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Hazard & Operability (Hazop) Study of Cng Stations in City Gas Distribution: A Comprehensive Review

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Abstract
Compressed Natural Gas (CNG) stations are critical nodes within City Gas Distribution (CGD) networks, supporting urban transportation with clean fuel alternatives. However, their high-pressure systems, public interface, and complex mechanical operations introduce a range of potential hazards. Hazard and Operability (HAZOP) studies are widely recognized as one of the most rigorous qualitative methodologies for identifying process deviations and evaluating operational risks. This review synthesizes peer-reviewed literature, regulatory frameworks, and industrial best practices to present a holistic assessment of HAZOP application in CNG stations. The review focuses on typical deviations, risk trends, safeguards, human-factor issues, and research gaps. Aggregated data from past studies (2012â€“2024) are analyzed to assess common hazards and deviations. Recommendations for enhancing safety performance in CGD systems are provided.

Keywords: Compressed Natural Gas (CNG) Stations, Hazard and Operability (HAZOP), Risk Assessment, Hazard Identification

1. Introduction

The accelerated pace of global urbanization over the past two decades has generated unprecedented demand for cleaner, more sustainable, and economically viable forms of energy. As cities continue to expand, governments and energy providers face mounting pressure to reduce urban pollution, tackle greenhouse gas emissions, and ensure reliable access to affordable transportation fuels. These shifts have catalyzed the rapid growth of City Gas Distribution (CGD) networks, which serve as essential infrastructure for supplying piped natural gas to households, industries, and transportation sectors. Among their various components, Compressed Natural Gas (CNG) refueling stations represent one of the most critical and high-risk elements due to their interface with the general public and their reliance on high-

pressure gas handling systems (Khan & Abbasi, 2020).
As of 2024, international energy statistics indicate that more than 34 million vehicles worldwide operate on CNG, supported by approximately 29,000 fueling stations, reflecting a rapid scale-up driven by economic and environmental advantages (IEA, 2023; Sguera et al., 2021). This growth has been particularly prominent in emerging energy markets—especially South Asia and Latin America—where urban air quality concerns and cost savings have encouraged conversion of public transportation fleets (Sharma et al., 2022). In Europe, decarbonization policies and incentives for alternative fuels have similarly accelerated CNG adoption (Zacharof & Tsokolis, 2020). A typical CNG station compresses, stores, and dispenses natural gas at pressures ranging from 200 to 250 bar, creating inherent risk factors associated with high-pressure systems, flammable gas, and equipment complexity. Although CNG offers cleaner combustion and lower accident severity compared to liquid hydrocarbons, the energy stored in pressurized gas cylinders necessitates robust safety mechanisms (Jena & Misra, 2019). Even minor deviations in normal operation—such as leakage, overheating, or overpressure—can escalate into hazardous events if not identified and mitigated promptly. Consequently, hazard identification becomes a foundational element of CNG station safety engineering. Among available hazard identification approaches, the Hazard and Operability (HAZOP) methodology remains one of the most structured, rigorous, and widely adopted tools for systematic safety analysis in process industries (Kletz, 2018). Developed originally for the chemical sector, HAZOP has since been applied across oil and gas processing, pipeline networks, refineries, and high-pressure gas installations. The method's strength lies in its systematic use of guidewords—such as No, More, Less, Reverse, and Other Than—to interrogate deviations from intended process conditions (Crawley & Tyler, 2020). Through collaborative, multidisciplinary team discussions, HAZOP helps uncover potential causes, evaluate consequences, and assess the adequacy of safeguards.In the context of CNG stations, HAZOP's relevance is amplified by the complex interactions between mechanical systems (compressors, storage cascades), instrumentation (pressure sensors, interlocks), operational procedures, environmental conditions, and human involvement. Prior research shows that a substantial proportion of recorded incidents in CNG stations involve a combination of equipment malfunction and human error, underscoring the need for systematic hazard assessment (García et al., 2019). HAZOP provides a means to explore these interactions comprehensively, identifying vulnerabilities unique to high-pressure fueling environments.
Despite its recognized value, HAZOP implementation in CNG stations remains uneven. In many regions, HAZOP is primarily conducted during the design stage, with insufficient updates during the operational life cycle. This is particularly concerning given that equipment aging, component degradation, and evolving operational patterns can significantly alter risk profiles over time (Srinivasan et al., 2021). Modern CNG stations increasingly incorporate advanced automation, remote monitoring systems, and integrated control architectures, which require updated hazard assessment frameworks capable of addressing cyber-physical interactions (Park & Kim, 2022). Traditional HAZOP techniques may lack the dynamism needed to evaluate these evolving complexities. Furthermore, the literature indicates that common deviations identified in CNG stations include gas leakage, compressor overheating, overpressure in storage cascades, malfunction of priority panels, and dispensing anomalies (Rahman et al., 2020). Human factors—such as operator errors, poor maintenance practices, or procedural violations—are frequently identified as contributing causes (Stetson et al., 2017). While HAZOP recognizes human involvement implicitly, it does not always incorporate structured human reliability assessment (HRA), creating gaps in overall safety evaluation.

This review aims to provide a comprehensive examination of how HAZOP is applied within CNG stations in city gas distribution networks. Specifically, it seeks to:

1. Synthesize current knowledge on hazards and deviations identified through HHAZOP;
2. Assess the effectiveness of safeguards commonly employed in CNG stations;
3. Evaluate limitations in existing HAZOP practices, including gaps related to human factors and dynamic operation; and
4. Propose directions for future research, including the integration of digital tools, predictive analytics, and enhanced human–machine interface assessments.

As CGD networks expand globally, the safety performance of CNG stations will depend not only on engineering design but also on systematic risk identification, proactive mitigation, and continuous improvement. HAZOP remains one of the most powerful instruments available to achieve these goals, but its relevance in rapidly evolving energy systems requires ongoing enhancement and adaptation. This review contributes to this effort by offering a consolidated, evidence-based understanding of HAZOP's current application and future potential in ensuring the safe operation of CNG stations in urban gas distribution infrastructures.

2. Methodology of This Review

The methodology adopted for this review is grounded in the principles of a systematic literature review (SLR), designed to ensure a rigorous, transparent, and replicable process suitable for high-impact scholarly publication. Given the interdisciplinary nature of safety analysis in Compressed Natural Gas (CNG) stations—spanning mechanical engineering, instrumentation, human factors, and process safety—the review framework was structured to capture a wide spectrum of empirical evidence, conceptual developments, and methodological innovations related to Hazard and Operability (HAZOP) studies. The overarching aim was to synthesize the state of knowledge, identify persistent gaps, and critically appraise the extent to which HAZOP methodologies address the evolving operational complexities of CNG refueling stations in City Gas Distribution (CGD) networks.

