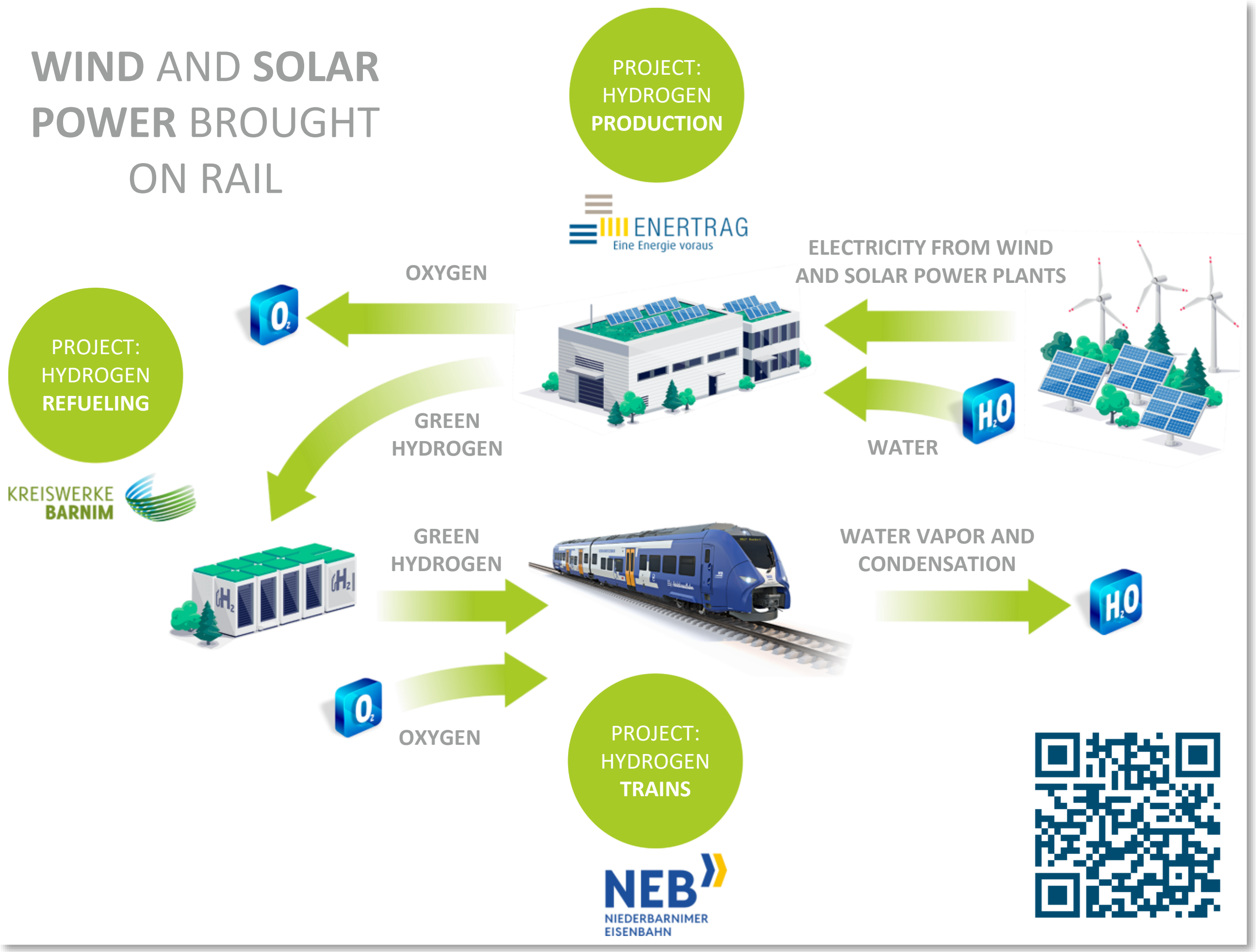
- Funded by German Federal Ministry (BMV) and State of Brandenburg (MWEKE)
- Duration: 2022 – 2035
- Funding: ~ 48 million EUR

Objective:

- Emission free regional transport using green hydrogen produced from local wind and solar energy

Sub-Objectives:

- Local hydrogen production through electrolysis
- Construction of a hydrogen refueling station for rail vehicles
- Replacement of diesel trains with seven hydrogen trains of type Siemens Mireo Plus H
  → in operation since Dec. 2024



[Wasserstoffschiene Heidekrautbahn – Project German Version]

BMV – Federal Ministry for Transport
MWEKE – Ministry for Economic Affairs, Energy, Climate Action and European Affairs

Motivation

Refueling of Hydrogen Rail Vehicles

Hydrogen in Rail Vehicles:

- Stored gaseous at 35 MPa
- Capacity of 180 kg hydrogen (2 separate systems)

Why is refueling with Hydrogen difficult?

