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Evaluation of Environmental Hazards and Occupational Safety Risks in LPG Handling Facilities of Automotive Industries

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Abstract

Liquefied Petroleum Gas (LPG) is widely used in industrial applications, including heating, metal processing, paint curing, and other manufacturing operations within the automotive sector. Although LPG offers operational advantages, its flammable nature creates significant hazards associated with leakage, fire, explosion, occupational exposure, and environmental consequences. Automotive manufacturing facilities may also face risks arising from inadequate ventilation, equipment deterioration, improper handling practices, ignition sources, and insufficient emergency preparedness.

This paper presents a systematic framework for evaluating environmental hazards and occupational safety risks associated with LPG handling facilities in automotive industries. The proposed methodology integrates hazard identification, workplace inspection, risk assessment, environmental monitoring, and evaluation of existing safety controls. Techniques such as Hazard Identification (HAZID), Hazard and Operability Study (HAZOP), Failure Mode and Effects Analysis (FMEA), and risk matrix assessment are considered for identifying and prioritising hazardous conditions. Environmental evaluation focuses on accidental gas releases, atmospheric dispersion, potential ignition, fire and explosion consequences, and relevant environmental impacts. Occupational safety evaluation addresses equipment integrity, worker exposure, operational procedures, maintenance practices, training, and emergency response.

A quantitative risk-ranking model is proposed to support the comparison of LPG-related hazards and the prioritisation of preventive measures. The paper also outlines strategies for improving engineering controls, gas detection, ventilation, fire protection, inspection, and safety management. The framework is intended to assist automotive manufacturers in developing a more systematic approach to LPG safety and environmental risk management. As the study is conceptual, the proposed model requires validation using facility-specific observations, exposure measurements, and incident data before its effectiveness can be established.

Keywords: Liquefied Petroleum Gas, automotive industries, environmental hazards, occupational safety, quantitative risk assessment, gas leakage, fire and explosion, HAZOP, HAZID, process safety management.

1. Introduction

Automotive manufacturing involves numerous industrial processes that require reliable energy supplies and controlled heating operations. LPG is used in some facilities for furnaces, ovens, paint-curing systems, industrial heating equipment, and other process applications. Depending on the plant configuration, LPG may be supplied through cylinders, manifolds, pipelines, or bulk storage installations.

Despite its usefulness, LPG presents significant safety concerns because it is highly flammable and can form an ignitable mixture with air when released. Under typical ambient conditions, LPG vapour is denser than air and can accumulate in low-lying or poorly ventilated locations. An uncontrolled release may therefore create a hazardous atmosphere, particularly near pits, drains, enclosed spaces, or equipment where ignition sources are present.

The principal hazards associated with LPG handling include:

- Leakage from storage vessels, valves, regulators, pipelines, joints, and flexible connections.
- Flash fires, jet fires, pool fires involving released liquid, and other fire scenarios where applicable.
- Vapour cloud formation and explosion risks under suitable release, mixing, confinement, and ignition conditions.
- Pressure-vessel failure and severe thermal consequences in fire-exposure scenarios.
- Cold burns from contact with escaping liquid or rapidly expanding LPG.
- Environmental impacts associated with accidental releases, combustion products, and secondary incidents.
- Occupational risks arising from unsafe procedures, inadequate maintenance, insufficient training, and deficiencies in emergency preparedness.

The Oil Industry Safety Directorate (OISD) provides technical guidance relevant to LPG installations, including design, storage, handling, inspection, maintenance, and fire protection. OISD-STD-144 addresses LPG installations, while OISD-STD-210 specifically concerns storage, handling, and refuelling of LPG for automotive use. The applicability of each standard depends on the type of facility and operation.

In automotive manufacturing facilities, LPG risk assessment should be integrated with wider occupational health, environmental management, maintenance, and emergency-response programmes. This requires a systematic approach that considers both the likelihood of hazardous events and their potential consequences.

1.1 Problem statement

LPG handling risks are sometimes assessed through separate inspections of storage equipment, occupational safety procedures, and environmental controls. Such fragmented approaches may not adequately address the relationship between gas leakage, atmospheric dispersion, ignition, worker exposure, and environmental consequences.

A comprehensive evaluation framework is therefore required to identify major hazards, assess their likelihood and severity, evaluate existing safeguards, and prioritise preventive and corrective actions.

1.2 Research objectives

The objectives of this research are:

1. To identify environmental hazards associated with LPG storage, handling, and distribution in automotive manufacturing facilities.
2. To evaluate occupational safety risks arising from LPG leakage, fire, explosion, equipment failure, and unsafe work practices.
3. To develop an integrated methodology combining hazard identification, risk ranking, and environmental consequence evaluation.
4. To assess the role of engineering safeguards, inspection, training, and emergency preparedness in LPG risk reduction.
5. To formulate a practical framework for prioritising preventive and corrective measures.
6. To propose a validation methodology for evaluating the effectiveness of the framework in real industrial settings.

1.3 Research questions

- What are the principal environmental and occupational hazards associated with LPG handling in automotive manufacturing?
- Which factors contribute most significantly to LPG leakage, ignition, and loss-of-containment events?
- How can environmental consequences and occupational safety risks be assessed within a common framework?
- Which engineering and administrative controls should receive priority based on the identified risks?
- How can the proposed framework be validated using actual facility data?

2. Review of Literature

2.1 LPG hazards in industrial facilities

LPG is a pressurised mixture of light hydrocarbons, principally propane and butane, that can be stored as a liquid and released as a gas under suitable conditions. Its flammability and pressure-dependent storage characteristics make equipment integrity, ventilation, leak prevention, and ignition control essential elements of industrial safety.

The Petroleum and Natural Gas Regulatory Board (PNGRB) regulations address the design, layout, storage, handling, inspection, maintenance, fire protection, gas monitoring, emergency management, and safety management of LPG facilities. The regulations also emphasise risk analysis and compliance with applicable statutory requirements.

In automotive manufacturing, LPG systems may supply process heating equipment, ovens, furnaces, or other production machinery. The relevant risk profile depends on the quantity stored, pressure and temperature conditions, piping configuration, location, ventilation, ignition sources, and operating procedures.

2.2 Environmental hazards and consequences

Environmental evaluation of LPG installations should distinguish between the direct effects of an accidental release and the consequences of subsequent combustion.

Potential environmental concerns include:

- Uncontrolled LPG releases and atmospheric dispersion.
- Fire and explosion effects on surrounding equipment and buildings.
- Combustion emissions, including carbon monoxide under incomplete combustion conditions.
- Smoke, heat, and secondary emissions from fires involving nearby materials.
- Contamination resulting from firefighting water or other incident-response activities where secondary pollutants are present.
- Off-site consequences affecting neighbouring industrial premises or surrounding communities.

LPG itself is not generally associated with persistent soil or groundwater contamination in the same manner as many liquid petroleum products. Nevertheless, incident-specific environmental effects can arise from associated fuels, fire debris, combustion products, and response activities.

Environmental risk assessment should therefore consider the entire accident sequence, from the initial release through dispersion, ignition, fire or explosion, and any secondary environmental effects.

2.3 Occupational safety risks

Occupational safety risks arise from both major accident hazards and routine operating conditions. Major accident scenarios include loss of containment, ignition of a flammable gas cloud, fire exposure of pressurised equipment, and failures of emergency protection systems.

Routine occupational hazards include cold burns from escaping LPG, unsafe maintenance, improper isolation, contact with hot equipment, manual handling, and inadequate work procedures. Workers involved in operation, inspection, maintenance, loading, unloading, and emergency response may have different exposure profiles.

The PNGRB regulatory framework identifies gas monitoring, fire protection, operating procedures, competent personnel, inspections, and emergency planning as important components of LPG facility safety.

2.4 Research gap

Existing technical standards and risk assessment methods provide a foundation for evaluating LPG facilities. However, an assessment intended specifically for automotive manufacturing must also account for the interaction between LPG systems and surrounding production activities, including vehicle movement, ignition sources, hot work, adjacent equipment, workforce movement, and other site-specific hazards.

The proposed study addresses this need by combining environmental consequence assessment with occupational safety evaluation and a common process for prioritising corrective actions.

The proposed contribution is an integrated evaluation methodology, not a claim that existing regulatory approaches are inadequate or that the framework has already demonstrated superior performance.

3. Research Methodology

3.1 Research design

The study adopts a framework-development approach based on systematic hazard identification, risk assessment, environmental consequence evaluation, and preventive-control planning.

A mixed-method approach is proposed. Quantitative methods will be used to evaluate risk ratings, equipment condition, environmental measurements, and selected accident scenarios. Qualitative methods will be used to review operating procedures, worker experiences, maintenance practices, training, and emergency preparedness.

The study can be conducted in six stages.

Stage 1 — Facility characterisation

Identify LPG equipment, process uses, storage arrangements, and operating conditions.

Stage 2 — Hazard identification

Review leakage sources, ignition sources, equipment failures, and worker activities.

Stage 3 — Environmental and occupational assessment

Assess release scenarios, exposure pathways, occupational risks, and existing safeguards.

Stage 4 — Quantitative risk evaluation

Apply risk matrices and, where data permit, consequence modelling or quantitative risk assessment.

Stage 5 — Risk mitigation planning

Prioritise engineering, operational, environmental, and emergency controls.

Stage 6 — Validation and reassessment

Verify controls, review results, and repeat the assessment after improvements.

3.2 Study area and scope

The proposed study should focus on LPG handling facilities within automotive manufacturing plants. Depending on the facility, the scope may include:

- LPG storage vessels or cylinder manifolds.
- LPG pipelines, regulators, valves, and pressure-control equipment.
- Gas supply systems serving industrial ovens, furnaces, and heating equipment.
- LPG unloading and transfer arrangements, if present.
- Gas detection, ventilation, and emergency isolation systems.
- Fire protection equipment and emergency access routes.
- Work areas surrounding LPG installations and associated production equipment.

The scope should be defined from the actual plant layout. A facility using a small cylinder manifold should not automatically be assessed using assumptions developed for a bulk storage installation.

3.3 Data collection methods

A. Site inspection: Inspect equipment condition, leakage indicators, corrosion, pipe supports, valve accessibility, ventilation, area classification, ignition sources, and emergency access.

B. Document review: Examine approved layouts, equipment specifications, inspection records, maintenance schedules, incident reports, operating procedures, training records, and emergency plans.

C. Worker and management interviews: Obtain information about operating difficulties, reported leaks, near misses, maintenance practices, work permits, and emergency response.

D. Instrumental measurements: Where relevant, use appropriate calibrated gas detectors and environmental monitoring instruments. Measurements should be recorded with their locations, operating conditions, instrument details, and quality-control procedures.

E. Scenario analysis: Develop credible release and ignition scenarios using facility-specific data. Numerical consequence modelling should only be undertaken when the necessary inputs, model assumptions, and validation information are available.

3.4 Hazard identification techniques

The following methods are suitable for different stages of the study.

Method	Application
HAZID	Systematic identification of major hazards and hazardous situations

HAZOP	Examination of deviations from intended process operation
FMEA	Analysis of equipment failure modes and their effects
Job Safety Analysis (JSA)	Identification of hazards associated with individual work activities
Risk matrix	Preliminary ranking by likelihood and severity
Quantitative Risk Assessment (QRA)	Numerical analysis of selected accident frequencies and consequences
Consequence modelling	Evaluation of gas dispersion, thermal radiation, overpressure, or other relevant effects

The methods are complementary rather than interchangeable. HAZID and HAZOP can identify hazardous scenarios, while QRA may be appropriate where sufficient failure-frequency, release, meteorological, and consequence data are available.

4. Environmental Hazard Evaluation

4.1 LPG leakage and atmospheric dispersion

LPG leakage is a principal initiating event in industrial gas-related accidents. Potential release sources include damaged pipework, faulty valves, failed seals, regulator malfunction, and equipment damage during maintenance.

The assessment should consider release location, release duration, phase of release, operating pressure, available inventory, ventilation, terrain, weather conditions, and nearby obstructions. Because LPG vapour can accumulate in low-lying locations, the investigation should examine drains, pits, enclosed areas, and other potential accumulation zones.

Gas dispersion modelling may be used to estimate the spatial extent and duration of hazardous concentrations under defined scenarios. Model outputs must be interpreted as scenario-dependent estimates rather than precise predictions of an actual accident.

4.2 Fire and explosion consequences

A release of LPG can result in different outcomes depending on the release conditions, ignition timing, confinement, and surrounding equipment.

Potential scenarios include:

1. Flash fire following ignition of a dispersed flammable vapour cloud.
2. Jet fire following ignition of a pressurised gas release.
3. Fire involving released liquid LPG where liquid-phase release and pooling conditions permit.
4. Vapour cloud explosion under conditions that produce sufficient flame acceleration and overpressure.
5. Fire exposure of a storage vessel, potentially leading to catastrophic vessel failure under severe conditions.

The study should select credible scenarios rather than assuming that every release will produce every consequence. Consequence modelling can help evaluate thermal radiation, flammable cloud extent, and explosion overpressure where appropriate.

4.3 Environmental impact pathways

The environmental evaluation should examine the pathways through which an incident could affect people, property, and the surrounding environment.

Environmental component	Potential impact	Evaluation approach
Ambient air	LPG release and combustion emissions	Gas monitoring and dispersion modelling
Soil and drainage	Secondary contamination from fire debris or response activities	Site inspection and targeted sampling when justified
Surface water	Contaminated firefighting runoff where relevant	Drainage review and runoff assessment
Nearby facilities	Fire spread, thermal exposure, and overpressure	Consequence analysis and separation-distance review
Surrounding community	Off-site exposure and emergency disruption	Receptor mapping and emergency planning

A normal operating assessment should also consider routine emissions and relevant environmental permits. An accidental-release assessment alone does not constitute a complete environmental impact assessment of the entire facility.

4.4 Environmental risk prioritisation

Environmental risk should be ranked according to the likelihood of a release or secondary event, the magnitude of the resulting impact, the duration of exposure, and the sensitivity of the affected receptors.

Where sufficient information is available, a structured consequence assessment should be used to distinguish minor releases from major accident scenarios. Qualitative ratings can be applied at the initial screening stage, but major hazards may require more detailed analysis.

5. Occupational Safety Risk Assessment

5.1 Identification of occupational hazards

Occupational risk evaluation should consider the severity of potential injury, the probability of hazardous events, the frequency of worker exposure, and the effectiveness of existing safeguards.

The following table summarises representative hazards that should be investigated during a facility assessment.

Hazard	Potential consequences	Assessment focus
LPG leakage	Flash fire, fire or explosion	Leak detection, equipment integrity, ignition sources
Fire exposure of pressurised equipment	Severe burns, vessel failure, potentially fatal consequences	Fire protection, isolation, emergency response
Contact with escaping liquid LPG	Cold burns and tissue injury	Connection integrity and safe operating procedures
Defective valves and pipelines	Loss of containment	Inspection, testing and maintenance
Electrical or static ignition sources	Ignition of a flammable atmosphere	Hazardous-area classification and equipment suitability
Unsafe maintenance or hot work	Fire, explosion or serious injury	Isolation, gas testing and permit-to-work controls
Inadequate ventilation	Accumulation of flammable vapour	Ventilation design and gas monitoring
Inadequate emergency preparedness	Delayed evacuation or ineffective response	Training, alarms, drills and access routes

5.2 Risk matrix methodology

A qualitative risk matrix can be used for preliminary prioritisation.

The risk score for a particular hazard is calculated as:

$$R=L\times S$$

where:

- R = risk score;
- L = likelihood rating;
- S = severity rating.

Both likelihood and severity are assigned values from 1 to 5 according to documented criteria.

Score	Likelihood interpretation	Severity interpretation
1	Rare	Negligible consequence
2	Unlikely	Minor injury or limited impact
3	Possible	Moderate injury or significant local impact
4	Likely	Serious injury or major impact
5	Almost certain	Potentially catastrophic consequence

The severity descriptions must be applied consistently, and the likelihood ratings should reflect the available evidence.

For illustration, a hazard assigned a likelihood of 3 and a severity of 4 receives a risk score of 12. This is a hypothetical example, not an observed LPG facility result.

Provisional risk bands may be defined as follows:

Risk score	Screening category	General response
1–4	Low	Maintain controls and monitor
5–9	Moderate	Review controls and plan improvements
10–16	High	Prioritise corrective action
17–25	Very high	Urgent review and risk reduction

These bands are illustrative and require facility-specific approval. Any imminent danger, failed critical safeguard, or applicable statutory non-compliance must trigger the relevant response regardless of the calculated score.

5.3 Quantitative risk assessment

Where adequate data are available, the study may extend beyond a qualitative risk matrix to quantitative risk assessment (QRA).

For a defined accident scenario i, a simplified expected-loss model can be expressed as:

$$EL=\sum_{i=1}^{n} f_i C_i$$

where:

- EL = expected consequence measure per unit time;
- f_i = estimated frequency of scenario i;
- C_i = consequence measure associated with scenario i;
- n = number of assessed scenarios.

The consequence measure must be defined consistently. For example, it may represent expected financial loss, environmental damage expressed using a justified metric, or another measurable consequence. These measures should not be combined indiscriminately.

For human safety, individual risk and societal risk may be evaluated where suitable data and modelling methods are available. A detailed QRA should consider equipment failure frequencies, release sizes, ignition probabilities, meteorological conditions, population distribution, and the effectiveness of protective systems.

The PNGRB LPG technical regulations provide a relevant regulatory foundation for assessing LPG facility safety and identifying circumstances in which detailed QRA may be required.

6. Integrated Environmental and Occupational Risk Evaluation Framework

The proposed framework combines environmental assessment and occupational safety evaluation through a structured workflow.

LPG facility and process data

Equipment, inventory, operating conditions and layout

Environmental assessment

Release, dispersion, fire consequences and environmental receptors

Occupational assessment

Worker exposure, equipment safety, procedures and emergency protection

Integrated hazard register

Scenario, likelihood, severity, affected receptors and existing controls

Risk-based corrective action plan

Engineering improvements, operational controls and emergency measures

Verification and continuous improvement

Inspection, monitoring, audit and reassessment

6.1 Integrated risk register

A common risk register should document each identified hazard and its associated controls.

Recommended fields include:

1. Facility area and equipment identification.

2. Hazard description and initiating event.
3. Potential environmental consequences.
4. Potential occupational consequences.
5. Existing preventive and mitigating controls.
6. Initial risk rating.
7. Additional control requirements.
8. Responsible department and target completion date.
9. Residual risk following implementation.
10. Verification evidence and review date.

The integrated register provides traceability between hazard identification, risk assessment, corrective action, and subsequent verification.

6.2 Evaluation of control effectiveness

Controls should be assessed according to their ability to prevent an initiating event or reduce its consequences.

Examples include:

- Preventive controls: equipment design, compatible materials, inspection, maintenance, suitable isolation arrangements, and safe operating procedures.
- Detection controls: fixed or portable gas detection, alarms, and appropriate monitoring systems.
- Mitigating controls: emergency isolation, suitable fire protection, evacuation arrangements, and emergency response procedures.

The presence of a control should not automatically be interpreted as evidence of effectiveness. The assessment should verify its suitability, availability, inspection status, testing history, and reliability under the relevant operating conditions.

7. