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Technical and Operational Assessment of a Large-Scale Hydrogen Mobility System Under Extreme Winter Conditions: Evidence from the Beijing 2022 Winter Olympics

Yingying Liu ¹, Xu Zhao ^{1,*}, Yuting Xue ¹, Yue Qiu ² and Mengqiu Cao ³ 

¹ School of Economics and Management, North China Institute of Aerospace Engineering, Langfang 065000, China

² School of English Studies, Beijing International Studies University, Beijing 100024, China

³ Bartlett School of Environment, Energy and Resources, University College London, London WC1H 0NN, UK

* Correspondence: zhaoxu123@nciae.edu.cn

Abstract

As the decarbonisation of transport continues, hydrogen fuel cell vehicles (HFCVs) are attracting increasing attention, particularly in heavy-duty and high-utilisation applications where long operating ranges and rapid refuelling are required. Transferring HFCVs from individual demonstrations to large-scale fleet operation, however, depends on the joint performance of vehicles, hydrogen supply, refuelling infrastructure and operational management. Our study examines the technical and operational feasibility of large-scale hydrogen mobility using the Beijing 2022 Winter Olympic and Paralympic Games as a case study. The analysis covers vehicle deployment and scenario matching, hydrogen production and road distribution, refuelling infrastructure, digital monitoring, fleet coordination, and operational performance under extreme winter and mountainous conditions. More than 1200 HFCVs operated for 52 days across over 80 routes and accumulated more than 3.5 million vehicle-kilometres, supported by 11 hydrogen refuelling stations and approximately 20 t d⁻¹ of hydrogen production capacity. The case study shows that successful fleet operation depended on matching vehicle configurations to transport tasks, coordinating hydrogen supply with refuelling demand, maintaining redundancy across the supply network - and integrating real time monitoring with fleet dispatch. These findings help to identify the main technical and operational conditions for large-scale hydrogen mobility and provide practical guidance for centralised applications, such as public transport, shuttle services and logistics fleets.

Keywords: hydrogen fuel cell vehicle; hydrogen mobility system; Beijing Winter Olympics; extreme winter operation; hydrogen value chain; hydrogen refuelling infrastructure; digital monitoring; case study



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1. Introduction

The decarbonisation of road transport has increased interest in hydrogen and fuel cell technologies as alternatives to fossil-fuel-based powertrains [1]. Hydrogen fuel cell vehicles (HFCVs) offer long driving ranges and relatively short refuelling times, making them particularly relevant to heavy-duty and high-utilisation transport applications where continuous operation is required [2]. As HFCVs move beyond small-scale demonstrations, their deployment increasingly depends on the availability of hydrogen supply, refuelling infrastructure, and operational support. The practical performance of a hydrogen fleet is

therefore determined by the operation of the wider mobility system rather than by vehicle specifications alone.

Hydrogen mobility has a distinct but conditional role within transport decarbonisation. HFCVs produce no carbon dioxide from onboard fuel conversion [3]. They also avoid conventional tailpipe pollutants [4]. Their well-to-wheel advantage depends on the hydrogen production route [5]. Compression and delivery conditions further influence life-cycle performance [6]. Vehicle utilisation then determines how this upstream burden is distributed across transport service [7]. Relative to diesel, this creates a route to lower operational emissions and local air-pollution exposure. Relative to battery-electric vehicles, the principal value is not universal energy efficiency, but the combination of high gravimetric energy density [1]. Short refuelling time provides an additional operational advantage [2]. Lower dependence on long charging dwell can preserve range, payload, and vehicle availability in heavy-duty or high-utilisation service [4]. These characteristics are most relevant to buses, long-distance or inter-zone shuttles, logistics fleets, and other centrally managed vehicles with high daily mileage, constrained turnaround time, and predictable depot or corridor refuelling. Battery-electric vehicles may remain preferable where routes are shorter, charging dwell is available, and electricity can be supplied directly. Hydrogen should therefore be evaluated as a complementary option for duty cycles in which range, payload, and rapid fleet turnaround outweigh its higher conversion and infrastructure requirements.

Previous studies have examined several aspects of HFCV development. Research on hydrogen mobility has identified infrastructure availability, cost, technology maturity, and market development as important factors affecting HFCV adoption [8]. Studies of heavy-duty fuel cell vehicles have focused on powertrain technologies, vehicle configurations, application scenarios and technical challenges [9], while other work has evaluated vehicle performance, emissions, and economic characteristics under different transport conditions [3]. Hydrogen production, storage, and distribution have also received considerable attention because fuel availability and delivery directly affect vehicle operation [10]. Hydrogen refuelling stations form the interface between supply and fleet demand, while station capacity, location, pressure compatibility and service performance influence vehicle availability [11]. These studies provide a substantial technical basis for hydrogen transport, but the operation of vehicles, hydrogen supply, refuelling facilities and fleet management has often been examined separately. The shift from individual vehicles to large fleets creates a different operational problem. Hydrogen should be produced and delivered when and where vehicles require it, while refuelling stations need to be able to accommodate concentrated arrivals without disrupting transport schedules. Vehicle configuration also has to reflect route distance, passenger demand, road conditions and available refuelling opportunities. These requirements become more demanding in winter and in mountainous environments. Low temperatures affect fuel-cell thermal management and vehicle energy consumption, while high altitude, steep gradients, cabin heating and intensive service schedules place additional demands on vehicle performance and energy supply [12]. Under these conditions, fleet operation depends on the combined performance of the vehicles and the infrastructure and management systems that support them.

The Beijing 2022 Winter Olympic and Paralympic Games provide a large-scale case study in which these conditions occurred simultaneously. More than 1200 HFCVs were deployed across the Beijing, Yanqing, and Zhangjiakou competition zones under temperatures approaching $-30\text{ }^{\circ}\text{C}$, elevations of up to 2198 m, and gradients of up to 16%. The fleet was supported by hydrogen production facilities, road distribution using tube trailers, dual-pressure refuelling infrastructure, digital monitoring, and coordinated fleet management. During the event, vehicles operated across a wide range of shuttle, inter-zone, and

dedicated transport services, creating a real-world setting in which vehicle performance and hydrogen supply had to be coordinated under intensive winter operations. This study investigates the technical and operational feasibility of the Beijing 2022 hydrogen mobility system. It examines the matching of vehicle configurations with transport requirements, the organisation of hydrogen production and road distribution, the performance of refuelling infrastructure and the role of digital monitoring and fleet coordination. Vehicle operating records, hydrogen supply and refuelling records, monitoring data, technical documents, and project materials are used to assess fleet operation and operational stage environmental performance. The study uses this case to identify the technical and operational conditions that supported large-scale HFCV deployment and to examine their relevance to centralised hydrogen transport applications, including public transport, shuttle services and logistics fleets.

Beijing 2022 was selected, because it combines fleet scale, a sustained operating period, demanding winter and mountain routes, and all major links from hydrogen production to vehicle dispatch within one event. Government reporting records more than 1200 HFCVs and over 3.2 million km of operation across the three competition zones [13]. The official Games time inventory uses a narrower boundary and reports 816 hydrogen-fuelled vehicles, including 140 MIRAI cars and 107 COASTER minibuses [14]. The project records analysed here cover buses, minibuses, and passenger cars operating for 52 days on more than 80 routes. Conditions included temperatures approaching -30°C , elevations up to 2198 m, steep gradients, bends, and snow- or ice-affected roads [15]. The deployment also connected hydrogen production, tube-trailer distribution, 35 and 70 MPa refuelling, digital monitoring, and fleet dispatch; a broader regional inventory reported more than 30 refuelling facilities and a dedicated data platform [16]. The case therefore allows the study to examine system coordination at fleet scale while retaining the boundaries of an event specific operation.

This study addresses three questions: (RQ1) how were vehicle classes matched to different service tasks and environmental conditions; (RQ2) how were hydrogen supply, road distribution, refuelling, monitoring, and dispatch coordinated to maintain transport service; and (RQ3) which operating lessons can be transferred to other centrally managed fleets, given the limits of the available records? The analysis reconstructs the system configuration, evaluates the indicators supported by consistent data, and distinguishes event-specific arrangements from more widely applicable operating practices.

2. Research Design and Methods

2.1. Case Study Design and Data Sources

This study examines the hydrogen mobility system deployed for the Beijing 2022 Winter Olympic and Paralympic Games. The analysis covers fuel-cell buses and passenger vehicles, hydrogen production and road delivery, refuelling infrastructure, digital monitoring, and operational coordination (Figure 1). Table 1 defines the spatial, functional, and temporal scope. The assessment addresses vehicle adaptation, fleet operation, hydrogen supply and refuelling, monitoring and coordination, and operational stage emissions.

Case study research is suitable for examining a contemporary system in its operating context and for combining evidence from different sources [17]. It also treats the case as a bounded, context dependent system [18] and relates empirical observations to an explanatory account [19]. This study therefore uses a single case design with system level explanatory aims. The Beijing 2022 hydrogen mobility system is the case, while fleet deployment, hydrogen supply, refuelling, monitoring, and dispatch are examined as linked components. The study reconstructs how these components operated together; it does not test the causal effect of an individual component.

