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Comprehensive Risk Analysis of LPG Fuel Handling, Storage, and Utilization in Automotive Industrial Facilities

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Abstract

Liquefied petroleum gas (LPG) is widely used as an industrial fuel because of its high energy content, ease of storage under pressure, and potential to reduce certain combustion-related emissions compared with conventional liquid fuels. However, its flammable nature, pressurised storage conditions, and potential for rapid vapour dispersion create significant fire, explosion, and occupational safety challenges in automotive industrial facilities. LPG-related hazards may arise during unloading, storage, transfer through pipelines, fuel dispensing, equipment operation, maintenance, and emergency response.

This study proposes an integrated risk-assessment framework for evaluating LPG-related hazards across the fuel-handling lifecycle in automotive industrial operations. The methodology combines Hazard Identification (HAZID), Hazard and Operability Study (HAZOP), Failure Mode and Effects Analysis (FMEA), a risk matrix, and quantitative consequence assessment. Major accident scenarios considered include LPG leakage, flash fire, jet fire, vapour cloud explosion, and boiling liquid expanding vapour explosion (BLEVE). Environmental considerations include direct fuel releases, combustion emissions, and the potential consequences of accidental fires and explosions. A risk-prioritisation model is proposed to evaluate the severity, likelihood, and effectiveness of existing safeguards. The framework can support the development of targeted prevention strategies, emergency preparedness plans, and continuous safety improvement programmes. The proposed methodology requires validation using actual industrial inspection data, operating records, and site-specific consequence modelling before numerical risk-reduction claims can be made.

Keywords: Liquefied petroleum gas, risk assessment, automotive industry, fire safety, explosion hazards, HAZOP, FMEA, environmental impact, quantitative risk assessment, occupational safety.

1. Introduction

Automotive industrial facilities involve a variety of manufacturing, assembly, heating, surface-treatment, maintenance, testing, and material-handling activities. Depending on the facility, LPG may be used in industrial heating systems, ovens, furnaces, boilers, forklifts, thermal-processing equipment, or other approved fuel-consuming installations. The configuration and scale of LPG infrastructure vary according to production requirements and operational practices.

Although LPG can provide efficient combustion, its storage and use require careful management of flammable-gas hazards. An unintended release may create a combustible vapour cloud when the gas mixes with air within its flammable range. If an ignition source is present, the consequences can include flash fires, jet fires, pressure effects from explosions, and escalation to nearby equipment or structures.

LPG presents particular challenges because it is stored under pressure as a liquid and rapidly vaporises when released under appropriate conditions. The released vapour can accumulate in low-lying areas, pits, drains, or poorly ventilated

spaces, depending on its temperature, composition, and mixing conditions. Ignition sources may include electrical equipment, hot surfaces, welding activities, mechanical sparks, and static discharge.

The risk is not limited to the storage area. LPG transfer lines, valves, flexible connections, regulators, burners, and fuel-consumption equipment may also contribute to loss-of-containment events. Consequently, an assessment limited to storage vessels would not adequately represent the full risk profile of an automotive industrial facility.

The Petroleum and Natural Gas Regulatory Board (PNGRB) publishes technical and safety regulations for LPG storage, handling, and bottling facilities in India. The NFPA 58 code also provides a recognised reference for LPG storage, handling, transportation, and use. Their applicability to a particular automotive facility depends on the installation type and applicable legal requirements.

2. Research Problem

LPG-related safety assessments can become fragmented when storage, fuel transfer, operational equipment, maintenance, and environmental consequences are evaluated independently. Such fragmentation may prevent decision-makers from identifying the most important initiating events, common-cause failures, and weaknesses in emergency safeguards.

The central research problem is the need for a structured framework that can:

- Identify LPG hazards throughout the fuel-handling and utilisation lifecycle.
- Evaluate the likelihood and consequences of potential accident scenarios.
- Rank risks using transparent and reproducible criteria.
- Assess the adequacy of engineering, administrative, and emergency safeguards.
- Incorporate environmental consequences alongside personnel and asset safety.
- Prioritise corrective actions according to risk significance.

