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SIMULATION-BASED ANALYSIS OF HYDROGEN REFUELLING STATION TO SUPPORT FUTURE HYDROGEN TRUCKS AND TECHNOLOGICAL ADVANCES

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ABSTRACT

Hydrogen is becoming increasingly relevant as an energy source to decrease carbon dioxide emissions across transportation, industry, and power generation sectors. One step to achieving this goal is to endorse the utilisation of hydrogen as a fuel in the transportation sector. A prerequisite for the widespread adoption of hydrogen trucks is accessible infrastructure, including refuelling stations. This paper presents a simulation model that analyses the potential spread of hydrogen infrastructure in the transport sector, focusing on refuelling station numbers and the feasibility of constructing new stations based on the projected increase in hydrogen trucks and refuelling speed. By simulating different scenarios, the model assesses infrastructure needs to meet projected hydrogen truck demand in the Bremen region in Northern Germany. Results suggest that with a refuelling rate of 5 kg/min and twelve stations, scenarios with over 50% hydrogen truck share are viable.

1 INTRODUCTION

The overall carbon footprint of various industries can be significantly reduced by producing hydrogen from low-carbon or renewable sources, such as green hydrogen from renewable energy sources like wind or solar power (Steinbacher et al. 2024). This shift towards hydrogen is essential for achieving decarbonisation goals and combating climate change by offering a cleaner alternative to traditional fossil fuel-based energy systems (Sam et al. 2023). Moreover, developing a sustainable hydrogen economy offers opportunities for domestic decarbonisation, economic development, and export (Mukelabai et al. 2022). The future cost of hydrogen depends on advancements along the supply chain, including production, conversion, transport, distribution, storage, and redistribution, with cost reductions driven by technological advancements like electrolyser technology. Expanding the hydrogen economy globally requires substantial investments but presents significant economic and environmental benefits regarding decarbonisation and energy transition (Mukelabai et al. 2022).

The road transport sector is a significant contributor to the total carbon emissions. It has been stated that emissions from the transport sector account for 22.9 % of total carbon emissions worldwide (Gilfillan et al. 2020). Heavy-duty traffic accounts for about eight per cent of global greenhouse gas emissions (Rose 2020). In 2021, around 740 million tonnes of carbon dioxide were emitted in the EU through the combustion of fuels in road transport. Heavy goods vehicles and buses accounted for 27%, and light commercial vehicles accounted for 10% (Bhat et al. 2021). This statistic highlights the significant impact of transportation on carbon emissions. The transition to hydrogen is seen as a promising solution to reduce carbon dioxide emissions, particularly in transportation, industry, and power generation sectors.

1.1 Research Contribution

This paper provides a simulation-based approach to analyse the potential spread of hydrogen infrastructure in the road-bound transport sector, focusing on the number of refuelling stations and the feasibility of constructing new stations based on the projected increase in the number of hydrogen trucks.

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As the demand for hydrogen grows, hydrogen as a fuel must continually evolve and optimise, addressing technological, economic, and regulatory aspects to unlock the full potential of hydrogen as a critical energy source in the global transition to a low-carbon energy future. Our literature research has shown that most works dealing with hydrogen refuelling stations are concerned with the optimal location of these stations to supply a predefined number of vehicles or trucks, but do not consider the scenario in which the demand for hydrogen increases and do not investigate the expected technological growth. The present work fills this gap and attempts to develop a simulation investigating the expected spread of hydrogen refuelling stations. The study uses a simulation approach that allows for detailed geospatial analysis, enabling a granular examination of the demand for hydrogen refuelling stations and their optimal distribution to support a growing fleet of hydrogen trucks. By simulating different scenarios, the developed discrete-event simulation model assesses the infrastructure requirements necessary to accommodate the expected rise in hydrogen demand from trucks, particularly in regions with high concentrations of hydrogen-consuming sectors, like mobility and public transportation.