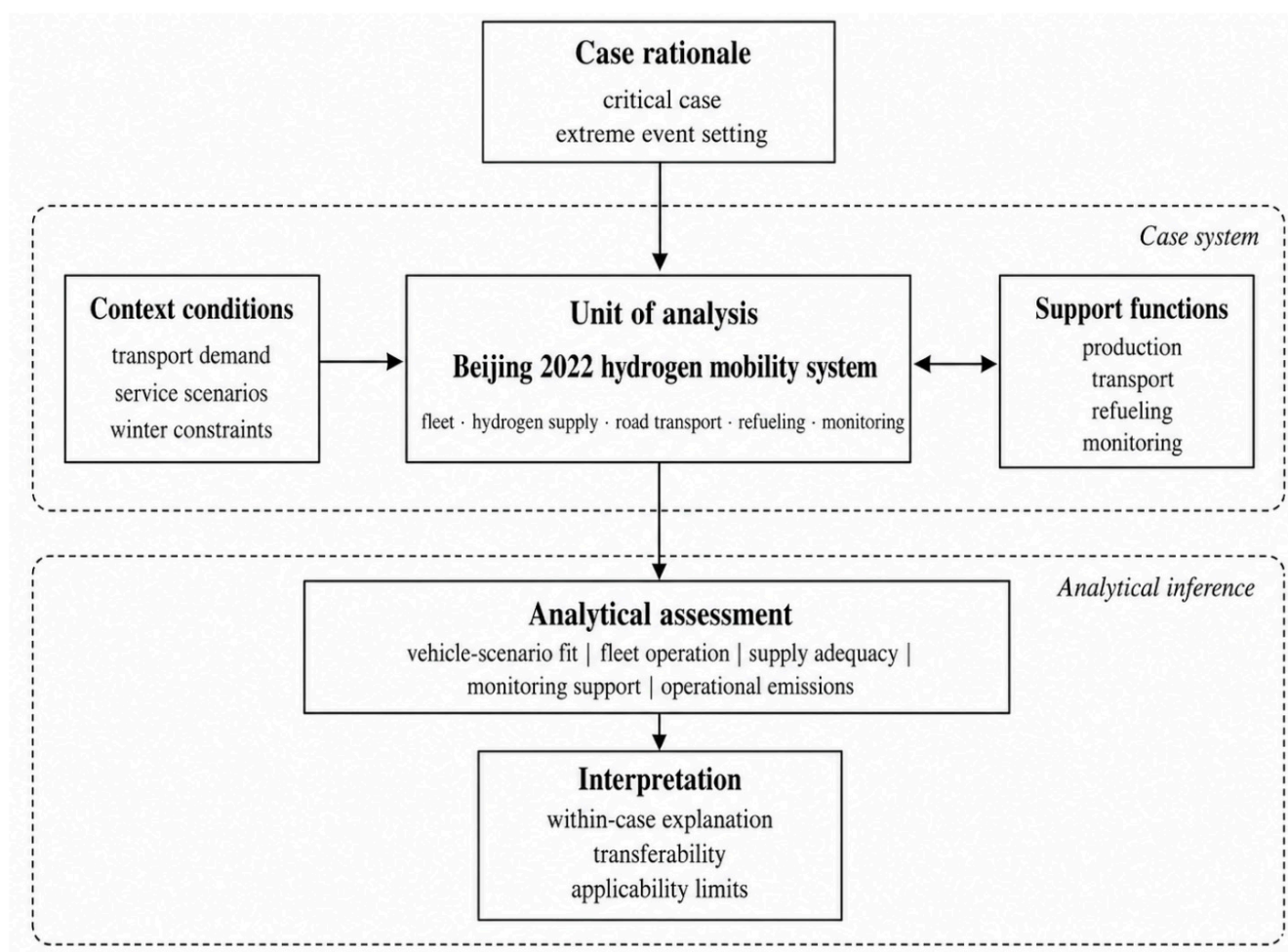


Figure 1. Research framework of the Beijing 2022 hydrogen mobility case study.

Table 1. Study scope of the Beijing 2022 hydrogen mobility case.

Scope Dimension	Coverage
Spatial coverage	Beijing, Yanqing, and Zhangjiakou competition zones and the hydrogen production, road distribution, and refuelling facilities serving event transport
System coverage	HFCV fleet, hydrogen production and road supply, refuelling infrastructure, digital monitoring, and operational coordination
Study period	Vehicle preparation and deployment, Olympic and Paralympic operations, and directly related event records
Assessment content	Vehicle adaptation, fleet operation, hydrogen supply and refuelling, monitoring and coordination, and operational-stage emissions

The spatial boundary covers the Beijing, Yanqing, and Zhangjiakou competition zones. The temporal boundary is the 52-day analytical window covering vehicle preparation and Olympic and Paralympic operations together with directly related records. The functional boundary includes the fleet, hydrogen production, road distribution, refuelling, monitoring, dispatch, and operational emissions. Triangulation compared vehicle counts, dates, locations, capacities, mileage, dispensing events, alerts, and reported outcomes across source categories. The analysis reconstructed the operating context, mapped vehicle classes to service scenarios, traced the supporting value chain, calculated indicators with compatible numerators and denominators, and compared the results with published evidence. This

design supports within case explanation and analytical transfer to similar centralised fleets, but not statistical generalisation or component-level causal attribution.

Case selection was purposive. The scale made vehicle allocation, clustered returns, and refuelling demand fleet-level problems. The 52 day period captured sustained operation rather than a short demonstration, and the three-zone network included urban, inter-zone, and mountain services with different routes and refuelling opportunities. The records also cover the main technical and organisational links of the system: four principal suppliers, more than 300 tube trailers, approximately 20 t d^{-1} of production capacity, 11 principal stations, 35 and 70 MPa vehicle interfaces, and a cloud-based monitoring and dispatch platform. Public reports give different totals because the Games time inventory uses a narrower boundary [14], whereas the wider regional demonstration includes additional facilities [16]. These features make the case suitable for examining vehicle–scenario fit, temporal capacity matching, redundancy, and digital coordination. Event-specific funding, reserve capacity, and administrative support are considered when interpreting transferability.

Figure 1 defines the Beijing 2022 hydrogen mobility system as the case and shows how operating context, supporting functions, evidence, and interpretation are connected.

Table 1 defines the spatial, functional, temporal, and assessment boundaries used to select records for the analysis.

Tables 2 and 3 identify the evidence used for each part of the analysis and retain the original time windows and denominators where reporting boundaries differ.

As shown in Tables 2 and 3, the analysis proceeded from transport demand and environmental conditions to vehicle configuration and system support. Service scenarios and route requirements were first used to reconstruct event demand. Vehicle classes and technical configurations were then related to these requirements. Hydrogen production, road distribution, refuelling services, and digital monitoring were examined alongside fleet operation. Reported operating outcomes were assessed using descriptive indicators and order-of-magnitude calculations where compatible data were available.

Table 2. Data sources and their analytical applications.

Data Source	Representative Content	Analytical Application
Vehicle planning and deployment records	Service scenarios, vehicle requirements, route characteristics, and fleet allocation	Reconstruct vehicle selection and deployment
Project technical documents	Vehicles, hydrogen production, distribution, refuelling, and monitoring technologies	Characterise technical configuration
Vehicle operating records	Fleet size, vehicle classes, mileage, routes, service period, and operating outcomes	Assess fleet operation
Hydrogen supply and refuelling records	Production capacity, road distribution, dispensed hydrogen and refuelling events	Assess hydrogen supply and refuelling service
Digital monitoring records	Vehicle status, operational alerts, and safety information	Assess monitoring and operational support
Project and public materials	Technical parameters and reported event outcomes	Cross check key information

Table 3. Provenance, coverage and analytical use of quantitative data.