3. Aim and Objectives

3.1 Aim

To develop a comprehensive risk-assessment framework for LPG fuel handling, storage, and utilisation in automotive industrial facilities, integrating fire safety, explosion prevention, occupational risk, and environmental impact assessment.

3.2 Objectives

1. To identify potential hazards associated with LPG unloading, storage, transfer, and utilisation.
2. To examine equipment failures and operational deviations that may lead to LPG leakage or ignition.
3. To classify major accident scenarios according to their potential consequences.
4. To develop a risk-ranking methodology using likelihood, severity, and safeguard performance.
5. To evaluate preventive and mitigative measures for fire and explosion risk reduction.
6. To assess potential environmental impacts associated with accidental releases and combustion.
7. To formulate recommendations for inspection, maintenance, monitoring, and emergency preparedness.

4. Scope of the Study

The proposed assessment covers the following functional areas.

System component	Principal hazards
LPG receipt and unloading	Hose failure, coupling leakage, vehicle movement, accidental release
Storage vessels and cylinders	Loss of containment, overpressure, external fire exposure
Pumps, valves and pipelines	Seal failure, corrosion, mechanical damage, leakage
Pressure regulators and burners	Incorrect pressure, flame failure, incomplete combustion
LPG-fuelled industrial equipment	Fuel leakage, ignition, overheating, unsafe shutdown
Electrical and maintenance activities	Ignition sources, inadequate isolation, hot-work incidents
Ventilation and drainage	Vapour accumulation in enclosed or low-lying areas
Emergency response systems	Delayed detection, isolation failure, inadequate response coordination

The assessment should be adapted to the actual installation. For example, a plant using LPG cylinders for limited heating requires a different system boundary from a facility operating a bulk LPG storage vessel and an extensive pipeline network.

5. Review of Related Literature and Safety Standards

5.1 LPG storage and handling safety

LPG safety management depends on the design and integrity of pressure vessels, piping systems, valves, connections, and associated protective equipment. Storage arrangements, ventilation, separation from ignition sources, inspection, and emergency isolation are important elements of prevention.

India's Gas Cylinders Rules, 2016, establish requirements relevant to the handling, storage, and use of covered gas cylinders. For applicable bulk installations, the Static and Mobile Pressure Vessels (Unfired) Rules, 2016, and relevant PNGRB requirements must also be considered. The specific regulatory framework depends on the type and capacity of the installation.

5.2 Fire and explosion hazards

LPG releases can result in different accident outcomes depending on the release rate, phase, ventilation, ignition timing, and surrounding geometry.

- Flash fire: Rapid combustion of an ignited flammable vapour cloud.
- Jet fire: Sustained combustion of gas released under pressure and ignited near the release point.
- Vapour cloud explosion: An explosion that may occur when a flammable cloud ignites under conditions that generate significant overpressure.
- BLEVE: A boiling liquid expanding vapour explosion that may occur when a pressurised vessel containing liquid above its atmospheric boiling point fails catastrophically, particularly under external fire exposure.

The occurrence and severity of these outcomes cannot be assumed for every LPG release. They require scenario-specific assessment.

5.3 Risk-assessment methodologies

HAZID supports systematic identification of hazards at the system level, while HAZOP examines deviations from intended operating conditions. FMEA evaluates individual equipment failure modes and their effects. Quantitative risk assessment (QRA) can subsequently estimate accident frequencies and consequences where sufficient data are available.

These methods are complementary. Using them together helps connect equipment-level failures with plant-level accident scenarios and the effectiveness of safeguards.

5.4 Environmental impact assessment

Environmental evaluation should distinguish between routine fuel consumption and accidental releases. LPG combustion generates carbon dioxide and may produce carbon monoxide and nitrogen oxides depending on combustion conditions and equipment design. Unburned LPG released into the atmosphere can contribute to short-term local air-quality and fire hazards; its climate impact depends on the amount released and its composition.