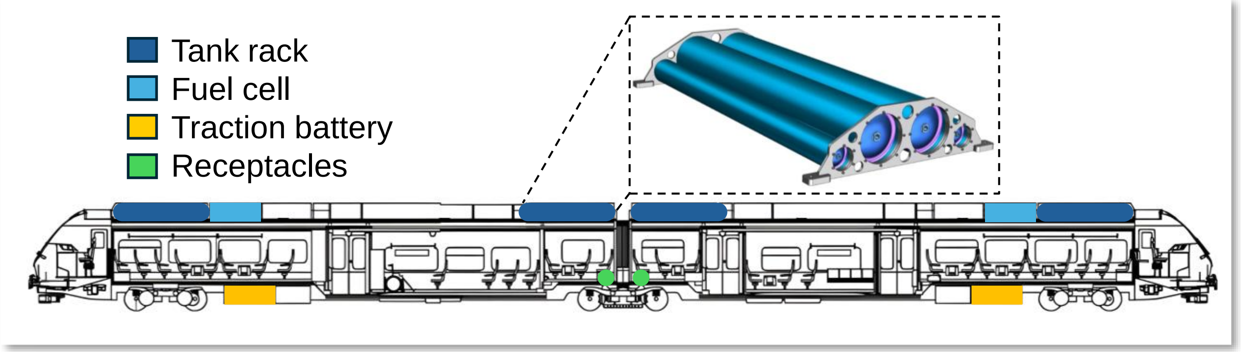
- Temperature increase during refueling:
  - Compression and Joule-Thomson effect
- To prevent damaging tanks and to ensure safety
  - Temperature limit: 85 °C

    → Standards developed to comply

None of the validated standards are usable for rail vehicles

Research Questions:

- What refueling speeds are achievable?
- Is one refueling method universally best?



Side view of the Siemens Mireo Plus H including drive train configuration and tank rack [paper sources 6,12, 14, 15]

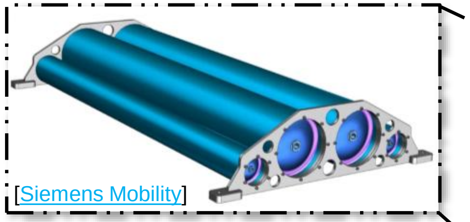
Standard	max. H_2-Mass	Pre-Cooling	max. Mass Flow
SAE J2601	≤ 6 kg	[-40, -20] °C	≤ 60 g/s
SAE J2601-2	purely informative, no protocols		
SAE J2601-5 (TIR)	≤ 180 kg	[-40, amb.] °C	≤ 120 g/s
H35 CEP protocol	≤ 42.5 kg	[-40, amb.] °C	≤ 120 g/s

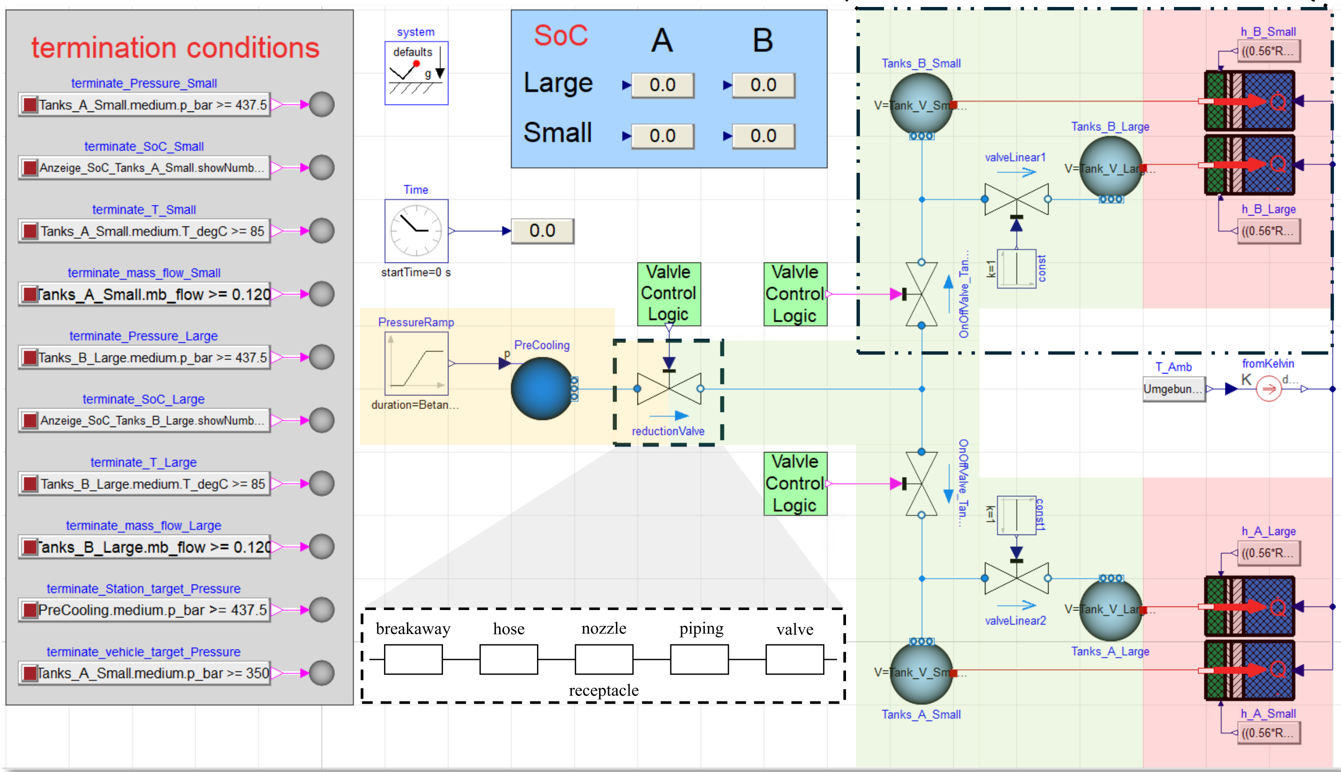
List of available refueling protocols [paper sources 7-10]

SAE – Society of Automobile Engineers
CEP – Clean Energy Partnership

Methodology
Refueling Model

- Simulation model built up in Dymola
  → Lumped parameter for fast simulation times
- Description of hydrogen refueling with following parts:
  - Termination conditions
  - Refueling station
  - Vehicle
  - Heat transfer
- Components between refueling station and vehicle summarized using one valve as flow resistance
- System characteristics of Mireo Plus H
  - Tank system with 90 kg
  - Tank system consists of 2 tank racks
- Different parameter-sets used for validation and investigation of refueling approaches





Hydrogen refueling model in Dymola

BY CHANGING REFUELING STATION PART, DIFFERENT REFUELING APPROACHES CAN BE INVESTIGATED

Methodology
Model Validation

Approach:

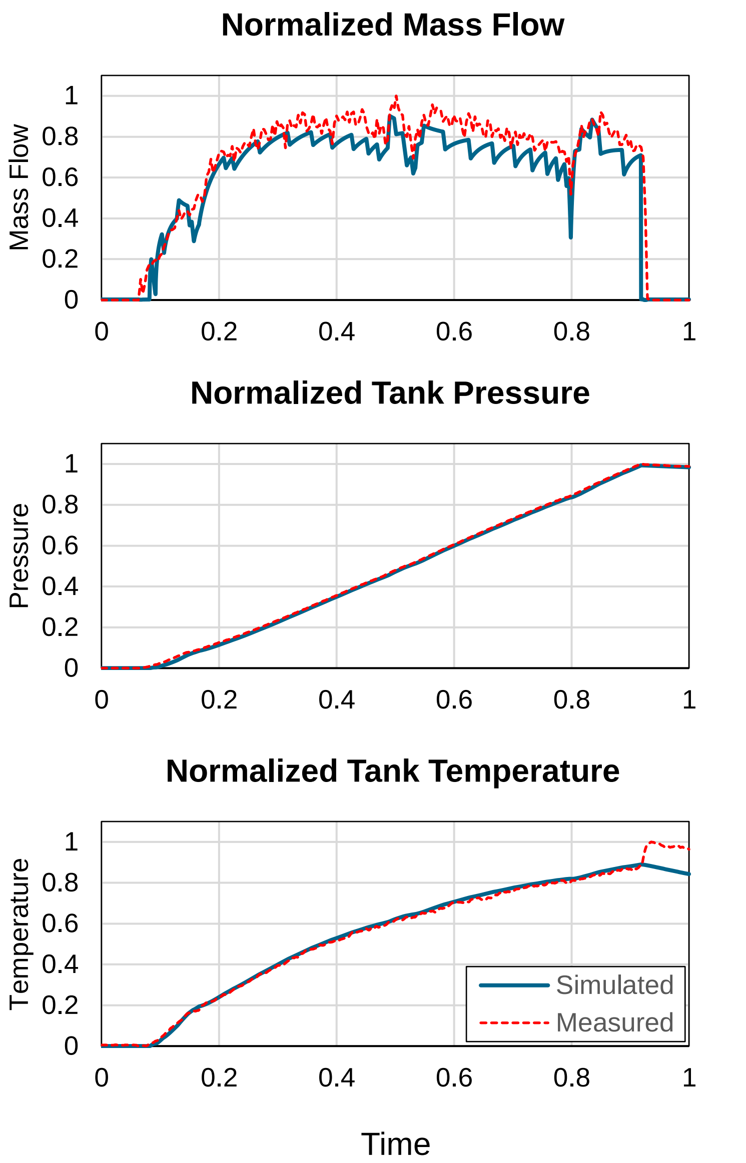
- Models validated against real-world measurement data
  - Station: ambient & pre-cooling temperature, mass flow, ramp rate
  - Vehicle: tank temperature & pressure
- Measurement data used as input for simulation model (ambient & pre-cooling temperature, ramp rate)