Data Type	Acquisition Channel and Source	Time Range	Vehicle or Station Coverage	Core Variables	Analytical Use and Evidence Boundary
Fleet inventory and activity	Project planning and operating records (restricted); government/Xinhua release [13]	Preparation and Games-related operation; 52-day analytical window in the project records	>1200 HFCVs; categorised total of 1206; Beijing, Yanqing and Zhangjiakou; >80 routes	Vehicle count and class, service days, route count, aggregate mileage (>3.5 million km in project records; >3.2 million km in [13])	Deployment scale, fleet activity indicators and continuity; totals are not merged when reporting boundaries differ
Games-time vehicle inventory	Beijing 2022 Post-Games Sustainability Report [14]	Games-time official-vehicle reporting period	816 hydrogen-fuelled official vehicles, including 140 MIRAI cars and 107 COASTER minibuses	Vehicle technology, class and Games time mileage reported for selected groups	Independent cross check of fleet composition; narrower denominator than the wider project fleet
Route allocation and vehicle specifications	Deployment plans, technical specifications and project test records (restricted); public post-event report [15]	Pre-Games testing through event operation	Zhangjiakou allocation sample (623 vehicle assignments); representative 12 m and 9 m buses; 212 inter-zone buses in [15]	Users, route length, gradient, vehicle size, fuel-cell power, storage pressure/capacity, range, rated refuelling time and cold-start observations	Vehicle scenario matching and winter-readiness interpretation; no route-level load or energy denominator
Hydrogen production and road logistics	Project technical documents and supply records (restricted); industry report used for boundary cross-check [16]	Event configuration and operating period	Four principal suppliers, >300 tube trailers, 11 principal stations; wider regional inventories report >30 facilities [16]	Nominal production capacity ($\sim 20 \text{ t d}^{-1}$), production route, trailer movement, delivery distance ($\sim 50\text{--}100 \text{ km}$), pressure and location	Supply architecture, redundancy and nominal supply-demand framework; delivered daily mass and peak inventory are incomplete
Station dispensing and service	Hydrogen supply/refuelling logs (restricted); trade media report relaying station/operator data [20]	Station-specific 55 day operating period in [20]	One representative Jinlong station for 62,693 kg and 5098 events; network-level queue and waiting-time observations	Dispensed mass, event count, pressure, rated refuelling time, queue length, waiting time and continuous-operation test	Mass per event and station day throughput; not a fleet-wide hydrogen-consumption or station-utilisation denominator
Digital monitoring and alerts	Cloud-platform monitoring records (restricted)	Event operating period; monitoring start/stop times not consistently available	724 monitored vehicles; 142 recorded alerts	Alert count and category, vehicle status and safety information; unique vehicle-event linkage incomplete	Monitoring coverage and alert intensity; cannot estimate unique vehicle failure probability or downtime
Service outcomes and operational emissions	Fleet operating records and project documentation (restricted); government release used for emissions cross-check [13]	Event operating period	Aggregate fleet and assigned transport services	Mileage, scheduled-service outcomes, reported on-time performance, incidents, interruptions and reported CO ₂ avoidance (>2.6 kt)	Operational continuity and tailpipe counterfactual check; trip denominator and upstream emissions are unavailable

Table 3. Cont.

Data Type	Acquisition Channel and Source	Time Range	Vehicle or Station Coverage	Core Variables	Analytical Use and Evidence Boundary
External comparison datasets	NREL fleet report [21]. Dynamometer energy study [22]. Real-world bus energy study [23]. Toyota event report [24]. Paris 2024 sustainability report [25]. Refuelling-station sizing study [26]. Refuelling-scheduling study [27]. Real-world fleet study [28]. Lifecycle pathway study [29].	2014 and 2025–2026 publications; comparator observation periods vary	Whistler buses, recent fuel-cell and battery-electric buses/trucks, Tokyo 2020 and Paris 2024 fleets	Hydrogen consumption, availability, load/HVAC effects, life cycle emissions, costs and infrastructure scheduling	Contextual comparison only; not pooled with Beijing data because vehicle classes, duty cycles and system boundaries differ
Interview evidence	No structured interview dataset was documented for the quantitative analysis; stakeholder quotations in public news reports were treated as secondary context	Not applicable	No defined interview sample, role distribution or site coverage	No interview derived quantitative variable was used	Excluded from quantitative denominators; interview protocols, dates and respondent metadata would be required for reproducible use

2.2. Evaluation Framework and Analytical Procedures

The evaluation covered vehicle scenario fit, fleet operation, hydrogen supply and refuelling, digital monitoring, and operational emissions. The four equations below can be directly applied to system sizing, supply adequacy analysis, reliability monitoring, and operational emissions estimation.

Fleet hydrogen demand across m vehicle classes was calculated as:

$$H_d = \sum_{i=1}^m \frac{N_i D_i C_i}{100} \quad (1)$$

where H_d is total hydrogen demand (kg), N_i is the number of vehicles in class i , D_i denotes the mean distance per vehicle (km), and C_i is hydrogen consumption (kg/100 km). A complete estimate requires class-specific distance and consumption data; aggregate mileage cannot replace missing disaggregated records.

Hydrogen-supply adequacy was evaluated using a dimensionless ratio.

$$S_h = H_s / H_d \quad (2)$$

where H_s is hydrogen available during the same period. Values above 1 indicate nominal supply above demand, whereas values below 1 indicate a deficit. Supply and demand must use the same temporal resolution because daily capacity can conceal peak constraints.

Alert intensity, expressed as alerts per monitored vehicle, was calculated as:

$$R_a = \frac{n_{\text{alert}}}{N_{\text{monitored}}} \quad (3)$$

where n_{alert} is the number of recorded alerts and $N_{\text{monitored}}$ is the monitored fleet. The ratio was 0.196 alerts per vehicle, based on 142 alerts from a total of 724 vehicles, and it is an intensity indicator. Repeated alerts from individual vehicles preclude its use as a failure probability.

Operational carbon dioxide avoidance was estimated as:

$$E_r = \sum_{i=1}^m N_i D_i (EF_{d,i} - EF_{h,i}) \quad (4)$$

where $EF_{d,i}$ and $EF_{h,i}$ are distance specific emission factors for matched diesel and HFCV classes. Under a tailpipe only analytical scope, $EF_{h,i}$ is zero. Applying the reported bus-equivalent diesel factor to aggregate mileage produced a value of approximately 2.66 kt, consistent with the reported reduction of above 2.6 kt. Because the fleet contained several classes and upstream data were incomplete, this was only an order-of-magnitude check.

The indicators supported descriptive assessment. Within this scope, ratios were interpreted as checks on scale, capacity alignment and operational intensity, providing a practical basis for system-level evaluation. A reported absence of interruption was treated as an event outcome, while alert counts were treated as signals requiring classification and were excluded from direct reliability measurement. This approach preserves the information contained in the project records, maintains analytical precision consistent with the data structure, and supports the identification of operational patterns relevant to fleet management.

3. System Configuration and Operating Conditions

3.1. Event Transport Demand and Environmental Constraints

Transport services during the Beijing 2022 Winter Olympic and Paralympic Games encompassed arrivals and departures, inter-zone transport, in zone shuttles, and ceremony-related services for athletes, officials, media, staff, volunteers, partners, and spectators. Routes differed considerably in terms of distance, passenger demand, service frequency and priority, resulting in a heterogeneous set of operating conditions across the fleet. Fleet scheduling had to account for both total energy requirements and periods of concentrated refuelling demand. Vehicle departures, route completion times, and returns to refuelling stations were closely linked, particularly during peak service periods. Route planning therefore considered vehicle range, reserve requirements, station location, and expected return times together with passenger-service schedules. Hydrogen supply and transport scheduling were consequently managed as connected operational tasks rather than as separate planning activities.

The most demanding conditions occurred in the mountainous competition zones, where temperatures approached $-30\text{ }^{\circ}\text{C}$, elevations reached 2198 m, and road gradients were as high as 16%. Vehicles also operated on icy roads, and had to negotiate sharp bends and sustained climbs. These conditions placed additional demands on cold starting, cabin heating, traction, hill holding, driving range, and refuelling. Project testing included cold-weather operation, tight-radius turning, and sustained climbing, consistent with previous studies showing that thermal management and stack temperature control strongly influence fuel-cell vehicle performance under winter conditions [30]. Figure 2 summarises the full hydrogen value chain.

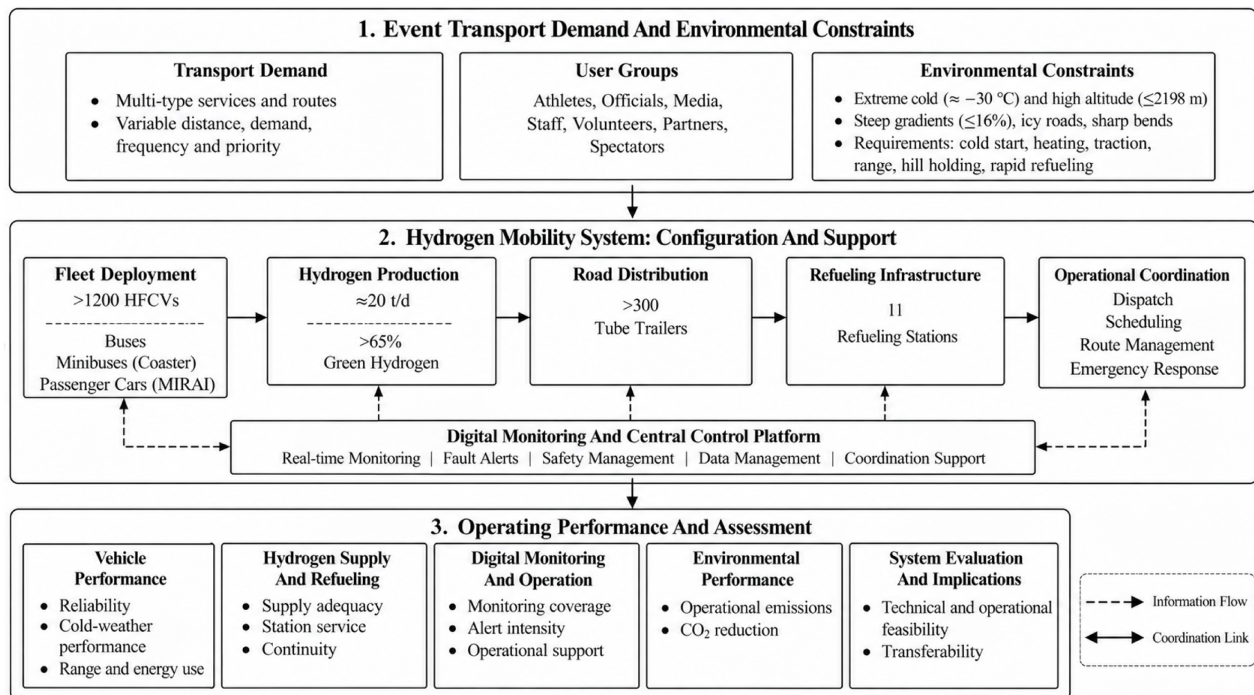


Figure 2. The full hydrogen value chain.

Figure 2 shows the physical and information flows linking transport demand, fleet deployment, hydrogen supply, refuelling, monitoring, and system assessment. Taken together, the operating conditions define a duty cycle envelope rather than a single winter test point. Temperature, elevation, gradient, route length, passenger demand and return time jointly determined the traction, heating and refuelling requirements faced by each vehicle. The evidence therefore supports classification of the operating tasks by severity and service pattern, but it does not support an optimised allocation because passenger loads, trip frequencies and route level hydrogen use were not recorded on a common denominator.

3.2. Fleet Deployment and Hydrogen Supply Infrastructure

The reported fleet exceeded 1200 vehicles and included buses, Coaster type minibuses and MIRAI (hydrogen fuel-cell vehicles produced by Toyota) passenger cars. Categorized records showed a total of 1206 vehicles. Our study uses a figure of more than 1200 for the rounded fleet size and reserves 1206 for the categorised total because each value has a different denominator.

Hydrogen supply was configured at a comparable scale. Eleven refuelling stations, four principal suppliers, more than 300 tube trailers, and a cloud-based monitoring platform supported the fleet. Reported hydrogen production capacity was approximately 20 t d^{-1} and more than 65% of this capacity was classified as green hydrogen, according to project documentation. Renewable electrolysis projects in Zhangjiakou supplied the local fleet with nearly 100% of green hydrogen during the event. The spatial arrangement of the three competition zones also made distribution architecture important.

Production capacity outside a zone could support the event only if tube-trailer availability, travel time, unloading capacity, and station storage converted that capacity into usable hydrogen at the required location. Multiple suppliers and trailers reduced dependence on a single route or facility, while the monitoring platform made mobile inventory visible to dispatchers. The effective resource combined production capacity with trans-

portable inventory, station access, and timely operating information. Figure 3 presents the deployment scale and descriptive operating indicators.

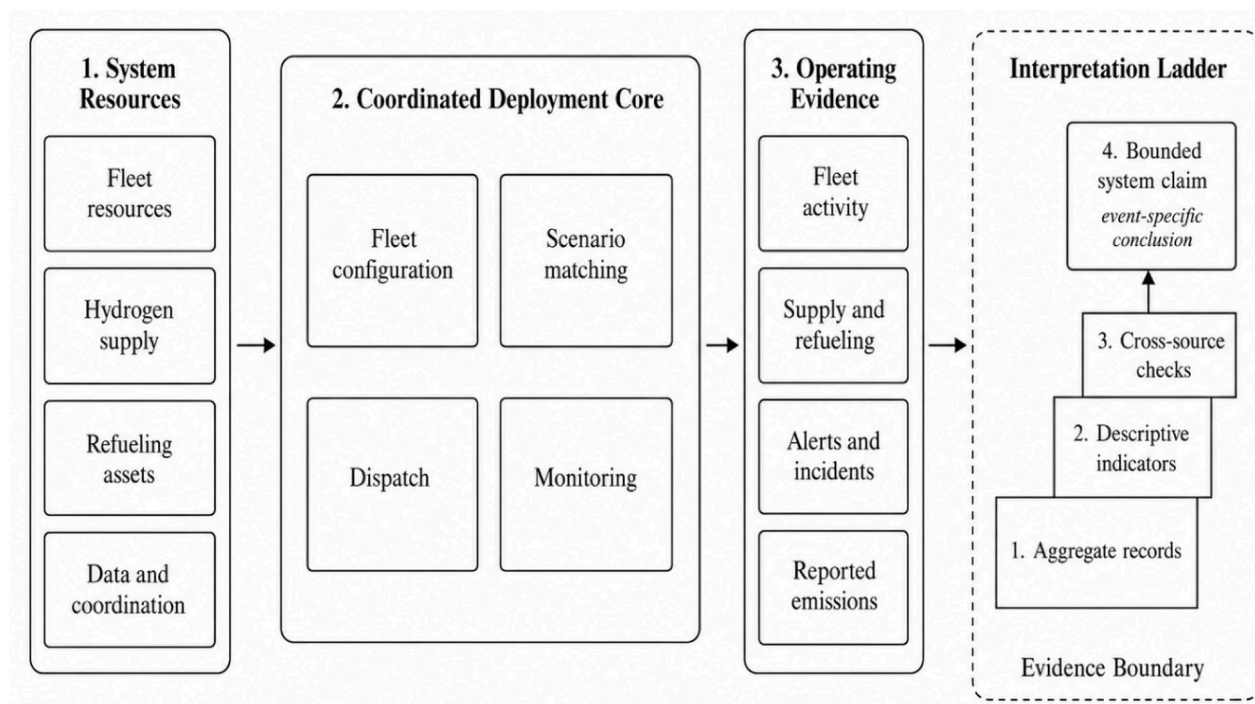


Figure 3. Deployment architecture and evidence coverage.

Figure 3 links system resources and coordinated deployment to the available operating evidence and the level of interpretation supported by that evidence. The configuration data also distinguish installed scale from utilised capacity. More than 1200 vehicles, approximately 20 t d^{-1} of nominal production capacity and 11 principal stations describe the envelope within which service was organised; they do not by themselves establish the hydrogen supply–demand ratio in Equation (2). A numerical ratio would require temporally matched hydrogen dispensing or consumption for the same vehicles and days, together with station inventories and delivery timing. The present records therefore demonstrate system coverage and redundancy, whereas capacity utilisation and surplus margin remain unquantified.

4. Hydrogen Fuel Cell Vehicle Applications and Performance

4.1. Vehicle Configuration and Scenario Matching

Fixed-route shuttle services required high passenger capacity, regular scheduling, and long operating windows. Large buses therefore formed the operational core of the fleet, while smaller buses and passenger cars were used to carry out lower-volume or specialised tasks. This scenario-first approach selected the vehicle size and powertrain configuration after defining users, route distance, road gradients, and dispatch requirements. Table 4 summarises the available Zhangjiakou deployment records. It covers a competition-zone sample drawn from the event fleet.

Scenario matching can be understood as a portfolio decision. Higher capacity buses concentrated passengers and reduced the number of vehicle movements along principal corridors, whereas smaller vehicles preserved flexibility for lower-volume and/or priority services. The appropriate configuration depended on the joint distribution of passenger load, distance, gradient, dwell time, and refuelling opportunity. Selecting the vehicle with the longest nominal range for every task would have increased capital and mass. Table 4,

below, illustrates how heterogeneous vehicle classes can be assigned to different operational roles when duty cycle information is available. Table 4 shows that vehicle allocation followed service needs - high capacity buses served recurrent shuttle routes, while smaller buses and passenger vehicles were used for lower volume, priority or ceremonial tasks.

Table 4. Representative vehicle deployments for different service scenarios in the Zhangjiakou competition zone.

Service Type	Users and Route Type	Distance/Maximum Gradient	Vehicle Type	Vehicles
TA shuttle	Athletes and team officials; links between Olympic Villages, venues, and hotels	3–43 km/6%	9.5 m bus; 12 m bus; Coaster	129
TG shuttle A	Technical officials, media, and accredited groups; links between venues and railway stations	3–8 km/6%	9.5 m and 12 m buses	118
TG shuttle B	Hotel-to-venue services	4–27 km/4%	12 m bus	120
DDS shuttle	Rights-holding broadcasters	3–28 km/6%	12 m bus	40
TW shuttle A	Staff, volunteers, and selected accredited groups	3–8 km/4%	11 m bus	56
TW shuttle B	Group services from hotels to venues	4–15 km/4%	12 m bus	60
TS shuttle	Spectators traveling from railway stations to venue clusters	7–8 km/6%	11 m bus	4
Dedicated T3	Olympic Family; hotels or Olympic Villages to venues	5–10 km/4%	MIRAI; Coaster	90
Opening/closing ceremonies	Athletes, media and officials	3–5 km/6%	Coaster	6

The representative 12 m and 9 m buses illustrate scenario-based configuration. Their fuel-cell power, storage pressure, hydrogen capacity, and traction systems differed, while both used integrated thermal management and low temperature protection. Reported ranges exceeded 600 km and 400 km, respectively, and rated refuelling time was 15–20 min. Table 5 provides the detailed specifications. These differences show why duty-cycle matching remains central to heavy-duty fuel-cell vehicle design [31]. Of the 623 vehicle assignments in Table 4, 527 (84.6%) served the seven shuttle categories. Larger buses were concentrated on recurrent passenger corridors, while smaller platforms supported lower-volume and priority movements. The 12 m bus carried 41.9 kg of hydrogen at 70 MPa and had a reported range above 600 km; the 9 m bus carried 21.6 kg at 35 MPa and had a reported range above 400 km. These specifications explain the allocation logic but do not support an efficiency comparison because occupancy, operating hours, and class-specific hydrogen use were unavailable.