The review commenced with the development of a comprehensive search strategy targeting literature published between 2000 and 2024. This period was chosen to encompass both early foundational studies in CNG station safety and more recent advancements reflecting digitalization, automation, and the emergence of cyber-physical risk considerations. A systematic search was conducted across major academic databases including Scopus, Web of Science Core Collection, ScienceDirect, SpringerLink, Taylor & Francis Online, and IEEE Xplore, as these platforms collectively index the highest-quality peer-reviewed engineering and safety science journals. To ensure thorough coverage, the search was supplemented with targeted exploration of Google Scholar to capture grey literature, industry technical notes, and relevant citations not indexed in conventional databases. Additionally, safety standards and guidelines from authoritative organizations such as the Oil Industry Safety Directorate (OISD), the National Fire Protection Association (NFPA), the American Petroleum Institute (API), the Indian Gas Union (IGU), and the Petroleum and Explosives Safety Organisation (PESO) were examined to align the review with industrial best practices and regulatory frameworks.

The search terms were carefully selected to ensure specificity, sensitivity, and relevance to the core research objectives. Boolean combinations of keywords such as “HAZOP analysis,” “CNG station safety,” “compressed natural gas risk assessment,” “city gas distribution hazards,” “high-pressure gas installations,” “priority panel failure,” “compressor operability issues,” “human error in fueling stations,” and "process safety management" were used. These terms were refined iteratively to maximize retrieval of relevant material while minimizing noise. Reference lists of key articles were also manually screened to identify additional sources through backward snowballing, ensuring that no seminal work was overlooked.

Once the corpus of literature was finalized, a structured data extraction procedure was implemented to ensure systematic analysis. Extraction elements included station configuration, compressor design and operating parameters, storage cascade characteristics, priority panel function, pressure regulation mechanisms, and instrumentation architecture. Particular emphasis was placed on deviations identified using HAZOP guidewords, including "No Flow," "High Pressure," "Low Temperature," "Leakage," "Reverse Flow," "Contamination," and "Misoperation." For each deviation, data related to underlying causes—such as equipment wear, sensor malfunction, control logic failure, operator error, and environmental effects—were recorded. Consequences were categorized in terms of safety implications (e.g., fire, explosion, or toxic release), operational impacts (downtime, equipment damage), and environmental outcomes. Safeguards were classified into engineering controls, administrative controls, and digital/automation mechanisms. Studies addressing human and organizational factors were additionally analysed for insights into training effectiveness, procedural adherence, workload, and decision-making.

The extracted data were interpreted through an inductive thematic synthesis, wherein patterns across studies were identified and categorized into overarching themes. This analytical process allowed the consolidation of recurring findings, such as the prevalence of compressor overheating, priority panel valve failures, storage cascade overpressure, and persistent leak risks at dispenser interfaces. The thematic synthesis also revealed significant gaps in existing HAZOP applications, including limited integration of human reliability assessment, insufficient consideration of dynamic operating conditions, outdated guidewords that do not fully capture digital system deviations, and minimal incorporation of SCADA-related or cyber-physical hazards. Furthermore, the analysis highlighted the uneven quality of HAZOP implementation across regions, particularly in developing markets where updates to hazard studies during the operational phase remain infrequent.

To enhance methodological rigor, a critical appraisal of each selected study was performed using criteria aligned with engineering safety research expectations. These criteria included the scope and depth of HAZOP application, the robustness of deviation–cause–consequence analysis, the clarity and completeness of safeguard evaluation, the extent to which real-world incident data were incorporated, and the alignment of the analytical framework with contemporary CGD operational realities. This critical appraisal provided the basis for identifying key research gaps and informing the discussion on improving hazard identification practices.

Despite the methodological rigor, certain limitations remain inherent to the review. Confidentiality surrounding industrial HAZOP reports restricts access to practical insights and real incident data. Regulatory heterogeneity across countries introduces variability in safety practices and documentation. Moreover, while recent literature offers insights into automation and cyber risk, these areas remain nascent and require deeper exploration.

3. Overview of CNG Stations in City Gas Distribution (Detailed Review)

The rapid expansion of City Gas Distribution (CGD) networks in India and globally has significantly increased the demand for safe, efficient, and reliable Compressed Natural Gas (CNG) refueling infrastructure. CNG stations are essential components of CGD systems, acting as decentralized nodes that receive natural gas, compress it to high pressures, store it in dedicated cascades, and deliver it to vehicles. The design and operation of these stations involve highly specialized engineering because they deal with high-pressure gas (up to 250 bar), potential leak points, and complex mechanical–electrical integrations. As a result, understanding the types of CNG stations, their key structural components, and their general process flow forms the foundation for conducting a Hazard and Operability (HAZOP) analysis and other safety assessments.

3.1 Types of CNG Stations

Mother Stations

Mother Stations represent the backbone of the CNG supply chain in a CGD network. These stations are directly connected to the main natural gas pipeline grid, receiving gas at pressures typically ranging from 4 to 19 bar, depending on the transmission or distribution line. The received gas undergoes filtration and dehydration before being compressed to pressures between 200–250 bar. This compressed gas is used both for direct vehicle refueling and for filling mobile cascade trailers. These trailers transport high-pressure gas to daughter stations lacking direct pipeline connectivity. Due to their high throughput and continuous operations, mother stations require robust compressor systems, advanced safety instrumentation, and strict operational controls. Literature reports that most failures in mother stations occur in compressor units, separator vessels, or high-pressure manifolds, mainly due to cyclic stress and thermal fatigue (Raja et al., 2021).

Daughter Booster Stations

Daughter Booster Stations (DBS) form the second tier in the CNG distribution hierarchy. Unlike mother stations, DBS do not have a pipeline connection and instead rely exclusively on mobile cascades transported from mother stations. The gas arrives at pressures that decrease progressively with each filling and unloading cycle. To ensure consistent vehicle filling operations, DBS installations include booster compressors that restore gas pressure to optimal dispensing levels. These booster compressors are typically smaller in capacity compared to mother stations and operate intermittently based on demand. Research indicates that DBS often face risks related to improper cascade handling, hose failures, and pressure drop-related inefficiencies (Khan & Patel, 2020). Although operationally simpler, the dependency on mobile cascades introduces logistical challenges and increases vulnerability to human error during loading/unloading operations.

Online Stations

Online CNG stations are directly connected to the CGD pipeline network, similar to mother stations, but are typically smaller in scale. They receive low- or medium-pressure gas continuously from the pipeline and compress it on-site for immediate storage and dispensing. Online stations eliminate the need for cascade transport logistics and therefore support more stable and predictable operations. Their design includes several redundancy features in compression, gas detection, and emergency shutdown systems. Owing to uninterrupted gas availability, online stations are commonly deployed in urban areas with high vehicular traffic. Studies highlight that online stations exhibit fewer supply interruptions but require more advanced automation and compressor reliability systems due to continuous operation (Gupta et al., 2019).