1.2 Hydrogen Stations

The benefits of using hydrogen in gas stations include its potential to enable zero-emission transportation, reduce carbon emissions, and contribute to a cleaner environment. Hydrogen can be produced from renewable sources, offering a sustainable alternative to traditional fossil fuels. Additionally, hydrogen fuel cells are efficient and can provide longer driving ranges compared to electric vehicles, making them a promising option for the future of transportation (Rousseau 2018).

One measure to achieve this goal is to promote hydrogen as a fuel in the transport sector. In order to increase the spread of hydrogen fuel cell trucks, new suitable infrastructure, such as refuelling stations, must be made available (Steinbacher et al. 2024).

Hydrogen is becoming increasingly integrated into gas stations. Hydrogen filling stations, also known as hydrogen stations, are designed to facilitate the refuelling of hydrogen fuel cell vehicles quickly and efficiently. At a hydrogen station, the process of refuelling is quite similar to that of refuelling at a conventional petrol station. However, hydrogen is supplied at high pressure, requiring a watertight connection between the vehicle's receptacle and the pump due to its volatile nature. The hydrogen is pumped into the vehicle's fuel tank, which powers the fuel cell to generate electricity for driving. The only local emission of this process is water vapour, which is expelled through the vehicle's exhaust pipe. Key components of a hydrogen filling station include hydrogen storage tanks, hydrogen gas compressors, a pre-cooling system, and a hydrogen dispenser that can dispense hydrogen at pressures of 350 bar, 700 bar, or dual pressure dispensing, depending on the vehicle type (Cerniauskas et al. 2019). A typical hydrogen car can be refuelled in about three minutes, while buses and trucks may take around seven minutes.

Expanding hydrogen stations is crucial for the widespread adoption of hydrogen-powered vehicles. These stations are vital in providing green hydrogen obtained through electrolysis from renewable electricity sources (Wie et al. 2024).

The current state of hydrogen refuelling stations globally is characterised by ongoing advancements and challenges in integrating hydrogen as a clean fuel source for various applications, particularly in the transportation sector. Studies highlight the technical, economic, and logistic challenges associated with implementing hydrogen-based systems, emphasising the need for efficient modelling and optimal sizing of system components to ensure effective operation and energy production (Hidouri et al. 2024).

Furthermore, the research explores the potential for large-scale hydrogen fuel production from by-product hydrogen obtained through processes like steam cracking of natural gas liquids, showcasing the economic benefits and emissions reduction potential of such initiatives on a global scale (Palmer et al. 2021). Additionally, the development of centralised and localised hydrogen generation by ammonia decomposition presents opportunities to supply fuelling stations, industries, and remote applications with pure hydrogen, contributing to the expansion of hydrogen infrastructure worldwide (Ashcroft et al. 2022). These insights reflect a growing interest in leveraging hydrogen as a sustainable energy source and highlight the progress and challenges associated with establishing and expanding hydrogen refuelling stations globally.

The location of hydrogen refuelling stations is critical in enabling the widespread adoption of hydrogen fuel cell vehicles (FCVs) and the transition towards a hydrogen economy. The main factors determining the location of hydrogen refuelling stations include technical, economic, and logistic considerations. These factors are crucial in establishing an efficient and effective network of hydrogen refuelling stations to support the adoption of hydrogen as a clean fuel source for various applications, particularly in the transportation sector.

- Technical Factors: The technical aspects involve proximity to existing infrastructure, energy supply sources, and transportation routes. The availability of suitable space for station installation, access to water and electricity for hydrogen production, and compatibility with hydrogen storage and dispensing equipment are key technical factors influencing station location decisions (Kong et al. 2021).
- Economic Factors: Land costs, construction expenses, operational costs, and potential return on investment are essential in selecting viable locations for these stations. Additionally, the demand for hydrogen fuel in specific regions and the availability of funding or incentives can impact the economic feasibility of station deployment (Isaac et al. 2023).
- Logistic Factors: Logistic factors encompass supply chain management, distribution networks, and accessibility. Stations must be strategically located to ensure convenient access for hydrogen fuel users, optimise delivery routes for hydrogen supply, and integrate smoothly with existing transportation infrastructure. Population density, traffic patterns, and proximity to significant highways or urban centres are vital logistic factors influencing station placement (Cerniauskas et al. 2019).