Table 5. Selected technical specifications of representative 12 m and 9 m fuel-cell buses.

Parameter	12 m Bus	9 m Bus
Dimensions (mm)	12,000 × 2550 × 3790	8995 × 2500 × 3630
Gross vehicle mass (kg)	18,000	13,800
Curb mass (kg)	14,100	10,650
Maximum gradeability	20%	15%
Fuel-cell engine	150 kW	80 kW
Hydrogen-storage system	6 × 134 L; 70 MPa; 41.9 kg	6 × 166 L; 35 MPa; 21.6 kg
Traction battery	60.26 kWh lithium manganate battery	60.26 kWh lithium manganate battery
Traction motor	2 × 100 kW	100 kW + 60 kW
Reported duty-cycle range	>600 km; 520 km reported during event operation	>400 km
Rated refuelling time	15–20 min	15–20 min

4.2. Performance Under Extreme Winter Conditions

Project tests and operating records covered cold soaking, unassisted cold starting, cabin warm-up, sustained climbing, and hill holding. Representative buses started within 5–10 s after extended cold soaking, while separate component tests reported stack starts at $-35\text{ }^{\circ}\text{C}$ and rapid battery self-heating.

Cold-weather readiness involved more than achieving a single minimum starting temperature.

Cabin heating, battery conditioning, fuel-cell warm-up, traction demand, and regenerative-braking availability compete for energy during the initial period of service. Repeated climbing and low-speed operation can further alter thermal loads relative to a standardised duty cycle. The project tests addressed several of these functions separately, while event records showed that the configured vehicles could complete the winter service trips to which they were assigned.

The evidence supports vehicle suitability under the observed event conditions, including low temperature, high altitude, and steep gradients. Durability across repeated winters remains unverified. Thermal management, stack temperature control, power management, and component durability therefore remain important constraints [4].

Cold-start results demonstrate functional readiness for the observed event conditions. Vehicle starts within 5–10 s after cold soaking and component starts at $-35\text{ }^{\circ}\text{C}$ address entry into service, while operations took place in a system exposed to temperatures approaching $-30\text{ }^{\circ}\text{C}$, elevations up to 2198 m, and gradients up to 16%. Matched warm-weather energy use and degradation data were not available, so the results describe start capability and trip completion rather than the energy penalty or multi-winter durability.

4.3. Operating Performance and Monitoring Alerts

During the 52-day service period, the fleet travelled more than 3.5 million vehicle kilometres across over 80 routes and fulfilled the reported transport assignments [32]. Project records reported no safety incidents, no on-road service interruptions, no complaints, 100% on time performance, and rapid emergency response. These outcomes met the reported event objectives [33]. However, missing route-level denominators prevented comparison between vehicle classes or with a matched diesel fleet; published assessments provide context but use different duty cycles [34].

Monitoring records covered 724 vehicles and contained 142 alerts. More than half were attributed to driving practices, low temperature battery charging, powertrain energy management, and durability limitations of certain materials. The records identify operational priorities but lack the identifiers needed to distinguish unique failures, repeated alerts and service interruptions. They therefore support an alerts-per-vehicle measure, while failure rate estimation remains outside the evidence coverage.

The alert distribution also shows why operating performance should be evaluated through both service outcomes and internal system signals. A fleet may complete all trips while still generating warnings that require intervention, driver guidance, or revised charging and energy management practices.

Conversely, an alert may occur without a service affecting fault. Linking each alert to a unique vehicle, timestamp, route, severity level, corrective action, and downtime would allow future deployments to distinguish detection sensitivity from operational disruption and to convert monitoring records into reliability evidence.

More than 3.5 million vehicle kilometres over 52 days corresponds to over 67,300 fleet-kilometres per day. The 724 monitored vehicles represent about 60% of the categorised fleet, although the fleet and monitoring boundaries are not fully aligned. The 142 alerts correspond to 0.196 alerts per monitored vehicle. Reported 100% on time performance

describes service completion, but a rate cannot be independently reconstructed without the number and timing of scheduled trips.

5. Integrated Technical and Operational Evaluation of the Hydrogen Value Chain

5.1. Hydrogen Production and Road Supply

Four principal suppliers supplied hydrogen from conventional and renewable production routes. Reported electrolysis capacity totalled $13 \times 500 \text{ Nm}^3 \text{ h}^{-1}$, while reported system-level hydrogen production capacity was approximately 20 t d^{-1} . More than 65% of this capacity was classified as green hydrogen according to project documentation. Multiple suppliers provided redundancy. The reported renewable production capacity and Zhangjiakou use of green hydrogen provide context for the operational emissions result, although capacity share and consumption share are not equivalent. This configuration illustrates the need to coordinate storage, delivery - and wider supply chain capacity [35]. Temporally matched supply and class-specific demand are needed to identify peak constraints. The configured network sustained event operations without reported hydrogen shortages.

Operational adequacy also depended on logistical buffering. Its value therefore relied on trailer turnaround, road conditions, unloading time, station inventory, and forecast demand. A robust planning model would treat these elements as a time-dependent network and test whether an interruption to one supplier, route, or station could be absorbed by the remaining resources. The event records indicate that the configured redundancy was sufficient for the observed service period.

Hydrogen was transported mainly by tube trailers over distances of approximately 50–100 km. Onboard systems monitored for hydrogen leaks and tracked remaining hydrogen, pressure, and location, transmitting these data to the cloud-based monitoring platform. Tiered responses could be triggered by leakage, accidents, or prolonged stops. Road distribution therefore linked physical delivery with monitoring and emergency management [36].

Production capacity and realised consumption must be distinguished. The reported 20 t d^{-1} is a nameplate supply capacity, whereas delivered mass, plant availability, station inventory, and daily demand were not recorded on a common basis. The records report no hydrogen shortage during the observed service period. Four suppliers, more than 300 trailers, and delivery distances of 50–100 km show that supply continuity depended on scheduling and logistics, as well as production capacity; the reserve margin cannot be calculated from the available data.

5.2. Refueling Infrastructure and Service Performance

The refuelling network supported vehicles at both 35 and 70 MPa through station-vehicle communication, fault diagnosis, and vehicle-specific control modes [37]. Refuelling rates differed by vehicle class, and the system completed an 18 h continuous-operation test at 70 MPa [38]. Vehicles were usually refuelled on arrival; even during clustered returns, queues consisted of less than five vehicles and waiting times were below one hour [39]. These outcomes reflect the combined effects of station configuration, controls, location, and operating strategy [40].

A representative Yanqing station dispensed approximately 63 t of hydrogen across 5098 events. The average over the full service period was 12.36 kg per event, close to the reported peak day average of 12.66 kg. This similarity provides a consistency check. Figure 4 summarises the station and supply indicators.

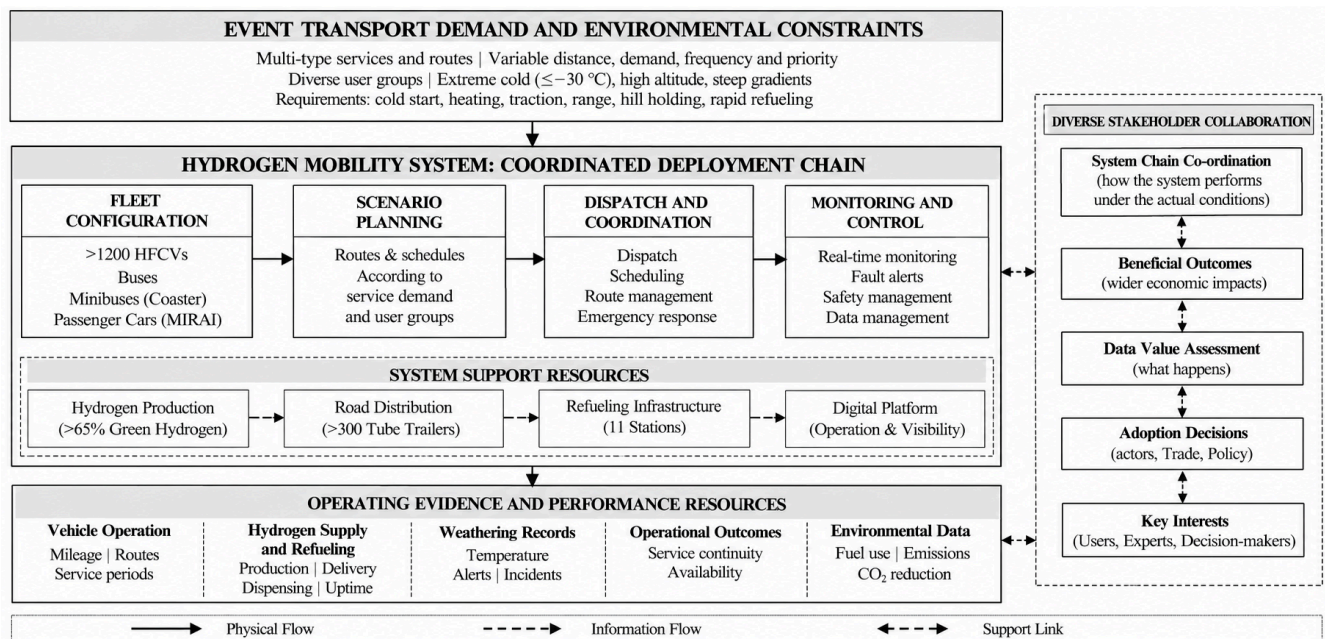


Figure 4. Hydrogen refuelling decision and service flow.

Average kilograms per refuelling event provide a useful consistency check. Fleet service also depends on hourly dispensing capacity, precooling and compression recovery, simultaneous arrivals, pressure compatibility - and the time for which vehicles can remain off route. The reported queue and waiting-time observations add an operational dimension to the mass totals, because they connect station throughput to vehicle availability. Future evaluations should report throughput distributions by hour and vehicle class so that nominal capacity, peak utilisation, and service delay can be assessed together. Figure 4 relates vehicle returns, station decisions, dispensing and monitoring to the indicators used for evaluating refuelling service.

The station data permit a more specific throughput calculation, when their source specific time window is retained. The public trade media record for the Jinlong station reports 62,693 kg dispensed in 5098 events over 55 operating days [20]. Equations (6) and (7) therefore give 12.30 kg per event, 92.7 events per station day and 1.14 t d^{-1} , consistent with the daily averages reported by the source. These values refine the rounded 63 t total, but they are not a fleet wide measure of hydrogen consumption. Likewise, the rated 15–20 min refuelling time and waiting times below one hour are service bounds rather than an observed mean refuelling duration. Event-level start and end timestamps, vehicle class and dispenser occupancy would be required to calculate mean refuelling time and station utilisation. Figure 4 relates vehicle returns, station decisions, dispensing and monitoring to the indicators used for evaluating refuelling service.

5.3. Digital Monitoring and Operational Coordination

The cloud-based monitoring platform combined data from hydrogen production facilities, tube trailers, refuelling stations, vehicles and fuel-cell systems to provide real time visualisation, automated alerts, dispatch support, fault classification and continuous operational oversight [41]. Access to a common data environment improved information exchange between participating organisations and shortened coordination time [42]. Established prognostic methods, model-based diagnostics and electrochemical impedance testing were able to further translate fuel-cell measurements into maintenance decisions [43]. No safety incidents were reported during hydrogen production, transport, refuelling and vehicle operation. The incident-free record suggests that preventive controls and emer-

gency procedures functioned effectively during the event. Within the event period, the records support conclusions concerning operational completion, monitoring coverage and response capability.

5.4. Integrated Hydrogen Value-Chain Assessment

System performance reflected the alignment of capacity, technical interfaces and data flows across the hydrogen mobility chain. Fleet demand was coordinated with hydrogen production, road transport and station service, while vehicle storage specifications were integrated with refuelling controls and physical assets were connected through a shared monitoring platform. Multiple hydrogen sources, refuelling stations, tube trailers and monitoring channels provided operational redundancy and reduced dependence on individual components. These arrangements strengthened service continuity during the event.

Fleet-scale performance depended on the coordinated operation of fuel-cell vehicles, hydrogen supply, refuelling infrastructure and digital management. Within the event-specific study scope, the integrated system provided sufficient capacity and operational support to complete the assigned transport tasks. The available records provide limited evidence on commercial optimisation, as long-term cost, utilisation and market value need to be assessed over a longer operating period.

The indicators describe different parts of system performance: fleet counts and mileage measure activity, production capacity sets a supply envelope, the Jinlong records measure one station's throughput, and alerts describe monitoring activity. Together with the reported completion of transport tasks, they show how the chain operated during the event. They do not isolate the contribution of individual components or demonstrate cost optimisation.

6. Operational Environmental Performance and Demonstration Value

6.1. Operational Emission Avoidance and Green Hydrogen

At the vehicle tailpipe, HFCVs avoided the carbon dioxide emissions associated with matched diesel vehicles. More than 2600 t of operational carbon dioxide reductions was reported in the project documentation. A simple mileage-based consistency check reproduced the same order of magnitude.

The estimate uses a counterfactual comparison to approximate atmospheric impact. It asks how much diesel tailpipe carbon dioxide would have been emitted if equivalent transport services had been delivered by matched conventional vehicles. The result is therefore sensitive to the selected diesel emission factor, the allocation of mileage between buses, minibuses and passenger cars, and the assumption that the fleets that are compared provide equivalent service. It confirmed that the reported reduction is plausible under the stated assumptions.

Hydrogen production, compression, transport and refuelling can generate upstream emissions, so the reported reduction falls short of a carbon-neutrality assessment [5]. Life cycle outcomes vary with the supply pathway, vehicle class, production route, and electricity assumptions [6].

A fuller carbon account would follow hydrogen from primary energy to delivered vehicle work [7]. Relevant stages include electricity or feedstock supply, hydrogen production, purification, compression, storage, tube-trailer transport, station operation, and vehicle use. Infrastructure construction and vehicle manufacturing may also be important when comparing long-lived systems, although their contribution should be allocated over service life. Each stage has a different activity measure and emission factor, so a single green hydrogen label cannot act as a substitute for a transparent inventory. The appropriate

comparison is between complete and consistently defined pathways that deliver the same passenger or vehicle service [44].

The hydrogen source also influenced the environmental performance of the case study. More than 65% of reported hydrogen production capacity was classified as green hydrogen, according to the project documentation, and the Zhangjiakou fleet used nearly 100% green hydrogen during the event. However, the production capacity share differs from the consumption share. A complete assessment would require knowledge of the delivered volumes by source, electricity mix, compression energy, transport distance and station energy use [45].

The distinction between production capacity and delivered consumption is especially important in a mixed supply system. A facility classified as renewable may represent a large share of nominal capacity, while supplying a smaller share of event hydrogen because of scheduling, outages, storage, or transport constraints. Electricity consumed for compression and station operation may also differ by location and time. Traceable delivery records linking source, batch, transport distance, station, and vehicle class would make it possible to calculate source specific emission intensity and to test whether renewable production was available during the periods of highest demand.

The case therefore supports an operational stage emissions benefit under the stated diesel counterfactual. A life cycle assessment would require hydrogen deliveries to be linked by source to vehicle class consumption, with operational and upstream emissions reported separately.

These distinctions preserve the environmental value of the deployment while clarifying its evidence base. They also identify the proportion that receives direct support. Replacing diesel tailpipe combustion removes on-route carbon dioxide and local exhaust emissions, while renewable hydrogen can reduce upstream emissions relative to fossil-based pathways. The magnitude of the total benefit, however, depends on the actual hydrogen mix and energy used across the supply chain. Reporting operational avoidance and upstream emissions as separate quantities would preserve the demonstrated result while allowing later studies to update the life-cycle estimate as better data become available.

The reported reduction of more than 2.6 kt CO₂ is an operational, tailpipe-based estimate for a mixed fleet. Because the mileage totals use different reporting boundaries and hydrogen consumption is not available by vehicle class or source, the result cannot be converted reliably to a passenger-kilometre life cycle intensity.

6.2. Demonstration Value and Transferability

The main transferable contribution lies in the planning framework. Projects should define the service scenario, match vehicle technology, coordinate hydrogen supply with station capacity, provide appropriate redundancy, and connect the chain through monitoring and response.

The demonstration generated at least four forms of learning. Technical learning was concerned with cold weather vehicle operation, dual pressure refuelling, and monitored hydrogen transport. Operational learning included route assignment, return-time management, station service, and alert response. Organisational learning involved how suppliers, station operators, fleet managers - and event authorities shared responsibilities. Data learning entailed establishing which records were needed to connect physical performance with management decisions. These forms of learning could be used to inform later projects even when fleet size, public funding and infrastructure ownership differ from the 2022 Olympic setting.

The configuration itself is less transferable because the event benefited from public coordination, dedicated funding, predictable routes, concentrated demand and clear re-

sponsibilities. Its lessons are therefore more relevant to transit, tourism, logistics and other depot-based fleets than to dispersed private passenger car markets.

Transferability therefore depends on whether a target application reproduces the functional conditions of the case study. A suitable application would therefore need to aggregate demand, provide stable routes or duty cycles, permit centralised or predictable refuelling, and assign responsibility for cross chain coordination. Transit depots, airport and tourism shuttles, port or logistics fleets, and other high-utilisation operations may satisfy these conditions to different degrees. Dispersed passenger car use lacks several of these and would require a denser public station network and different redundancy arrangements.

The findings transfer most directly as an operating framework rather than as a fixed vehicle-to-station ratio. Other fleets can apply the sequence of duty cycle classification, vehicle assignment, hydrogen-demand estimation, peak period station sizing, monitored dispatch, and contingency planning, while determining asset quantities from local routes and loads. Post-deployment data on utilisation, energy use and cost are then needed to assess commercial performance.

7. Discussion

7.1. From Vehicle Capability to System Capability

The case study draws a clear distinction between vehicle capability and fleet capability. Cold starting, driving range, gradeability and thermal management determine whether an HFCV can operate under severe winter conditions. The technological progress of fuel cells has been extensively reviewed in the literature [46]. Hydrogen is increasingly recognised as a key element in the global energy transition [47].

At a large deployment scale, the effective capability of the fleet is shaped by the sequence of activities that surrounds vehicle operation. A vehicle may have adequate range but still lose service time if refuelling demand is concentrated within a narrow return window. Additional hydrogen production does not remove a bottleneck if tube-trailer delivery, station storage, or dispensing capacity cannot keep pace with vehicle demand. The same logic applies to dispatch: route length, passenger service windows, vehicle return times, station location, and available fuel should remain compatible over the operating day. What matters in practice is not the highest specification achieved by one component, but whether the individual capacities can be used at the time and place required by transport services. The storage and delivery aspects of hydrogen mobility have also been summarized in the literature [48]. This is where system capability differs from a collection of technically capable assets. The monitoring records make this distinction more concrete. From a fleet of 724 monitored vehicles, 142 alerts were recorded, including issues related to driving practices, low-temperature charging, energy management, and material durability. At the same time, the assigned transport services were completed without reported on-road interruptions. The two observations describe different levels of performance: alerts capture deviations within the operating system, whereas service completion records whether those deviations affected the transport task.

Monitoring plays a specific operational role in this relationship. Its significance does not lie simply in generating warnings. The information had to be connected to driver guidance, maintenance, dispatch adjustment, fault handling, and emergency response before it could contribute to continuity of service. Reliability at fleet scale is thus broader than component failure probability. It also involves the capacity to detect abnormal conditions, contain their consequences, and maintain or restore service before disruption spreads through the transport schedule [49]. In a tightly coupled operating environment, these response functions become part of system performance rather than auxiliary support.

Accordingly, the case study shifts the analytical focus away from isolated vehicle specifications. Vehicle technology made winter operation possible, but production and road supply determined fuel availability; refuelling stations determined access to that fuel; dispatch connected vehicles with transport demand; and monitoring provided the information needed to intervene when operating conditions changed. In the case of centralised and high-utilisation HFCV applications, these relationships are likely to be as important as range, fuel-cell power, or cold-start performance when judging whether a fleet can sustain continuous service.

Fleet comparisons show why duty cycle and reporting boundary matter. The 20-bus Whistler fleet associated with Vancouver 2010 accumulated more than 4 million km over four years, operated for up to 22 h day^{−1} at temperatures from −20 °C to 34.7 °C, and reported three-year average hydrogen consumption of 15.67 kg H₂/100 km and adjusted availability of 70% [21]. Beijing operated a much larger and more varied fleet for a shorter event period, so the results are comparable mainly as evidence of winter service continuity, not as a direct efficiency ranking.

More recent studies provide vehicle level benchmarks. A 2025 chassis-dynamometer study reported 5–8 kg H₂/100 km for a production fuel-cell city bus, with simulated passenger load raising traction demand by almost 30% and HVAC settings increasing hydrogen consumption by up to 15% [22]. A 2026 ten-month study of a double decker hydrogen bus reported 0.120 kg H₂-eq/km and identified temperature, mean speed, stop intensity, and passenger load as important predictors [23]. Beijing lacks class specific hydrogen use, route profiles, and availability data, but its 3.5 million vehicle kilometres and reported uninterrupted service demonstrate continuity at fleet scale. The comparison indicates that future fleet evaluation should relate hydrogen use and reliability to route, load, and auxiliary demand.

7.2. Scenario-Based Design, Coordination, and Redundancy

The heterogeneous transport tasks required by the 2022 Beijing Olympics made a uniform vehicle configuration impractical. Principal shuttle routes required high passenger capacity and sustained daily operation, whereas dedicated services and lower-volume routes placed greater value on flexibility. Large buses, smaller fuel-cell buses, Coaster type vehicles, and passenger cars therefore performed different functions within the fleet. Vehicle selection was linked to route distance, passenger demand, road gradient, expected operating time, and refuelling opportunity rather than to a single technical specification. The resulting fleet configuration reflects a basic requirement of large-scale hydrogen mobility, namely that vehicle technology should be selected after the operating task has been defined. China's hydrogen strategy has been compared with other international approaches [50]. The industry chain for fuel cell vehicles in China has also been analysed [51]. This approach extends beyond vehicle procurement. Onboard hydrogen storage determines the interval between refuelling events, but its operational value depends on station pressure compatibility, dispensing capacity, vehicle return patterns, and the amount of time that can be allocated to refuelling without affecting scheduled service. A vehicle with greater nominal range may reduce refuelling frequency, but additional storage also increases vehicle mass and does not remove constraints elsewhere in the system. Critical issues for new energy vehicles in China have been identified in previous work [52]. Conversely, a station with high nominal capacity can still become a bottleneck when vehicle arrivals are concentrated within a short period. The relevant design problem is therefore one of capacity matching. Route requirements establish vehicle demand; vehicle operation generates the timing and quantity of hydrogen demand; station configuration determines how rapidly that demand can be served; and road distribution determines whether station inventory can be replen-

ished at the required rate. Designing these elements independently increases the likelihood that excess capacity in one part of the system will coexist with a constraint in another.

Coordination was particularly important because hydrogen supply and transport service operated on different time scales. Production capacity was generally expressed in terms of a daily amount, while fleet demand could change substantially within a few hours as vehicles completed routes and returned to stations. Tube-trailer deliveries introduced another time interval through loading, travel, unloading, and turnaround. Station storage provided temporary separation between these processes, but it did not eliminate the need to anticipate demand. Scheduling therefore required information about vehicle deployment, expected return times, station inventory, trailer availability, and planned service intensity. The digital monitoring platform supported this process by making operating information available across organisational boundaries. In this setting, coordination was not an additional management layer imposed on the technical system; it was the mechanism through which separately owned and operated assets could function as a continuous transport service [53].

Redundancy addressed a different problem. The event relied on multiple hydrogen suppliers, tube trailers, refuelling stations, vehicles, and monitoring channels, thus reducing dependence on individual assets. These resources were not interchangeable in a simple sense. An additional hydrogen supplier could compensate for a production interruption only when delivery capacity and station access remained available. An alternative refuelling station was useful only when vehicles could reach it within their route and scheduling constraints. Spare vehicles could preserve passenger service, but they could not compensate for a wider shortage of hydrogen. Redundancy therefore had to correspond to specific points of failure and to the operational consequences associated with those failures. This distinction is important when the Beijing 2022 configuration is considered beyond the event setting. A high reserve capacity was compatible with an operating environment in which continuity of service had priority and short disruptions could affect tightly scheduled transport tasks. Routine commercial fleets have to negotiate a different balance. Additional suppliers, station capacity, spare vehicles, storage, and parallel monitoring channels improve the ability to absorb disruption, but they also increase capital expenditure, maintenance requirements, staffing needs - and the possibility of low asset utilisation. The appropriate level of redundancy cannot be determined from the number of backup assets alone. It depends on the expected frequency and duration of disruptions, the amount of service that would be lost, the time required to restore operation, and the cost of maintaining alternative capacity.

The operational value of redundancy also depends on whether reserve resources can be activated in time. Shared demand forecasts, station inventory information, clear escalation procedures, and the authority to redirect hydrogen deliveries or reassign vehicles determine how quickly a physical backup can be brought into use. Without these arrangements, reserve capacity may exist on paper while remaining unavailable when operating conditions change. For centralised HFCV fleets, resilience therefore depends on both the existence of alternative resources and the procedures that connect those resources to real time operating decisions.

The experience of Beijing 2022 thus provides a practical basis for treating scenario definition, capacity coordination, and redundancy as related design decisions rather than separate planning tasks. Route and service requirements determine the initial fleet configuration; the resulting operating pattern shapes hydrogen and refuelling demand; and the consequences of disruption determine where reserve capacity is most valuable. This relationship is particularly relevant to applications with predictable routes and concentrated

refuelling demand, where system configuration can be developed around observable duty cycles instead of relying primarily on generalised vehicle or infrastructure specifications.

Large event comparisons also show how vehicle mix and operating context affect infrastructure needs. Tokyo 2020 planned around 500 MIRAI vehicles alongside Sora buses and fuel-cell forklifts [24]. Paris 2024 used 500 MIRAI cars within a 2740-vehicle electrified official fleet and also included buses and forklifts supplied with renewable hydrogen [25]. Beijing differed in its larger share of heavy passenger vehicles, winter and high-altitude routes, and reliance on road delivered hydrogen across several competition zones. Fleet size alone therefore does not describe infrastructure difficulty; vehicle mix, pressure compatibility, return-time concentration, station throughput, and supply topology also matter.

Model-based studies reinforce the importance of refuelling schedules. In a modelled 10 bus fleet, station tank size and refuelling schedule affected compression energy and hydrogen price [26]. A 2026 city-scale study found that flexible refuelling over 24 h reduced the required electrolyzers and dispensing points from three to one compared with a restricted 03:00–07:00 window [27]. Beijing's monitoring and dispatch arrangements are consistent with temporal coordination, although the available data cannot establish whether its infrastructure was cost-optimal.

7.3. Conditional Replicability for Public Transport and Other Centralised Fleets

Transfer should focus on functions rather than Beijing's asset counts. An urban bus operator would first measure route distance, passenger load, gradients, temperature, layover time, and vehicle return patterns; it could then select vehicle classes, estimate hydrogen demand, and size depot or corridor refuelling. Alternative supply and station access should be linked to defined failure scenarios, and vehicle, station, and delivery records should use common identifiers and timestamps.