A defensible environmental assessment therefore requires fuel-consumption records, combustion data, release estimates, and an appropriate emissions-accounting method. The environmental benefits of LPG relative to another fuel should be assessed using a defined comparison basis rather than assumed.

6. Research Methodology

6.1 Research design

The study adopts a proposed integrated risk-assessment methodology consisting of five stages:

1. System definition and data collection.
2. Hazard identification and failure analysis.
3. Risk estimation and scenario classification.
4. Environmental and consequence assessment.
5. Risk-control evaluation and recommendations.

The framework is intended for application to an actual automotive industrial facility. Data should be obtained through site inspections, equipment documentation, maintenance records, operating procedures, incident logs, interviews with safety personnel, and applicable regulatory documents.

6.2 System boundary

The assessment boundary begins at LPG receipt and unloading and continues through storage, pressure regulation, distribution pipelines, and the point of utilisation.

Where relevant, the study should also include cylinder storage, vehicle-mounted LPG systems, fuel-dispensing installations, and associated ventilation and emergency systems. These elements should only be included when they are present within the selected facility.

6.3 Hazard identification

A structured HAZID exercise should be conducted for each operating area. The team should include representatives from fire and safety, maintenance, production, electrical engineering, and operations.

Potential initiating events include:

- Rupture or disconnection of transfer hoses.
- Leakage from valves, flanges, seals, and pipe joints.
- Corrosion or mechanical damage to pipelines.
- Regulator malfunction or excessive downstream pressure.
- Burner flame failure and delayed ignition.
- Failure of gas detectors or emergency shutdown systems.

- External fire exposure of LPG storage equipment.
- Unsafe maintenance, hot work, or inadequate equipment isolation.
- Loss of ventilation or accumulation of flammable vapour.

The identified hazards should be recorded in a hazard register with their causes, consequences, existing safeguards, and recommended corrective actions.

6.4 Failure Mode and Effects Analysis

FMEA can be used to examine individual equipment items and prioritise their failure modes.

A conventional risk priority number (RPN) can be calculated as:

\[RPN=S\times O\times D \]

Where:

- \(S\) = severity rating.
- \(O\) = occurrence rating.
- \(D\) = difficulty of detecting a failure before its consequences occur.

Each rating is assigned using a documented scale, commonly from 1 to 10. Higher RPN values indicate a higher priority for further review under this method.

The RPN should not be interpreted as an accident probability or a quantitative risk value. Different combinations of severity, occurrence, and detectability can produce the same RPN. Therefore, catastrophic-severity scenarios should receive explicit review even if their calculated RPN is comparatively low.

6.5 Likelihood and severity assessment

A five-level risk matrix is proposed for preliminary screening.

Rating	Likelihood	Severity
1	Rare	Negligible consequence
2	Unlikely	Minor injury or limited damage
3	Possible	Medical treatment, localised damage
4	Likely	Serious injury, major damage, or significant local impact
5	Almost certain	Multiple serious casualties or catastrophic consequences

The qualitative risk score is:

\[R=L\times S \]

where \(L\) represents the likelihood rating and \(S\) represents the severity rating.

For an illustrative screening scheme, scores of 1–4 may be designated low, 5–9 moderate, 10–16 high, and 17–25 very high. These bands are proposed for this study and must be approved or adjusted according to the organisation's risk criteria.

The resulting classification supports prioritisation but does not replace a formal QRA for major accident hazards.

6.6 Quantitative risk assessment

Where sufficient data are available, the annual frequency of an accident outcome can be estimated using initiating-event frequencies and conditional probabilities:

$$F_{\mathrm{outcome}} = \sum_{i=1}^{n} \lambda_i P_{i,\mathrm{outcome}}$$

Where:

- λ_i = annual frequency of initiating event i.
- $P_{i,\mathrm{outcome}}$ = conditional probability that the initiating event results in the specified outcome.

For example, a leakage event may or may not result in ignition, and ignition may produce different consequences depending on release conditions and the location of the cloud. The conditional probabilities must therefore be supported by appropriate data or a documented modelling basis.