By carefully evaluating these technical, economic, and logistic factors, stakeholders can make informed decisions regarding the optimal locations for hydrogen refuelling stations to support the growth of hydrogen-based transportation systems and contribute to a more sustainable energy future.

Hydrogen station planners determine the demand for hydrogen fuel cell vehicles in a given area through various methods and considerations. The first two methods are demand-oriented, while the last two methods are supply-oriented

- Mathematical Models: Planners utilise mathematical models to guide the planning of hydrogen infrastructure, considering factors like geographic locations and technology types to support future fuel cell vehicles, particularly long-haul fuel cell trucks (Hernández et al. 2021).
- Network Modelling: This technique estimates the demand for hydrogen refuelling stations in a specific area. For instance, a study indicates that a network of about 140 stations with a daily demand capacity of 30 tons of hydrogen per location in Germany is needed (Rose 2020).
- Integration with Production and Delivery Systems: The design and cost of hydrogen stations are integrated with production and delivery systems to ensure efficient deployment strategies that meet the demand for fuel-cell electric vehicles (Greene et al. 2020).
- Location Planning Strategies: Planners recommend hydrogen refuelling station candidates among existing gas stations with surplus surface areas in high-demand neighbourhoods, indicating a strategic approach to meet local demand and demand uncertainty (Fuse et al. 2021).

1.3 Hydrogen Trucks

The literature does not explicitly state the current market share of hydrogen trucks. However, plenty of works provide some insights into the transition towards hydrogen-powered heavy-duty trucks (HDTs) and the opportunities and challenges associated with this shift.

Li et al. (2022) discuss the transition of HDTs from diesel to hydrogen fuel cells, highlighting the potential benefits of this transition, such as the ability to maintain the contribution of HDTs to freight transport at nearly zero carbon dioxide emissions. The paper also outlines the challenges, including the high total usage cost, research and development barriers, and market share competition from other alternatives. Greene et al. (2020) focus on the current status and future cost projections of hydrogen delivery and dispensing infrastructure. It estimates that the levelized cost of hydrogen delivery and dispensing could reach \$5/kg by 2025 at stations supplied by liquid hydrogen tanker trucks and \$2/kg at stations supplied by pipelines, given research and development accomplishments and aggressive market penetration of fuel cell vehicles. Albatayneh et al. (2023) discuss the future of electric and hydrogen cars and trucks, mentioning significant investments in hydrogen vehicles and the potential benefits for heavy transport in remote areas. However, hydrogen vehicles, including trucks, may face challenges competing with electric vehicles due to cost and infrastructure issues. While the exact market share of hydrogen trucks is not provided, it is stated that hydrogen trucks are part of an emerging market with growth potential, especially in niche areas and for heavy-duty transport, despite facing competition and challenges from electric vehicle technologies. The market share is likely still relatively low but with the potential for significant growth in the coming years as hydrogen fuel cell technology and infrastructure continue to evolve.

2 SIMULATION APPROACH

In order to analyse what hydrogen infrastructure is needed for different possible future scenarios and whether this infrastructure is sufficient or not, simulation is the most suitable approach for conducting such studies. Figure 1 shows a screenshot of the simulation model for three and twelve stations.