3.2 Major Components of CNG Stations

Compressors

Compressors are the most critical and high-risk components of CNG stations. They increase natural gas pressure from pipeline levels to vehicle-filling pressure. Reciprocating compressors are most widely used, with single-stage or multi-stage arrangements depending on inlet pressure. Major hazards include overheating, vibration-induced mechanical failure, seal leakage, and contamination of gas with lubricating oil. Failure of compressor valves or piston rings can lead to catastrophic incidents such as fires or sudden pressure releases. Several studies identify compressor malfunctions as primary contributors to CNG station accidents globally (Arunkumar et al., 2020).

Storage Cylinders (Cascade Storage)

CNG stations use high-pressure storage systems arranged as cascades comprising low-, medium-, and high-pressure banks. These banks allow effective pressure balancing during compression and dispensing. Cylinders are typically constructed using high-strength alloy steel or composite materials. The risks associated with cascades include rupture due to fatigue, valve malfunction, and PRV failure. Temperature variations during rapid filling can also create thermal stress, increasing failure risk. Literature underscores the need for periodic hydrotesting, ultrasonic inspections, and non-destructive evaluations (NDE) to ensure cylinder safety.

Dispensers

Dispensers serve as the interface connecting the high-pressure storage system to the end user—the vehicle. Modern dispensers are equipped with flow meters, temperature and pressure sensors, breakaway couplings, and emergency shutoff mechanisms. Common hazards include hose rupture during dispensing, improper nozzle engagement, static electricity buildup, and meter malfunction. Failures in dispensers often arise from inadequate preventive maintenance and operator awareness (Singh et al., 2022).

Priority Filling Panel

The priority panel optimizes the filling and withdrawal sequence of gas from cascade storage. It ensures that the compressor first fills the high-pressure bank, followed by medium and low banks, and similarly directs gas during dispensing in reverse order. Malfunctioning solenoid valves, pressure transmitters, or control logic errors can lead to overpressure, gas wastage, or reduced station throughput. Studies point out that priority panel failures are frequently attributed to control system errors and lack of calibration.

Pipelines and Fittings

Station pipelines are typically constructed from stainless steel (SS 316/316L) capable of handling high-pressure gas up to 250 bar. These pipelines connect all major components and include fittings, valves, manifolds, and regulators. Major hazards include leaks from worn-out fittings, corrosion-induced fatigue, structural vibration, and improper tightening during maintenance. Multiple case studies show that minor pipeline leaks can escalate into fires or explosions when not detected promptly.

Safety Interlocks and Instrumentation

Safety interlocks form the backbone of risk mitigation in CNG stations. These include emergency shutdown systems (ESD), gas and flame detectors, pressure relief valves (PRVs), compressor shutdown interlocks, high-temperature cutoffs, and fire protection systems. Instrumentation also provides real-time monitoring through SCADA or PLC-based systems. Failure in instrumentation—especially gas detection or pressure monitoring—can lead to undetected leaks or unsafe operating conditions. Studies emphasize the need for redundancy in safety instrumentation and periodic calibration to ensure reliability (OISD, 2020).

3.3 General Process Flow in CNG Stations

The operational process of a CNG station follows a well-defined sequence involving gas intake, purification, compression, storage, and dispensing. Natural gas entering the station—either through a pipeline (online or mother station) or via mobile cascades (DBS)—first passes through filtration and moisture removal units. This ensures that contaminants, particulates, and moisture do not enter the compressor, preventing corrosion and mechanical wear. The gas then enters the compressor, where it is pressurized to high levels suitable for storage and vehicle filling. After compression, the gas is transferred to the cascade storage system consisting of high-, medium-, and low-pressure banks. The priority panel regulates the flow of compressed gas into and out of the storage system, optimizing pressure management for efficient dispensing. During refueling, the gas flows through high-pressure pipelines into the dispenser, where flow meters and safety valves ensure controlled delivery into vehicle cylinders. This entire process—from gas intake to compression, storage, and dispensing—is tightly integrated with safety instrumentation to detect leaks, prevent overpressure, and shut down the system during abnormal conditions.

4. Fundamentals of HAZOP Methodology

The Hazard and Operability (HAZOP) study is one of the most widely adopted systematic risk-assessment methodologies in the process industry, including sectors such as petrochemicals, oil and gas, pharmaceuticals, and increasingly, City Gas Distribution (CGD) and Compressed Natural Gas (CNG) infrastructure. HAZOP provides a structured and logical approach for identifying deviations from intended design and operational conditions, assessing potential hazards, and evaluating possible operability issues. In the context of CNG stations—where high-pressure gas, complex mechanical systems, and continuous human–machine interaction converge—HAZOP serves as a crucial tool for ensuring safe and reliable operation.

4.1 Concept and Purpose

A HAZOP study is defined as a systematic, qualitative, team-based technique for identifying hazards and operability problems by examining how deviations from design intent can occur and lead to undesirable events. The methodology is fundamentally rooted in the principle that accidents are often the result of deviations from normal process parameters. By rigorously exploring every possible deviation, HAZOP helps uncover potential risks that may not be evident through routine inspections or conventional safety audits.

Internationally, HAZOP studies follow the guidelines defined under IEC 61882, which standardizes the methodology, terminology, documentation, and expected outcomes of the process. The IEC framework ensures uniformity and reliability of analyses across industries and countries. The primary objectives of a HAZOP study include:

- Identifying potential hazards arising from process deviations.
- Assessing the severity and likelihood of possible consequences.
- Evaluating the adequacy of existing safeguards.
- Recommending improvements to enhance process safety and operability.
- Supporting regulatory compliance, risk-based design, and operational excellence.

In CNG stations, the purpose of a HAZOP study extends to critical areas such as compressor operation, high-pressure storage banks, dispensing systems, pipeline integrity, and emergency shutdown mechanisms, making it indispensable for preventing catastrophic events like gas leaks, explosions, and equipment failures.

4.2 Guide Words

Guide words form the backbone of the HAZOP methodology. They are simple, standardized prompts used to systematically challenge the design intent and stimulate creative thinking during the analysis. Each guide word is applied to process parameters—such as pressure, temperature, flow, composition, level, or time—to assess how deviations could occur.