Airport and tourism shuttles share the Olympic case's concentrated terminals and predictable returns. Port, municipal service, and logistics fleets can also use central refuelling, although tonne-kilometres, payload, and shift structure become more important. Replication should begin with instrumented routes and one seasonal operating cycle, followed by evaluation of station queues, supply resilience, utilisation, life-cycle emissions, and service cost. Dispersed private-car use is less comparable because demand location and refuelling time cannot be centrally scheduled.

7.4. Limitations and Implications for Future Deployment

The principal limitation of this study lies in the level of aggregation of the available records. Fleet totals, operating mileage, refuelling activity, and monitoring information were compiled for different purposes and did not always share the same unit of observation. The total fleet was reported as both more than 1200 vehicles and 1206 categorised vehicles, while monitoring data covered a subset of 724 vehicles. Route-level mileage, vehicle specific hydrogen consumption, and daily operating records were not consistently available. The 142 monitoring alerts could therefore be used to describe alert intensity, but not to establish vehicle level failure rates because repeated alerts, downtime, and severity could not be linked to individual vehicles. A more useful data structure for subsequent large-scale demonstrations would connect each trip to a common vehicle identifier and timestamp. Vehicle class, route, passenger or load category, ambient conditions, hydrogen consumption, refuelling activity, alerts, maintenance activities - and downtime could then be examined as part of the same operating record. The supply side requires an equivalent linkage between hydrogen source, tube-trailer movement, station inventory, dispensing time, and vehicle demand. Such records would make it possible to examine route-specific

energy consumption, peak refuelling demand, recurring faults, station congestion, and the operational consequences of equipment or supply interruptions. They would also remove several of the denominator inconsistencies encountered in the present analysis.

The environmental results are similarly constrained by the available data. The reported reduction in carbon dioxide refers to vehicle operation - and does not constitute a complete life cycle assessment. Hydrogen production, compression, transport, station operation, and the electricity or feedstock used in hydrogen production all affect upstream emissions. The distinction is particularly important in a system that combined conventional and renewable hydrogen sources. A more complete assessment would require the quantity and origin of hydrogen actually consumed by each vehicle class to be calculated rather than production-capacity shares alone. Commercial performance could not be assessed with the same level of detail as technical and operational performance. Beijing 2022 was organised around a fixed transport obligation, dedicated infrastructure, extensive coordination, and public objectives. These conditions justified reserve capacity and operational arrangements that may not be economical under routine fleet operation. Vehicle acquisition and maintenance costs would have to be considered together with hydrogen price, tube-trailer logistics, station investment, station utilisation, staffing, spare capacity, and the cost of service interruption. Post-event records are especially important in this respect. Whether the stations continued to achieve adequate utilisation, whether vehicle performance was maintained after several winters, and how operating costs changed after dedicated event support was withdrawn would provide a stronger basis for assessing commercial viability.

Recent life cycle studies clarify the meaning of the reported CO₂ reduction. An analysis of 106 heavy-duty fuel-cell trucks in six Chinese applications found that results varied with hydrogen source and utilisation; in Beijing, industrial by-product hydrogen generally produced lower greenhouse-gas emissions than diesel and battery-electric trucks except at low utilisation [28]. A 2026 US study estimated current life cycle greenhouse gas reductions of 5–50% for fuel-cell medium- and heavy-duty vehicles relative to diesel, compared with 10–60% for battery-electric vehicles, with the range driven by duty cycle, vehicle efficiency, and fuel-cycle assumptions [29]. These studies show that Beijing's tailpipe estimate cannot be treated as a life-cycle result. A full comparison would include hydrogen production, compression, delivery, station electricity, equipment manufacture, and asset utilisation on a common service basis. Paris 2024 demonstrates the use of renewable hydrogen in an event fleet [25], but source labels still need measured quantities and system boundaries.

A matched comparison of HFCVs, diesel vehicles, and battery electric vehicles would require the same route, load, temperature, timetable, reliability requirement, and functional unit, together with vehicle, fuel, infrastructure, maintenance, and labour data. The Beijing records provide aggregate HFCV mileage and a diesel-tailpipe counterfactual, but not the class-specific consumption, passenger loads, costs, or matched diesel and electric observations needed for a numerical ranking. Recent fleet evidence [28] and life cycle pathway estimates [29] provide context, but neither substitutes for a comparison under the Olympic duty cycle.

These constraints do not affect all deployment settings equally. The configuration observed in Beijing 2022 is most relevant to fleets in which demand can be aggregated and vehicle movement can be planned in advance. Public transport, airport and tourism shuttles, port operations, logistics fleets, and other depot-based services share several of these characteristics. Their routes are relatively stable, refuelling can be concentrated at a limited number of locations, and fleet operators can coordinate vehicle assignment with hydrogen supply. Dispersed private passenger car use presents a different infrastructure problem because demand is less predictable and depends on a geographically broader public refuelling network. In the case of centralised fleets, deployment can proceed from

measured duty cycles rather than from generalised assumptions about vehicle range or station capacity. Route distance, load, operating hours, climate, and return patterns provide the basis for selecting an initial fleet and estimating hydrogen demand. Early operation can then establish peak station throughput, trailer turnaround requirements, reserve capacity, maintenance workload, and response procedures before further expansion. This sequence is particularly important because the preferred configuration will vary with route topology, climate, hydrogen source, ownership structure, and service priorities. It is therefore better to treat scaling a hydrogen fleet as a progressive operational decision than as a direct replication of the Beijing 2022 configuration. Table 6 summarises the elements of the case study that are transferable to other centralised hydrogen mobility applications and the conditions under which they remain applicable.

Table 6. Transferable principles and case specific applicability conditions.

Transferable Principle	Case Evidence	Applicability Conditions
Scenario-first vehicle selection	Several vehicle classes were matched to route, passenger-demand, and gradient requirements	Reliable duty-cycle data are required before procurement
Capacity coordination across the hydrogen value chain	Hydrogen production, transport, refuelling stations, and the fleet were configured as one system	Daily aggregate analysis must be supplemented by peak-period analysis
Supply redundancy	Multiple suppliers, stations, and tube trailers	Redundancy may reduce long-term asset utilisation
Digital integration	Cross-chain monitoring, alerts, and dispatch support	Effectiveness depends on data quality, interoperability, and response protocols
Operational emissions accounting	Mileage and matched diesel comparisons support a tailpipe estimate	Life-cycle carbon assessment requires upstream data
Centralized fleet deployment	Fixed routes, depots, and coordinated organisation	The model has limited direct applicability to dispersed private passenger-car markets

8. Conclusions

The Beijing 2022 Winter Olympic and Paralympic Games provided a rare opportunity to examine hydrogen mobility at fleet scale under intensive winter operating conditions. More than 1200 HFCVs completed 52 days of transport service across more than 80 routes and accumulated over 3.5 million vehicle-kilometres. Their operation was supported by hydrogen production and road distribution, 11 refuelling stations, digital monitoring, and coordinated fleet management. The scale and continuity of this deployment demonstrate that hydrogen mobility can support demanding centralised transport services when vehicle operation and hydrogen infrastructure are planned as connected parts of the same service system. Vehicle performance alone did not determine the outcome. Route requirements influenced vehicle configuration; vehicle deployment shaped the timing and location of hydrogen demand; road distribution and station capacity determined whether that demand could be met; and digital monitoring supported dispatch, fault handling, and operational response. The practical capability of the fleet therefore emerged from the compatibility of these functions over the operating day. This distinction is particularly important for large HFCV fleets, where an adequate vehicle range or high hydrogen production capacity cannot compensate for constraints in refuelling, distribution and scheduling.

The deployment also indicates the settings in which this operating model is most applicable. Centralised fleets with predictable routes, concentrated demand - and planned refuelling offer the clearest conditions for coordinating vehicles with hydrogen supply. Public transport, shuttle services, airport and tourism transport, port operations, and logistics fleets share many of these characteristics. Direct transfer to dispersed private passenger-car markets is less straightforward, because refuelling demand is spatially distributed and infrastructure has to serve less predictable travel patterns.

Operational records further show substantial potential for reducing transport emissions. The reported reduction of more than 2.6 kt of CO₂ is consistent with avoided diesel tailpipe emissions during the event. Project records also indicate extensive use of green hydrogen in Zhangjiakou, although the fleet-wide consumption share by hydrogen source was not available. A complete environmental assessment, however, requires hydrogen production, compression, transport, station operation, and other upstream processes to be included alongside vehicle operation. The next stage of hydrogen mobility deployment will depend less on demonstrating that large fleets can operate and more on whether comparable performance can be achieved under routine commercial conditions. Station utilisation, hydrogen cost, vehicle and infrastructure durability, tube-trailer logistics, reserve capacity, maintenance requirements, and data interoperability will become increasingly important once dedicated event support is removed. For centralised applications, expansion should therefore follow verified duty cycles and operating records, while fleet size, station capacity, hydrogen delivery and reserve resources need to be adjusted to actual demand rather than reproduced directly from the Beijing 2022 configuration.

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Abbreviations

The following abbreviations are used in this manuscript:

Abbreviation	Definition
H ₂	Hydrogen
HFCV	Hydrogen fuel cell vehicle
MPa	Megapascal
CO ₂	Carbon dioxide
C-WTVC	China World Transient Vehicle Cycle

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