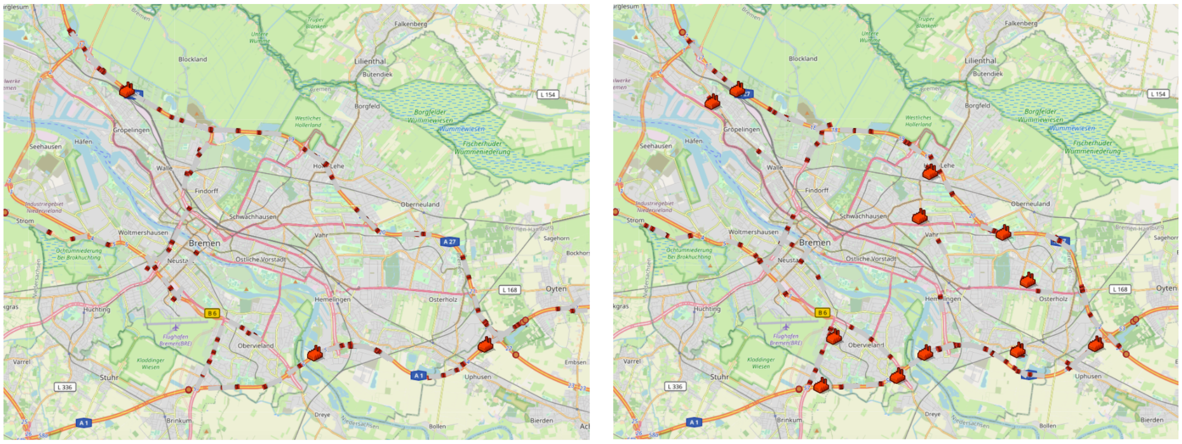

Figure 1: Screenshot of the simulation model, with three (left) and twelve (right) stations, based on OpenStreetMap.

2.1 Definition of Scenarios and Experiment

The scenarios are defined by various parameters that can influence a possible change in infrastructure based on technological advances and economic and geospatial data. It includes the share of trucks using hydrogen as a fuel, the refuelling rate and the number of hydrogen stations are shown in Table 1. The experiment scenarios are defined as combining these three parameters, giving 36 possible scenarios.

Table 1: Simulation parameters for scenario design.

Parameter	Category	Value Range
GIS Map of Bremen	Geospatial data	GIS Map of 2024
Daily truck traffic	Economic, environmental	Data from 2017
Refuelling rate	technological advance	1; 3 or 5kg/min
Share of hydrogen truck	Economic	5%; 15%; 25% or 50%
Number of hydrogen stations	Economic	3; 6 or 12 stations

Specific and concrete numbers regarding the exact share of hydrogen trucks in the next decades are not readily available due to the dynamic nature of technology adoption, regulatory changes, and market developments. Predictions and forecasts often vary among organisations, and they can change over time based on new information and trends. However, some studies and reports have provided estimates, although these are subject to a certain degree of uncertainty. For example, the International Energy Agency (IEA) has projected that hydrogen fuel cell trucks could represent a significant share of heavy-duty vehicle sales by 2030 and beyond, potentially reaching double-digit percentages of the total market share in some regions. Therefore, different shares are assumed for this experiment.

Other parameters, such as the tank capacity of a hydrogen truck, are not considered in this study, as no information on tank volume could be found in the literature. However, the tank capacity can vary depending on factors such as the size of the truck, its intended use, and technological advancements. Generally, hydrogen trucks can have tank capacities ranging from around 20 kilograms (for smaller vehicles) to over 80 kilograms (for larger trucks) (Hyundai, 2024; Nikola, 2024). These tanks typically store hydrogen gas at high pressure, often at 350 bar, to maximise storage capacity within a limited space. As hydrogen fuel cell technology advances, we may see improvements in tank capacity and efficiency.

The simulations run for a duration of four simulated days. Furthermore, if the queue length at a station exceeds 100 trucks during the simulation, the scenario is terminated and not considered in the results. This precaution ensures that unrealistic scenarios are excluded from the study.