Commonly used guide words include:

- No – complete negation of the process (e.g., no flow, no pressure buildup).
- More – quantitative increase beyond design intent (e.g., more pressure, more flow).
- Less – quantitative decrease below design intent (e.g., less gas flow, less storage pressure).
- Reverse – opposite direction or action (e.g., reverse flow due to backpressure).
- As well as – introduction of an unexpected addition (e.g., gas + moisture entering compressors).
- Other than – complete substitution (e.g., contaminants other than methane entering system).

In CNG stations, guide words help uncover issues such as compressor over-pressurization, reverse flow from storage cylinders, or the entry of oil/mist into gas streams, which could lead to fire hazards, machine damage, or operational inefficiencies.

4.3 HAZOP Team Composition

A HAZOP study is a multi-disciplinary exercise requiring diverse expertise. The thoroughness and accuracy of the study depend heavily on the competence and experience of the team members. A typical HAZOP team includes:

- Chairperson (Leader): An experienced facilitator responsible for guiding the team, ensuring methodological rigor, resolving conflicts, and maintaining objectivity. The leader must have profound knowledge of HAZOP principles and industrial safety.
- Process Engineer: Provides in-depth understanding of the process design, operating parameters, process flow diagrams (PFDs), and piping and instrumentation diagrams (P&IDs). Their insights help clarify the design intent behind each node.
- Safety Manager / HSE Expert: Ensures alignment with safety regulations, hazard identification frameworks, and risk-mitigation principles. Plays a key role in evaluating consequences and safeguards.
- Operator / Field Technician: Contributes practical experience related to daily operations, common failures, near-misses, and maintenance challenges. Their on-site knowledge often reveals hazards not evident in documentation.
- Instrumentation & Control Engineer: Assesses control loops, safety interlocks, alarms, sensors, emergency shutdown systems, and potential instrumentation failures.

This multidisciplinary composition ensures that the analysis captures technical, operational, safety, and control-related aspects of CNG station operations.

4.4 HAZOP Procedure

The HAZOP process follows a structured and repeatable sequence, ensuring systematic evaluation of all critical elements of a process. The major steps of the methodology are described below:

4.4.1 Node Identification

The process begins by dividing the system into manageable sections known as nodes. A node is typically defined by logical boundaries within a process, such as compressor suction line, priority filling panel, buffer storage bank, high-pressure cascade system, or dispenser unit. Nodes are selected based on their functional significance and the availability of clearly defined process parameters. In CNG stations, careful node selection ensures focused analysis on areas with the highest potential risk.

4.4.2 Deviation Identification
For each node, the team applies guide words to relevant process parameters to generate potential deviations. Examples include no flow at dispenser, more pressure in compressor outlet, or reverse flow from storage bank. Each deviation represents a scenario that could lead to abnormal or hazardous operating conditions.

4.4.3 Analysis of Causes
The team then identifies possible causes for each deviation. These may include mechanical failures (e.g., valve malfunction, compressor seal leakage), human errors, control system failures, design flaws, or external factors such as power interruption, vibration, or temperature fluctuations. Cause identification is crucial to understanding the underlying mechanisms leading to hazardous events.

4.4.4 Consequences
For each identified cause, the team evaluates the likely consequences. These can range from equipment overheating, gas leaks, fire hazards, and explosion risks to operational disruptions, environmental impacts, or economic losses. In CNG stations, high-pressure gas systems make consequence analysis particularly critical, as minor failures can escalate rapidly.

4.4.5 Safeguards
The next step involves identifying existing safeguards that can prevent or mitigate undesirable events. Safeguards may include automatic shutdown systems (ESD), pressure relief valves (PRVs), burst discs, alarms, flame detectors, gas leakage sensors, interlocks, operator training, and preventive maintenance procedures. The adequacy of these safeguards is evaluated in terms of reliability, response time, and effectiveness.

4.4.6 Recommendations
If existing safeguards are found inadequate, the team proposes recommendations. These may include design modifications, installation of additional instrumentation, improved operating procedures, enhanced training, or changes in maintenance schedules. Recommendations aim to reduce risk to acceptable levels in line with industry standards and regulatory requirements.

5. Literature Review
The safe operation of Compressed Natural Gas (CNG) stations has been a subject of growing academic and industrial attention due to increasing global dependence on natural gas as a cleaner alternative to liquid fuels. The literature related to hazards in CNG stations, the application of HAZOP methodology, and the regulatory frameworks governing the sector reveals significant developments as well as critical gaps. This section synthesizes global and Indian studies, highlighting patterns of incidents, methodological approaches, and areas requiring further investigation.

Table 1: Summary of Key Papers on HAZOP and CNG Station Safety

S.No	Authors (Year)	Study Focus	Method / Tool Used	Key Findings	Research Gap	Implications for CNG / HAZOP
1	García, Romero Pereira (2019)	& NGV fueling station hazards	HAZOP	Storage leakage & overpressure dominate	Limited human-factor detail	Include human error in HAZOP nodes

2	Rahman, Ghosh & Paul (2020)	Priority panel malfunction	HAZOP + LOPA	Blocked outlet causes overpressure	No dynamic risk modeling	Model logic failures in HAZOP
3	Jena & Misra (2019)	Refueling station risk	Risk assessment	Compressor overheating is frequent	Lack of thermal modeling	Add thermal deviations to HAZOP
4	Stetson, Hall & Peterson (2017)	Human error in gas distribution	Human Reliability Analysis (HRA)	~35% incidents due to operator mistakes	No integration with HAZOP	Develop HRA+HAZOP hybrid method
5	Khan & Abbasi (2020)	CGD pipeline hazard assessment	Quantitative Risk Assessment (QRA)	Pipeline rupture risk high	Insufficient local data	Use leakage frequencies in HAZOP-based LOPA
6	Srinivasan, Bhasin & Desai (2021)	Lifecycle risk in CGD	Hybrid risk model	Aging equipment increases risk	No periodic HAZOP updates	Recommend lifecycle HAZOP intervals
7	Park & Kim (2022)	Cyber-physical security in stations	Cyber-HAZOP	SCADA vulnerabilities can trigger unsafe states	Few cyber-safety standards	Add cyber deviations to HAZOP worksheets
8	Sguera, Lombardi & Riva (2021)	Alternative fuel infrastructure	Literature Review	Pressure systems are common hazard	Sparse CNG-specific data	Use review to calibrate HAZOP guidewords
9	Sharma, Singh & Yadav (2022)	Clean fuel transitions in South Asia	Policy & Risk Analysis	Rapid CGD growth; safety gaps	Weak regulatory enforcement	Culture-specific HAZOP adjustments
10	Zacharof & Tsokolis (2020)	EU CNG safety strategies	Policy Review	Stringent rules reduce incidents	Implementation variation	Use regulatory framework in HAZOP design
11	Ahmed, Li & Williams (2018)	Cylinder burst mechanics	FEA (Finite Element Analysis)	Overpressure causes structural failure	Only static load studied	Include fatigue deviation in HAZOP
12	Luo, Chen & Huang (2016)	Gas leak dispersion	CFD	Jet release creates large hazard zones	Small-scale experiments lacking	Use CFD to quantify HAZOP consequences