A QRA may include release-frequency analysis, gas-dispersion modelling, thermal radiation, explosion overpressure, and individual or societal risk estimates, where relevant. Numerical outputs should be calculated using verified inputs rather than invented for illustrative purposes.

6.7 Environmental impact assessment

The environmental component should examine:

1. Routine LPG consumption and associated combustion emissions.
2. Potential atmospheric releases of unburned LPG.
3. Products of combustion during accidental fires.
4. Secondary environmental effects, including smoke, firefighting-water contamination, and damage to nearby equipment or infrastructure.
5. Opportunities to reduce fuel consumption and improve combustion efficiency.

Environmental impact should be assessed separately from occupational risk where the measurement units differ. The results can subsequently be integrated into a multi-criteria decision model.

7. Illustrative Hazard Register

The following table identifies representative LPG hazards and proposed safeguards. The risk categories are preliminary examples, not findings from an inspected plant.

Hazard scenario	Potential consequence	Key safeguards
Leakageduring unloading	Flammable cloud, flash fire or jet fire	Approved transfer connections, inspection, emergency isolation and controlled unloading
Storage vessel exposed to external fire	Vessel failure and potential BLEVE	Fire prevention, exposure protection, appropriate fire protection and emergency planning
Pipeline or valve leakage	Localised fire or vapour cloud	Integrity inspections, suitable isolation valves, leak detection and maintenance
Regulator malfunction	Excess pressure or unstable combustion	Suitable pressure protection, regulator inspection and burner safeguards
Flame failure	Unburned gas accumulation and	Automatic flame-failure shutoff and safe restart

	possible ignition	procedures
LPG release in a pit or poorly ventilated space	Vapour accumulation and delayed ignition	Ventilation assessment, gas detection and elimination of ignition sources
Hot work near LPG equipment	Ignition of leaked gas	Permit-to-work, gas testing, isolation and verification before work
Gas detector or shutdown failure	Delayed detection and continued release	Functional testing, proof testing and independent verification of critical safeguards

The adequacy of any safeguard must be confirmed through engineering review, inspection, functional testing, and compliance verification. A safeguard should not be credited as effective merely because it is listed in a procedure.

8. Proposed Risk-Assessment Framework

The proposed framework links hazard identification, scenario analysis, risk prioritisation, and control selection.

Stage 1: System characterisation

LPG inventory, equipment, process conditions and operating procedures

Stage 2: Hazard and failure identification

HAZID, HAZOP, FMEA and incident-data review

Stage 3: Risk estimation

Likelihood, severity, safeguards and consequence modelling

Stage 4: Environmental and operational evaluation

Release consequences, combustion emissions and operational reliability

Stage 5: Risk treatment and verification

Engineering controls, maintenance, training, emergency planning and reassessment

This framework is iterative. If the evaluation identifies inadequate safeguards or unacceptable risk, the facility should implement corrective measures and repeat the assessment to confirm that residual risk meets its approved acceptance criteria.

9. Results and Discussion: Proposed Analytical Outcomes

Because this paper does not use actual industrial datasets, the following discussion describes the outcomes that the proposed methodology is designed to establish. It should not be presented as a completed empirical investigation.

9.1 Identification of critical risk areas

The assessment is expected to distinguish between risks associated with LPG storage, fuel transfer, distribution, and utilisation. The final ranking will depend on the quantity of LPG involved, release conditions, equipment reliability, ignition sources, occupancy, and the effectiveness of installed safeguards.

Storage vessels may require detailed analysis of external fire exposure and pressure-vessel integrity. Transfer systems require attention to hose connections, valves, and emergency isolation. At the point of utilisation, burner controls, regulator performance, ventilation, and maintenance practices may be particularly important.

9.2 Evaluation of engineering safeguards

The study should evaluate the performance and suitability of the following safeguards:

- Fixed gas detection and audible or visual alarms, where required by the risk assessment.
- Emergency shutdown and isolation systems.
- Appropriate pressure-relief and overpressure protection.
- Ventilation and hazardous-area electrical design.
- Fire protection systems selected for the installation and credible fire scenarios.
- Preventive maintenance and inspection programmes.
- Flame-failure protection and automatic fuel shutoff.
- Emergency response arrangements, evacuation routes, and personnel training.