2.2 Structure of the Simulation Model

In this paper, a multi-agent-based and discrete-event simulation is developed, whereby all restrictions of the processes are described. The simulation model is implemented using the simulation tool AnyLogic 8.7.11 and models the refuelling processes of trucks crossing the city of Bremen. The trucks, the stations, and the other entities are modelled as agent objects as provided by the simulation tool. All process times vary stochastically. Each agent's logic is modelled using state diagrams or the process modelling library. The agents are linked with each other in such a way that the different processes are initiated and triggered via defined messages (events) in the simulation. The initial fuel state of each truck when entering the city of Bremen and the number of arrival trucks per hour are modelled with uniform distribution functions. In summary, Figure 2 provides an overview of the structure of the developed simulation.

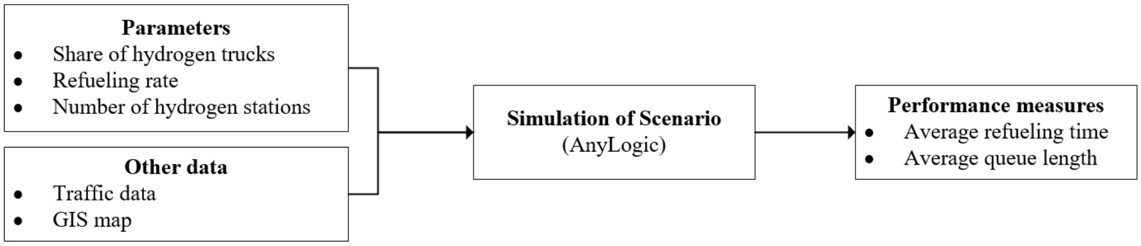

Figure 2: Structure of the developed simulation.

In the developed simulation, the average daily heavy vehicle traffic volumes in Bremen are used in the simulation (Bau Bremen 2015). The data indicates the number of trucks crossing a predefined location and intersection in both directions daily. The simulation does not consider other vehicle types, such as cars. The number of trucks crossing the most important intersections is extracted, and the hourly traffic volumes are calculated. The refuelling rate, for instance, 1 kg/min, specifies the quantity of hydrogen (H_2) refuelled per minute. Table 2 shows an example of the most frequently used intersections. It is essential to highlight that out of roughly 18,000 trucks, some have been logged multiple times due to traversing various intersections within the city on the same day.

To include the dynamics of a real-world traffic system, further process parameters have been considered, like the location of stations, the arrival frequency of trucks depending on the daily traffic data,

Table 2: Example of an intersection with a high number of trucks passing through a daily.

location/intersection	**Number of trucks passing through daily**
Bremer Kreuz (A1 / E 22)	7670
Brinkum (A1)	7330
Industriehafen (A27)	4030
Bremer Kreuz (A27 / E 234)	2600

and the tank capacity when arriving in Bremen. The location of the stations is determined based on traffic data, while the other process parameters are modelled using uniform distributions. Each station has five dispensers to supply the trucks. The station has a storage for 30 tons and is supplied by a tanker if its stock falls below three tons. Considering the arrival frequency, most trucks (90 %) drive through Bremen between 06:00 and 20:00, and the remaining 10 % between 20:00 and 06:00. The process parameters considered in the simulation are summarised in Table 3. For instance, in the 50% scenario, the arrival frequency is 18 * 50% = 9 trucks per minute. Moreover, whenever the initial tank (the tank volume on arrival in Bremen) is less than 10 kg, the truck selects the nearest station with the shortest queue length.

Table 3: Parameter with uniform distribution.

Process parameter	Value
Arrival frequency per minute	18 times share of hydrogen truck
Initial tank	Uniform distribution(3kg, 30kg)

To evaluate the different scenarios, we considered the following performance measures: The average refuelling time is the duration a truck occupies the station until it completes refuelling. This duration encompasses both the waiting time and the actual refuelling process. The refuelling process includes the refuelling time according to the current tank status, the refuelling rate and a three-minute fixed manoeuvring time. The average queue length indicates the number of trucks waiting for refuelling at a station.

Figure 3 illustrates the logic employed to model a dispenser. The simulation model utilises blocks from the AnyLogic fluid library. Each dispenser is linked to the station via a small pipe (pipe H2) and is characterised by a flow rate and a unique identifier (index). When a truck arrives at the station and an available dispenser is selected, the truck proceeds to the dispenser. The volume of H2 required is then calculated based on the truck's tank capacity.