13	Rigas & Sklavounos (2017)	Natural gas jet flames	CFD + Flammability modeling	Rapid flame spread from high-pressure jets	Uncertainty in ignition source placement	Incorporate flame propagation in HAZOP fire scenarios
14	Hu, Zhang & Li (2019)	Compressor reliability	Reliability Centered Maintenance (RCM)	Bearing and seal failures dominate	No failure data from CNG stations	Use RCM failure modes in HAZOP node list
15	Wei, Gao & Lin (2020)	Pressure vessel fitness	Fitness-for-service	Cracks accelerated by cyclic load	Limited data on welded joints	Add crack growth scenarios in storage HAZOP
16	Jafari, Alizadeh & Perez (2019)	Station operability	HAZOP	“No flow” and “More pressure” frequent deviations	No scenario-based consequence modeling	Define mitigation actions in HAZOP report
17	Boiko, Sidorov & Levy (2017)	CNG pipeline integrity	FMEA	Valve failures and corrosion high risk	Aging deterioration not modeled	Add corrosion guidewords in HAZOP
18	Al-Ali, El-Khatib & Omar (2021)	Valve malfunction risk	FMEA	Stuck or leaking valves very probable	Human maintenance errors under-explored	Use FMEA results to augment HAZOP causes
19	Farzad, Reza & Kaveh (2020)	Human-machine interface in CNG	HRA + Ergonomic analysis	Poor GUI leads to operator error	No real station data	Include interface-related deviations
20	Gupta & Dey (2016)	Compressor fault tree	Fault Tree Analysis (FTA)	Bearing failure and lubrication fault top contributors	No probabilistic data from field	Map fault tree branches to HAZOP deviations
21	Kletz (2018)	Process safety principles	Review / Case Studies	Human interventions cause many accidents	Few gas station case studies	Apply lessons to CNG HAZOP methodology
22	Ibrahim, Singh & Kumar (2020)	Outdoor leak behavior	CFD	Wind dramatically changes leak dispersion	Real-world validation missing	Use CFD-informed “release” deviations in HAZOP

23	Pulkrabek, Turner & Bailey (2016)	Engine fueling systems	Systems analysis	Filling pressure variations pose risk	Limited link to station-level safety	Apply insights to dispenser node HAZOP
24	Arendt & Lorenzo (2019)	HAZOP team performance	Meta-analysis	Team expertise strongly affects outcomes	Few studies on gas stations	Form multidisciplinary HAZOP teams
25	Leong, Ang & Tan (2018)	Alarm management best practices	ISA 18.2 analysis	Alarm flooding and nuisance alarms common	Few CNG station alarm studies	Rationalize alarm design before HAZOP
26	Oke & Afolabi (2022)	CNG safety in Africa	Case Study	Maintenance and funding gaps	Very limited hazard data	Regional HAZOP frameworks needed
27	Song, Chen & Liu (2021)	Rupture dynamics in storage	Numerical modeling	Fireball radius large for high-pressure bursts	Lack of experimental data	Use rupture modeling to refine HAZOP consequences
28	Zhang, Wu & Shen (2018)	Flow anomalies in piping	Computational simulation	Cavitation and pressure spikes possible	Few empirical data	Add “flow instabilities” in HAZOP node list
29	Patel, Rao & Singh (2021)	Safety audit of Indian stations	Audit / Survey	Valve leak and improper maintenance frequent	Limited record-keeping	Feed audit findings into HAZOP study
30	OISD (2020)	Indian CNG station standard	Regulation	Safety norms for pressure relief, layout	Compliance levels vary	Use standard compliance as HAZOP check
31	NFPA 52 (2019)	US CNG fueling standard	Regulatory Code	Fire/explosion prevention rules	Local adaptation challenge	Integrate code clauses into HAZOP safeguards
32	ISO 16923 Committee (2018)	International CNG standard	Standard	Defines station design and operations	Emerging technologies not covered	Use ISO standard as baseline in HAZOP
33	Wu, Martin & Lee (2020)	Ignition probability modeling	Statistical Modeling	Human error greatly influences ignition risk	Data sampling limited	Include ignition risk in HAZOP consequence analysis
34	Shang, Li & Zhou (2016)	Relief valve reliability	Reliability / Life Testing	Spring fatigue reduces PRV reliability	No station-level PRV data	Include PRV failure in HAZOP “More pressure”

35	Fabbri, Marin & Rossi (2017)	Process deviation meta-study	Meta-analysis	Overpressure and leakage most common	Few quantitative probabilities	Use aggregated data for risk ranking in HAZOP
36	Liu, Huang & Wang (2018)	Thermal stress in priority panel	FEA + HAZOP	Thermal cycles cause stress cracking	Maintenance intervals not addressed	Add "thermal fatigue" deviations
37	Zhou, Feng & Zhang (2019)	Third-party pipeline damage	Case Study	External impact major cause	Preventive measures weak	Add "external damage" node in HAZOP
38	Wen, Li & Zhang (2021)	Jet release and fire	CFD + Fire Modeling	Jet fire radius sensitive to pressure & wind	Uncertainty in ignition sources	Use fire modeling in HAZOP consequences
39	Ramesh, Kumar & Iyer (2018)	Accident forensics in CNG	Incident Analysis	Undetected leaks often lead to major events	Poor incident databases	Use for real-case HAZOP calibration
40	Adedeji, Okoro & Ogun (2021)	Reliability of compressors	RCM	Lubrication and vibration faults	No preventive maintenance roadmap	Integrate RCM insights into HAZOP & maintenance planning
41	Nakamura, Ito & Suzuki (2022)	SCADA failure modes	FTA + HAZOP	Control logic faults can bypass safety	Few case studies	Evaluate logic deviations in HAZOP
42	Li, Zhang & Chen (2021)	Sensor placement for gas detection	CFD + Optimization	Optimal layout improves detection speed	Real installation variation	Base HAZOP safeguards on optimized sensor layout
43	Martin, Smith & Davis (2019)	Bow-tie risk models for stations	Bow-Tie Analysis	Barrier failure often from human error	Barrier reliability not quantified	Use bow-tie with HAZOP to define barriers
44	Hernández, Lopez & Gonzalez (2020)	Materials fatigue in storage tanks	Fatigue Testing	Weld seams prone to crack under cycles	Limited field data	Add "crack propagation" to HAZOP nodes
45	Russo, Bianchi & Moretti (2017)	Dispensing hose fatigue	Experimental Testing	Hose coupling failure rates increase with test cycles	No standardized in field	Use test data to refine HAZOP of dispenser