Performance:

- Models accurately capture key physical processes

Mass Flow	Pressure	Temperature
– slightly underestimated – large rel. deviations at start/end due to low flow rates – at higher flow rates rel. deviation < 20 %	– rel. deviation < 3 % – rel. deviation decreased over time	– rel. deviation < 0.5 % (until end of refueling) – increase to 1.5 % at end due to unmodeled thermal effects

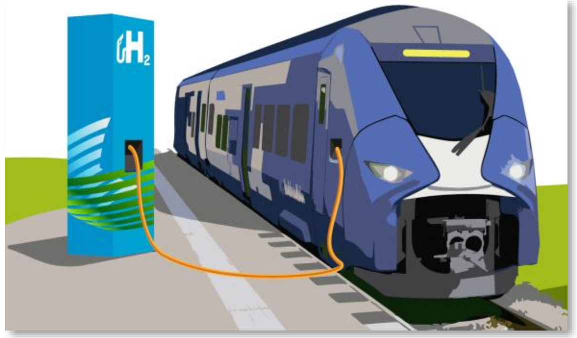
VALIDATED FOR USE IN HYDROGEN REFUELING ANALYSIS



Methodology

Refueling Approaches

Hydrogen Trailer: Simple overflow process → not controllable (p, T)
- ✓ No infrastructure needed
- – Pressure reduces with each refueling



Methodology
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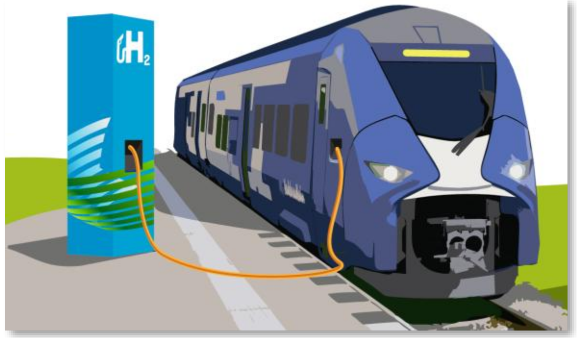

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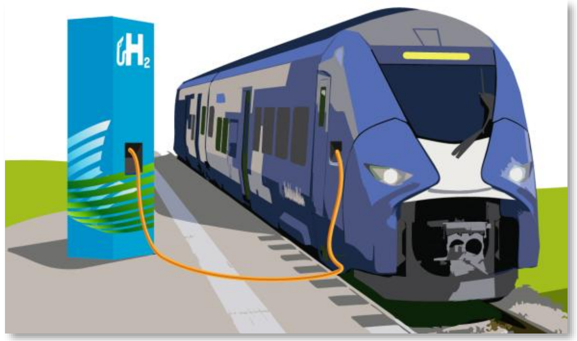
SAE J2601 – Communication

– Refueling parameters (tables) determined by data available to station (e.g. T_{amb}) – No Feedback from vehicle during refueling	– Additional data before refueling (less conservative tables) – Feedback from vehicle to monitor refueling (e.g. T_{tank})

Methodology
Refueling Approaches



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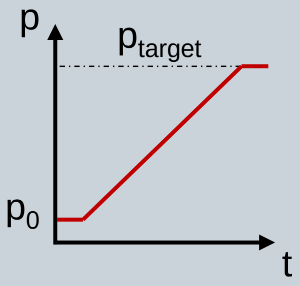
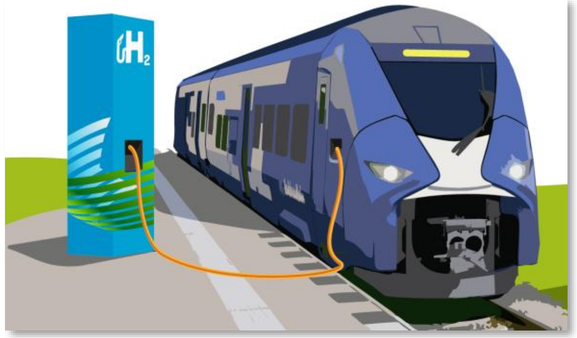
SAE J2601 – Strategy

Table-based
– Fixed pressure ramp rate (PRR) applied until pre defined target pressure reached – With communication: top-off with reduced ramp rate at the end for higher SoC



SoC – State of Charge

Methodology
Refueling Approaches



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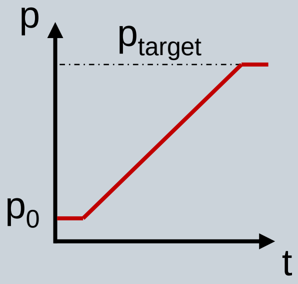


MC-Formula

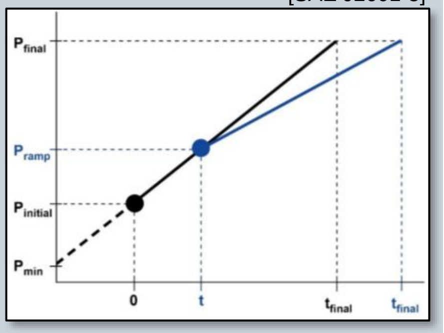
– Dynamic calculation of PRR every second

→ Influenced by expected refueling time t_{final}

→ Dependent on mass-avg. temp. of dispensed hydrogen

$$PRR = \frac{P_{final} - P_{ramp}}{t_{final} * \left(\frac{P_{final} - P_{initial}}{P_{final} - P_{min}}\right) - t}$$

[SAE J2601-5]



SoC – State of Charge

Simulation Results

Trailer vs Ramp-Rate

Boundary Conditions:

- **15 °C** Ambient Temperature
- **15 %** initial State of Charge
- **350 bar** Vehicle Target Pressure
- **None** Pre-Cooling

Hydrogen Trailer:

- 350/500 bar with 31.5 m^3

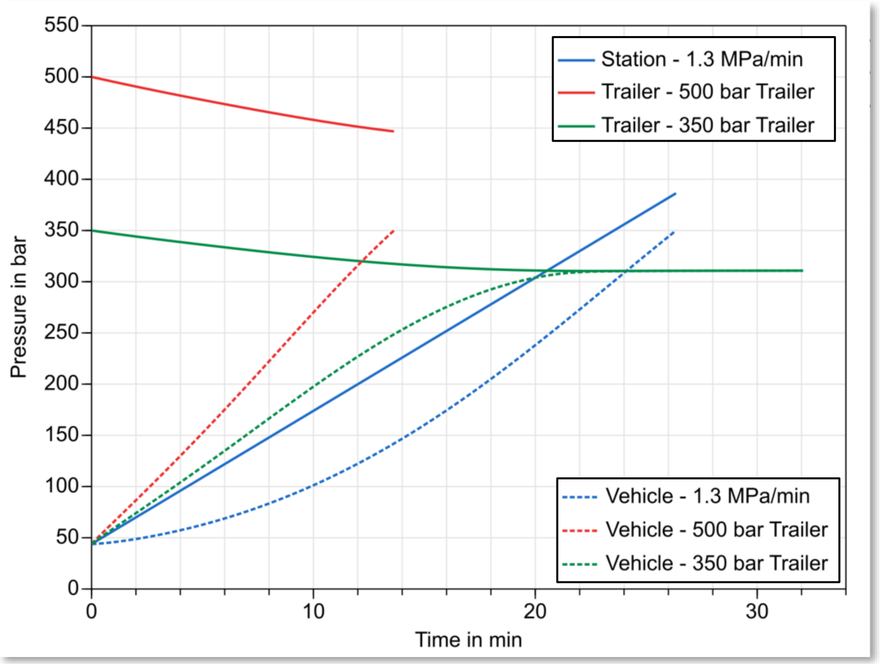
Table-Based:

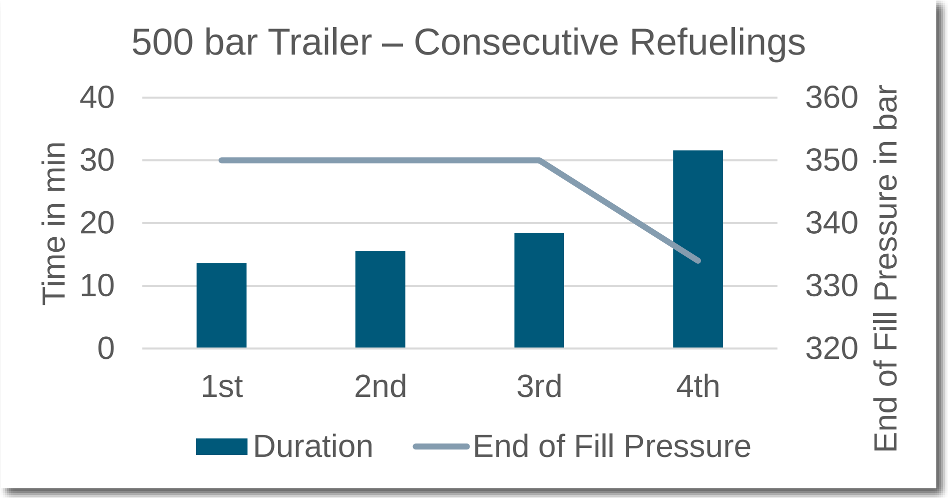
- 1.3 MPa/min

End of Fill …	500 bar	350 bar	1.3 MPa/min
… SoC	87.3 %	82.8 %	88.5 %
… Pressure	350 bar	311 bar	350 bar
Duration	13.6 min	32.1 min	26.4 min

*per tank system each 90 kg

Trailer refueling can be fast – depends on initial Trailer pressure
Ramp refueling is repeatable





Simulation Results

MC-Formula vs Table-Based

Boundary Conditions:

40 °C
Ambient Temperature

15.7 %
initial State of Charge

Standard
Station Target Pressure

-20 °C
Pre-Cooling

$$PRR = \frac{P_{final} - P_{ramp}}{t_{final} * \left(\frac{P_{final} - P_{initial}}{P_{final} - P_{min}}\right) - t}$$

MC-Formula*:

- with/-out communication

Table-Based:

- 2.1 MPa/min (SAE J2601-5, H35 Cat. D HF)

End of Fill …	MC-Formula (comm.)	MC-Formula (non-comm.)	2.1 MPa/min
… SoC	100 %	56.4 %	64.8 %
Average PRR	2.5 MPa/min	2.5 MPa/min	2.1 MPa/min
Station Target Pressure	Target SoC 100 %	367 bar	367 bar
Duration	19.4 min	12.4 min	15.1 min

*per tank system each 90 kg

MC-Formula without communication has no advantage over Table-Based strategy
MC-Formula with communication leads to complete refueling

*MC-Formula refueling logic implemented with simplifications

Conclusion

What refueling speeds are achievable?

- Achievable SoC range: 56 – 100 %
- Max. speed refueling speed: 14 min (5.3 %/min) with 87 % end of fill SoC

Is one refueling method universally best?

- No single “best method” → depends on use case

Method	Good for:	Limitations
Trailer	- Temporary/low-infrastructure deployment - Fast when trailer SoC high	- Performance drops with trailer SoC
Table-Based	- Simple implementation in station	- Incomplete fills w/o communication
MC-Formula	- Fast and complete fills with communication	- No advantage w/o communication

Recommendation:

- Vehicle-to-station communication for fast and safe refueling of hydrogen trains

→ Revision of intended communication interface necessary wasserstoff schiene HEIDEKRAUTBAHN

DLR

Thank you for your attention!

ENERTRAG
Eine Energie voraus

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NEB
NIEDERBARNIMER EISENBAHN

Federal Ministry of Transport

LAND BRANDENBURG

b-tu Brandenburg University of Technology Cottbus - Senftenberg

DLR Deutsches Zentrum für Luft- und Raumfahrt
German Aerospace Center

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Imprint

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