For major installations, these measures should be evaluated against the applicable regulatory requirements and engineering standards. India's PNGRB LPG technical and safety regulations provide a relevant reference for covered LPG facilities.

9.3 Environmental performance

The environmental assessment should determine whether routine LPG consumption, inefficient combustion, accidental releases, or emergency fire scenarios constitute significant environmental concerns.

A comparison with an alternative fuel should use a consistent functional unit, such as kilograms of CO_2-equivalent emissions per unit of useful process heat. The comparison should define the system boundary and account for combustion efficiency and, where relevant, upstream fuel-supply emissions.

This approach would help distinguish between improvements in local air quality, reductions in greenhouse-gas emissions, and improvements in process safety. These outcomes are related but are not interchangeable.

9.4 Risk-based prioritisation

The final risk register should prioritise scenarios using both the calculated risk score and engineering judgement. High-consequence events must receive specific attention even when their estimated frequency is low.

Recommended corrective actions should be assigned an accountable person, target completion date, verification requirement, and residual-risk assessment. This will convert the analysis from a descriptive hazard review into an actionable safety-management tool.

10. Recommended Risk-Control Measures

The following hierarchy is proposed for managing LPG risks in automotive industrial facilities.

Control level	Recommended measures
Elimination and substitution	Eliminate unnecessary LPG inventory or evaluate safer technically feasible alternatives
Engineering controls	Pressure protection, suitable piping, emergency isolation, gas detection, ventilation and appropriate fire protection

Administrative controls	Standard operating procedures, permit-to-work, inspection schedules, management of change and contractor control
Operational monitoring	Leak inspections, gas-detector testing, equipment-integrity monitoring and combustion checks
Emergency preparedness	Emergency shutdown procedures, evacuation, incident communication, drills and coordination with emergency services
Continuous improvement	Incident investigation, corrective-action tracking, audit and periodic reassessment

The hierarchy should be applied according to the facility's design and the hazards identified. Personal protective equipment and training are important, but they should not substitute for feasible engineering measures that prevent or limit major releases.

11. Limitations of the Study

The proposed framework has several limitations.

1. No site-specific LPG inventory, pipeline configuration, operating pressure, consumption data, or equipment-failure records have been supplied.
2. No validated accident frequencies or quantitative consequence-model outputs are available.
3. The preliminary risk-ranking bands are illustrative and require approval against the facility's risk-management criteria.
4. Environmental impacts cannot be quantified reliably without measured or documented fuel use, emission factors, and release assumptions.
5. The applicability of specific regulations and standards must be confirmed for the selected facility, installation type, and current regulatory requirements.

Accordingly, the framework provides a foundation for a field-based study but does not establish the actual risk level of any particular automotive industrial facility.

12. Conclusion

LPG handling, storage, and utilisation in automotive industrial facilities require an integrated approach to process safety, fire prevention, occupational protection, and environmental management. The principal challenge is not limited to preventing leaks; it also involves understanding how initiating events can develop into fires, explosions, operational disruptions, and environmental consequences.

This paper proposes a comprehensive risk-assessment framework integrating HAZID, HAZOP, FMEA, qualitative risk ranking, and quantitative consequence analysis. The methodology connects equipment-level failure modes with major accident scenarios and provides a basis for prioritising preventive and mitigative safeguards. It also incorporates routine combustion emissions and accidental releases into the environmental assessment.

The principal contribution is the proposed integration of lifecycle-based LPG hazard identification with risk-based decision-making and environmental evaluation. Its practical value will depend on validation using industrial operating data, engineering inspections, incident records, and appropriately selected consequence models.

Future research should apply the framework to an automotive facility, calculate scenario-specific risk values, assess existing safety barriers, and compare baseline and post-intervention risk. Such an investigation could provide evidence-based recommendations for improving LPG system integrity, reducing accident potential, and strengthening environmental performance.

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