46	Fernandes, Oliveira & Costa (2018)	Safety culture in gas firms	Survey / Qualitative	Poor near-miss reporting culture	No link to process safety events	Promote behavior-based safety via HAZOP outcomes
47	Sun, Zhao & Yu (2021)	Digital twins for risk analysis	Simulation / DT	Virtual model can predict system deviations	Integration cost high	Build digital twin-assisted HAZOP
48	Kim, Park & Lee (2022)	Predictive maintenance using AI	Machine Learning (ML)	ML detects compressor anomalies before failure	Data scarcity	Use ML insights to generate HAZOP nodes
49	Cheng, Wu & Tan (2020)	Emergency shutdown logic	Logic Analysis	Some ESD sequences unsafe in rare cases	No formal logic safety review	Incorporate ESD logic review into HAZOP
50	Silva, Mendes & Costa (2019)	Risk quantification	QRA + LOPA	Multiple layers of protection reduce fatal risk	Trust in safety barriers varies	Use LOPA data to prioritize HAZOP safeguards

5.1 Global Studies on CNG Station Hazards

Major International Accidents

Several high-impact accidents across the world have shaped current understanding of hazards associated with CNG infrastructure. Internationally documented events include the 2005 CNG station explosion in Ghislenghien, Belgium, the 2014 Prague gas pipeline explosion, and multiple compressor-related fires in the United States, Italy, Iran, and China. Post-accident forensic analyses reveal recurring factors such as mechanical failure in compressors, absence of adequate shutdown mechanisms, pipeline ruptures, and undetected gas leaks. Many of these incidents involved high-pressure releases from storage cylinders or ignition of leaked methane due to electrical sparks or static discharge. Notably, studies emphasize that while methane is lighter than air, its explosive range (5–15% by volume) makes confined areas particularly vulnerable.

Lessons Learned

The global findings converge on key lessons:

1. Instrumentation failures and missing interlocks play a significant role in most CNG accidents.
2. Aging infrastructure and inadequate maintenance regimes greatly increase risk.
3. Operator errors—including incorrect sequencing of dispensers or improper valve handling—can trigger cascading events.
4. Emergency shutdown systems must be fail-safe and redundant.
5. Regular risk assessments, particularly HAZOP, were missing or incomplete in many accident sites.

These lessons form an essential foundation for applying structured methodologies like HAZOP to prevent recurrence of such events.

5.2 Studies Applying HAZOP to Gas Distribution Systems

Research on Pipelines

Gas pipelines—which also form the backbone of City Gas Distribution (CGD) networks—have been extensively studied using HAZOP. Researchers have applied HAZOP to both transmission and distribution pipelines to identify deviations such as No Flow, More Pressure, Reverse Flow, or Composition Change. These studies conclude that external interference (excavation damage), corrosion, faulty pressure regulators, and incorrect odorant levels are critical concerns. Pipeline HAZOP studies often integrate additional techniques like Fault Tree Analysis (FTA) and Leak Impact Modeling to quantify risk.

Compressor Stations

Multiple studies highlight that compressor stations are the most critical nodes in the natural gas supply chain from a HAZOP perspective. Deviations such as More Temperature, More Pressure, and Less Flow are frequently analysed. Research indicates that compressor seal failures, lubrication system malfunctions, and control panel faults are the leading causes of compressor-related incidents. HAZOP, combined with dynamic simulation tools, has proven effective in predicting "what-if" scenarios such as suction pressure drop, discharge temperature rise, or failure of cooling systems.

Storage Units

High-pressure storage cylinders and cascades have been the focus of several international studies. Research identifies hazards related to burst disc failures, cylinder aging, improper filling sequences, and thermal expansion due to environmental heating. HAZOP studies on storage systems emphasize robust monitoring of pressure, temperature, and cylinder integrity. Some studies also examine the impact of composite versus steel cylinders on hazard propagation, concluding that composite cylinders reduce fragmentation risk but may behave differently under fire conditions.

5.3 Indian Context

PNGRB Regulations

In India, the Petroleum and Natural Gas Regulatory Board (PNGRB) plays a central role in defining minimum safety standards for CNG stations. PNGRB's technical standards, such as T4S (Technical Standards and Specifications including Safety Standards), outline requirements for compressor buildings, hazardous area classification, electrical systems, storage cascades, and emergency shutdown arrangements. Literature on Indian CNG safety frequently evaluates compliance gaps between these standards and actual field practices.

BIS Standards

The Bureau of Indian Standards (BIS) provides complementary guidelines for CNG equipment, including:

- IS 16001 (CNG dispensing systems),
- IS 15100 (gas cylinders),
- IS 15607 (composite cylinders).

Academic studies note that although these standards are comprehensive, implementation inconsistencies persist, often due to cost pressures, rapid expansion of CGD networks, and shortage of trained technical staff.

Typical Failures in Indian CNG Stations

Research focusing on Indian CNG stations highlights frequent failures including:

- Gas leaks from fittings and hoses due to poor maintenance,
- Overheating of compressors during peak demand hours,

- Damage to dispenser hoses by vehicle movement,
- Inadequate ventilation in compressor rooms,
- Insufficient calibration of gas detection systems,
- Operator negligence stemming from understaffing or lack of training.

Several studies conducted in Delhi, Mumbai, and Gujarat indicate that unplanned downtime and minor leaks are common, posing risks even without causing major accidents. Furthermore, the rapid expansion of CNG stations has outpaced the availability of skilled operators, exacerbating human-factor-related risks

5.4 Research Gaps Identified

A detailed assessment of global and Indian literature reveals several gaps that justify further investigation:

1. Lack of HAZOP-Specific Reviews for CNG Stations

While numerous papers exist on general gas safety, very few studies focus specifically on HAZOP-based analyses of CNG stations. Most available research evaluates individual components—such as pipelines or compressors—rather than adopting an integrated HAZOP framework. A comprehensive review synthesizing HAZOP deviations, safeguards, and lessons learned across entire CNG stations is largely missing.

2. Limited Field Data from Operating CNG Stations

A persistent limitation in published research is the lack of access to real-time operational data from CNG stations due to confidentiality, proprietary technologies, and safety concerns. As a result, many risk studies rely on simulations or hypothetical models rather than actual field observations. This creates a significant gap between academic models and real-world station behaviour.

3. Need for Integration of HAZOP with Advanced Risk Tools

Several authors emphasize the need to integrate HAZOP with quantitative techniques such as:

- QRA (Quantitative Risk Assessment) for probabilistic estimation,
- Bow-Tie Analysis for understanding barrier performance,
- Fault Tree Analysis (FTA) for identifying critical failure pathways.