Consequently, the valve opens to allow the H2 to flow at the specified rate. Once the truck's tank is complete, the valve closes and departs from the station. The simple logic of the dispenser is integrated with the more complex logic of the station.

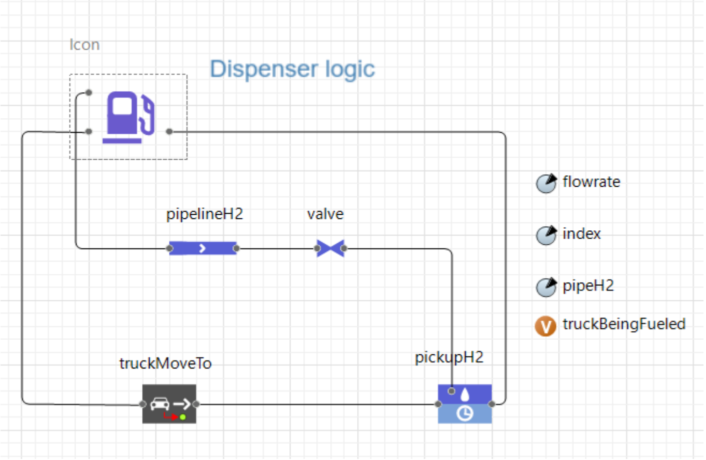

Figure 3: Screenshot of simulation logic of a dispenser.

3 SIMULATION RESULTS

This section describes the simulation run of the nine possible combinations for each value of a share of hydrogen trucks.

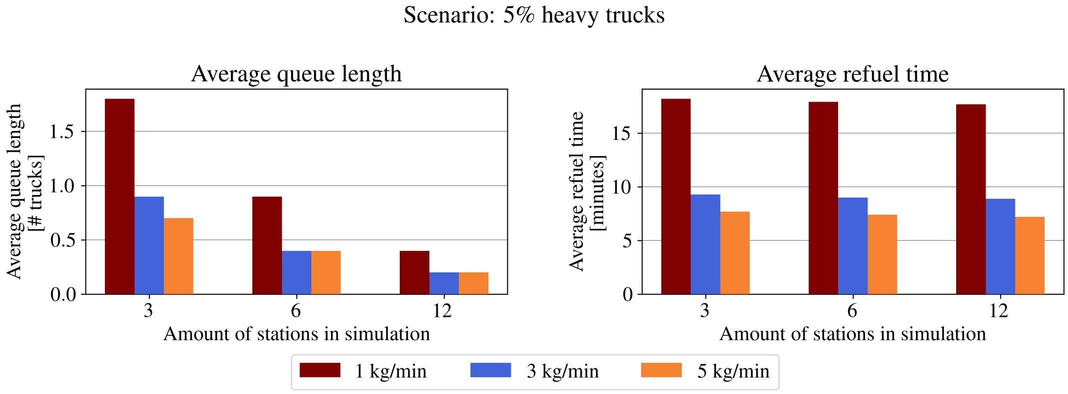

Figure 4: Simulation results of the scenarios with a 5% share of hydrogen trucks.

Figure 4 shows the results of the simulation experiments for a share of 5% hydrogen-powered trucks. The left shows the average queue length, while the right figure shows the average refuel time. With an enhanced refuelling speed, three stations are adequate at a 5% share. Notably, the results indicate negligible differences between three and twelve stations. Despite the average time a truck spends at a station being approximately 7.7 minutes, increasing the stations to twelve yields only a 20-second improvement (Figure 4, right).

However, a rise in the proportion from 5% to 15% indicates an impending need for increased station numbers. With three stations in this scenario, the average refuelling time exceeds two hours, which could be reduced to 64.8 minutes with enhanced refuelling speed, still representing a considerable duration (Figure 5, right). Therefore, opting for six stations and a refuelling speed improvement of 3 kg/min yields favourable outcomes. Further improvements, such as 7.5 minutes with a refuelling speed of 5 kg/min, demonstrate efficiency gains and obviate the need for additional investments in new station construction. In this context, highlighting the significance of technological advancement, the scenario featuring six stations with a refuelling rate of 3 kg/min surpasses the scenario with twelve stations and a refuelling rate of 1 kg/min.

Figure 6 shows the results of the simulation experiments for a share of 25% hydrogen-powered trucks. In this scenario, the simulation is terminated prematurely at three stations because the queue lengths surpass

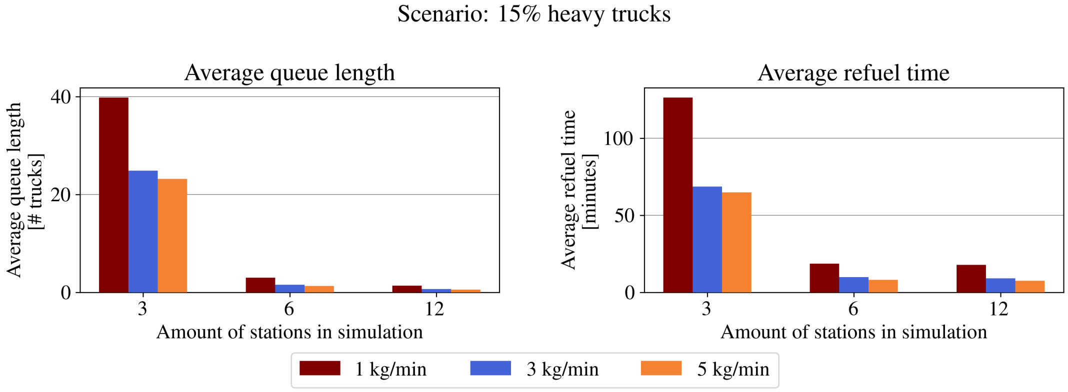

Figure 5: Simulation results of the scenarios with a 15% share of hydrogen trucks.

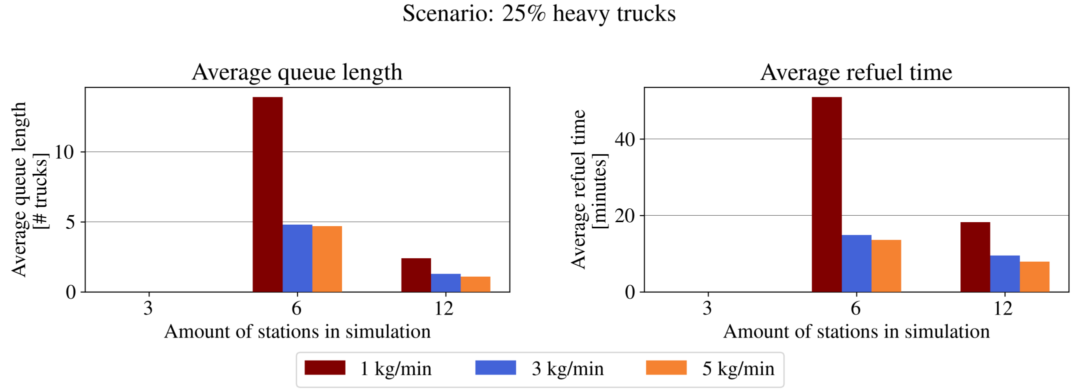

Figure 6: Simulation results of the scenarios with a 25% share of hydrogen trucks.

the predefined critical threshold of 100 trucks per station, as specified in the simulation configuration. Consequently, no results were obtained for the three stations. The average refuelling time for six stations and refuelling speed of 5kg/min is still acceptable at 13.6 minutes. This average can be improved to 7.9 minutes with a number of 12 stations. Here, to emphasise the importance of technological progress, the scenario with six stations and a refuelling rate of 3 kg/min outperforms the scenario with twelve stations and a refuelling rate of 1 kg/min.

In the scenarios where the share is set at 50% (Figure 7), the simulation was cancelled for 3 and 6 stations due to the queue length reaching unacceptable levels. Under these circumstances, only scenarios featuring 12 stations can effectively handle the anticipated surge in hydrogen trucks in the future. The results demonstrate that the expansion of station numbers indeed influences both refuelling time and queue length. On the one hand, they are escalating the proportion of hydrogen trucks without corresponding technological advancements, resulting in a linear rise in refuelling station numbers. This necessitates significant investments and may impede the widespread adoption of hydrogen. Conversely, augmenting refuelling speed demonstrates that the projected surge in hydrogen vehicles can be effectively managed with strategically positioned stations.

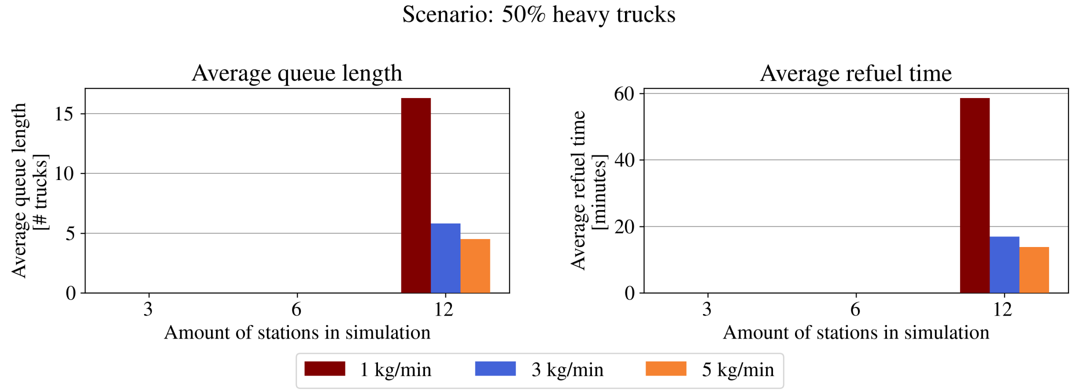

Figure 7: Simulation results of the scenarios with a 50% share of hydrogen trucks.

In summary, doubling the stations or refuelling rate in the same case does not necessarily result in halving refuelling times. Additionally, the results underscore the importance of investing in technological advancement rather than solely focusing on constructing more stations. Another aspect not addressed in this paper is extending the range of trucks, which could facilitate the adoption and proliferation of hydrogen trucks.

4 CONCLUSION

Hydrogen is increasingly recognised as a pivotal energy source for reducing CO2 emissions, especially in transportation, industry, and power generation sectors. A crucial step towards achieving this goal involves advocating for using hydrogen as a fuel in the transportation sector. To facilitate the widespread adoption of hydrogen fuel cell trucks, it is imperative to establish new, appropriate infrastructure such as refuelling stations. This paper introduces a simulation model designed to analyse the potential expansion of hydrogen infrastructure within the transportation sector, focusing on the number of refuelling stations and the feasibility of constructing new stations based on projected increases in the number of hydrogen trucks and refuelling speeds. The model simulates various scenarios and evaluates the infrastructure requirements necessary to accommodate the anticipated surge in hydrogen demand from trucks, particularly in the Bremen region.

A comprehensive set of 36 scenarios were simulated, encompassing variations in the number of stations, refuelling speed, and anticipated proportion of hydrogen-powered trucks. The findings underscore the significance of enhancing refuelling speed over expanding the number of stations. Within this framework, the results demonstrate that with a refuelling speed of 5 kg/min and twelve stations, a scenario with a share exceeding 50% is achievable. We intend to examine additional factors that may influence the simulation outcomes in future works. This includes investigating the impact of station locations and evaluating whether an optimal station placement, determined by traffic patterns, could affect the results. Furthermore, we will explore anticipated technological advancements in fuelling capacity and truck range.

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