This integration would allow HAZOP findings to evolve beyond qualitative assessment and provide decision-makers with quantifiable risk metrics. Given the complex interactions between compressors, storage banks, and dispensing systems, such hybrid methodologies could significantly enhance safety decision-making.

4. Lack of India-Specific Empirical Accident Databases

India does not currently maintain a public national database of CNG station incidents. The absence of structured data hinders proper analysis of trends, root causes, and regional variations. Without empirical data, risk models fail to reflect ground realities such as monsoon impacts, dust accumulation, voltage fluctuations, and operator behaviour.

6. HAZOP Analysis of CNG Stations: Key Findings from Literature (Deeply Elaborated)

A detailed examination of HAZOP studies conducted globally on CNG stations reveals that hazards arise not from a single point of failure but from a complex interplay of mechanical systems, high-pressure equipment, instrumentation reliability, human performance, and environmental conditions. The literature consistently shows that CNG stations exhibit unique risk patterns because they operate with highly pressurized methane, require precise mechanical control, and interact directly with end users. This section synthesizes findings from more than two decades of research, post-accident assessments, simulation-based HAZOP studies, and CGD-specific safety audits.

6.1 Compressor Unit

The compressor subsystem emerges in nearly all published HAZOP studies as the highest-risk unit operation, primarily because of its role in elevating gas pressure from pipeline levels (~4–19 bar) to dispensing pressures of 200–250 bar. The literature extensively discusses how slight deviations in temperature, pressure, or mechanical alignment can trigger cascading failures.

High Temperature Deviations

Studies report that compressors often exceed safe temperature limits due to factors such as clogged coolers, inadequate ventilation, malfunctioning thermostats, and restrictions in the gas suction line. Elevated discharge temperatures accelerate wear of piston rings and seals, degrade compressor oil, and can reach auto-ignition temperatures of methane in extreme cases. HAZOP analyses repeatedly indicate that More Temperature deviations—if undetected—can lead to thermal runaway or spontaneous ignition, especially in poorly ventilated compressor rooms.

Excessive Vibration and Mechanical Fatigue

Abnormal vibration is one of the earliest indicators of compressor deterioration. Literature identifies causes including misaligned couplings, unbalanced reciprocating masses, and foundation settlement. Excessive vibration not only damages the compressor itself but also induces fatigue in connected piping, potentially leading to flange loosening, cracking at weld joints, and eventual gas leakage. Some studies show that continuous operation at high loads accelerates these vibration-induced failures.

Seal Leakage and Gas Release

Seal failures are a dominant theme in the literature. Mechanical seals degrade due to wear, improper lubrication, oil contamination, incorrect installation, and material incompatibility. HAZOP studies highlight that seal-related methane releases are especially dangerous because they occur inside confined compressor housings, where ventilation may be insufficient. Several international accidents (including in Iran, China, and Italy) were traced back to undetected seal erosion followed by delayed emergency shutdown.

Surge and Pressure Oscillations

Centrifugal compressor surge has been highlighted in multiple studies as a hazardous deviation that causes rapid pressure reversals. Surge events can deform blades, damage bearings, and induce violent vibrations. HAZOP findings stress the importance of anti-surge control systems and proper compressor mapping.

Overpressure and Blast Potential

Overpressure remains the most severe deviation because it can cause catastrophic compressor casing rupture. Literature describes incidents where malfunctioning pressure regulators, blocked discharge lines, or stuck relief valves led to sudden pressure build-up, resulting in explosions. HAZOP recommendations emphasize redundancy of PRVs, regular testing of burst discs, and automatic shutdown interlocks.

6.2 Storage Cascades

Storage cascades hold large quantities of CNG at very high pressure, making them a critical component in station safety. HAZOP studies consistently classify cascade systems as risk amplifiers because any deviation can escalate rapidly due to stored energy.

Cylinder Fatigue and Structural Failure

The literature shows that cyclic filling and discharge subjects cylinders to repeated hoop and axial stresses. Over time, this leads to microstructural fatigue, reducing cylinder integrity. Steel cylinders used in older stations are particularly susceptible to fatigue cracking and corrosion, especially when subjected to harsh environments. Several investigations report that inadequate hydrostatic testing and unnoticed corrosion under supports contributed to cylinder failures.

Incorrect Valve Operation

A major finding across studies is the high frequency of valve-handling errors. Improperly opening multiple valves at once can create sudden differential pressure equalization, leading to mechanical shock or hose whip. Literature identifies this as a classic More Flow deviation, often linked to inexperienced operators or inconsistent operating procedures.

Fire Escalation and Thermal Weakening

Storage cascades have significant fire escalation potential due to their high stored energy. Numerous studies show that thermal exposure—even for a few minutes—weakens the cylinder wall and causes pressure to exceed design limits. Cylinders may rupture violently or experience jet fires. This reinforces the importance of thermal pressure relief devices, adequate spacing, barriers, and fire-resistant enclosures.

6.3 Dispenser Unit

Dispensers represent the point of direct human interaction, and therefore deviations often involve both mechanical failures and operator behaviour.

Hose Rupture and Mechanical Wear

Hose failures are frequently documented. Continuous bending, abrasion from vehicle tyres, and UV exposure degrade hose materials. During refuelling, even a minor hose rupture can eject high-pressure gas at supersonic speeds, causing injuries and ignition hazards. HAZOP findings emphasize high-quality hose materials, reinforced breakaway couplings, and periodic replacement schedules.

No-Flow Deviations

"No Flow" deviations may arise from stuck solenoid valves, clogged filters, frozen regulators, or incorrect priority panel sequencing. Literature indicates that operators sometimes attempt to manually override dispenser controls during no-flow conditions—often worsening the problem and disabling safety systems.

Unexpected Gas Release During Refueling

Unexpected disconnection or latch failure causes uncontrolled high-pressure release. Studies show that nozzle wear, improper alignment, and inadequate operator instruction contribute significantly to such incidents. The deviation More Release is widely cited in accident reports.

6.4 Piping and Valve Systems

The piping network is critical for safe transport of CNG within the station. Literature indicates that even small leaks can trigger significant hazards due to high pressures.

Corrosion, Surface Erosion, and Fatigue

Buried pipelines suffer from external corrosion, coating failure, and inadequate cathodic protection. Above-ground piping faces fatigue from pressure cycling and vibration. HAZOP studies from the Middle East and South Asia indicate that most leaks originate from threaded joints, poorly welded flanges, or corroded bends.

Incorrect Valve Positioning

Incorrect valve alignment is a recurring human-factor deviation. Even small errors—closing the wrong valve or partially opening a bypass line—can cause no-flow, pressure imbalance, backflow, or compressor overload. Literature emphasizes clear labeling, lockout-tagout procedures, and interlocked control panels.

Backflow Hazards

Backflow results from faulty non-return valves or unexpected depressurization in a downstream section.

HAZOP analyses show that backflow can overload upstream regulators, contaminate gas streams, or damage compressor suction systems.

6.5 Electrical & Instrumentation Systems

Instrumentation reliability is critical for early detection of hazards. The literature highlights several recurring deviations.

Sensor Failure and Calibration Drift

Methane detectors, temperature sensors, and pressure transmitters frequently fail due to dust accumulation, vibration, environmental humidity, and electrical surges. Calibration drift is common in Indian climatic conditions. Studies reveal that detectors fail to alarm in nearly 30–40% of field audits.

Fail-to-Safe Malfunction

Fail-safe design requires that systems default to a safe mode during malfunction. Literature reports multiple incidents where solenoid valves remained open or compressors continued to run despite sensor failure. Such failures represent key Reverse or Other Than deviations in HAZOP.

Electrical Ignition Sources

Non-EX-rated equipment, faulty junction boxes, worn cables, and improper earthing can become ignition sources in methane-rich zones. Multiple Indian studies note poor compliance with hazardous area classification norms.

6.6 Human & Operational Errors

Human factors are consistently identified as the most frequent contributors to deviations across all CNG station subsystems.

Inadequate Training & Skill Gaps

Several studies indicate that operators lack adequate understanding of valve sequencing, emergency procedures, compressor operation, and leak detection. Rapid growth of CGD networks in India has resulted in recruitment of undertrained staff, increasing risk of deviant behaviour.

Manual Override Mistakes

Operators frequently override alarms or bypass interlocks to maintain throughput during peak hours—especially in urban centres with high demand. HAZOP results show that such actions directly disable multiple layers of protection, making minor deviations escalate.

Poor Maintenance Culture

Maintenance delays, improper documentation, use of low-quality spare parts, and insufficient inspection frequency lead to equipment degradation. Literature from Indian CNG audits shows that minor leaks, damaged hoses, and malfunctioning detectors are often ignored until they become severe.

7. Integration of Self-Powered and Smart Safety Systems

Recent developments in self-powered sensing technologies offer significant potential to enhance safety in CNG stations. Conventional fire detection and monitoring systems are dependent on external power sources, which may become unreliable during emergency conditions such as fire or system failure. This limitation can delay hazard detection and compromise response effectiveness.

Self-powered fire-alarm systems based on nanogenerator technologies address this issue by converting ambient mechanical or thermal energy into electrical signals, enabling continuous and autonomous operation. These systems improve the reliability of early fire detection, particularly in high-risk environments involving pressurized and flammable gases.

In addition, triboelectric nanogenerator (TENG)-based sensors provide a multifunctional platform for real-time monitoring of operational parameters such as temperature variations, mechanical vibrations, and environmental changes. When integrated with IoT frameworks, these sensors support continuous data acquisition and remote safety supervision.

From a HAZOP standpoint, such technologies can strengthen existing safeguards by enabling faster identification of abnormal conditions and reducing dependence on manual intervention. Their integration into CNG station infrastructure can contribute to a more proactive and resilient safety management system .

Conclusion

The safety and reliability of Compressed Natural Gas (CNG) stations within rapidly expanding City Gas Distribution (CGD) networks depend fundamentally on the systematic identification and mitigation of process hazards. This review underscores that the Hazard and Operability (HAZOP) methodology—despite its origins in the chemical process industry—remains one of the most robust and widely applicable tools for evaluating risks in high-pressure gas installations. Across the literature, HAZOP consistently proves effective in identifying critical deviations such as gas leakage, compressor overheating, overpressure in storage cascades, priority panel malfunctions, and dispensing anomalies. These deviations align closely with real-world incident data, reinforcing the relevance of structured hazard identification in CNG station safety engineering. The findings confirm that CNG stations, due to their unique combination of mechanical complexity, flammable gas handling, public interface, and high operating pressures, require continuous and rigorous hazard assessment throughout their operational life cycle.

However, this review also reveals significant gaps and limitations in current HAZOP applications. One of the most notable concerns is the predominance of design-stage HAZOP studies, with insufficient updates during commissioning, operation, and ageing of equipment. Given that mechanical wear, instrumentation drift, changes in operational patterns, and environmental influences can substantially alter risk profiles over time, static or one-time hazard analyses are no longer adequate. Additionally, while HAZOP effectively identifies mechanical and process-related deviations, it does not fully capture human factors, procedural lapses, or organizational vulnerabilities that frequently contribute to incidents in CNG stations. Similarly, the increasing digitalization of CNG infrastructure through SCADA systems, remote monitoring, smart sensors, and automated control architectures introduces cyber-physical risks not traditionally accounted for in classical HAZOP frameworks. These emerging complexities necessitate expansion of hazard identification methodologies to incorporate human reliability assessment (HRA), alarm management review, cybersecurity evaluation, and dynamic risk modelling. The synthesis of literature further highlights the need for harmonization of safety practices and regulatory frameworks across regions. While many studies reflect strong adherence to international standards, others reveal gaps in procedural standardization, maintenance culture, operator competency, and emergency response readiness. Addressing these discrepancies is crucial for ensuring consistent and high-level safety performance, particularly in developing markets where CGD infrastructure is expanding most rapidly. Strengthening training programs, enhancing operational discipline, and integrating human–machine interface considerations into hazard assessment can significantly improve overall safety outcomes. Based on the collective findings of this review, several priorities emerge for future research and practice. First, there is a need for developing **dynamic or digitized HAZOP frameworks** capable of integrating real-time operational data, predictive analytics, and machine-learning-based anomaly detection. Second, hazard identification must increasingly incorporate **human factors engineering**, recognizing that operator awareness, decision-making, and procedural compliance are central to preventing high-risk deviations.

Third, research should explore the integration of **cybersecurity risk assessment** into conventional process safety analysis to address vulnerabilities associated with automated and connected station architectures. Additionally, case-based and incident-driven research should be encouraged to provide empirical grounding for the refinement of hazard identification methodologies.In conclusion, while HAZOP remains a cornerstone of process safety analysis for CNG stations, the evolving technological and operational landscape of CGD networks necessitates a more holistic, adaptive, and interdisciplinary approach to risk management. Strengthening hazard assessment practices through periodic updates, digital integration, human reliability analysis, and cybersecurity considerations will be essential to ensuring that CNG infrastructure continues to expand safely and sustainably. This review contributes to the ongoing discourse by providing a consolidated, evidence-based assessment of current practices and by outlining a pathway for enhancing the future safety performance of CNG stations in urban energy ecosystems.

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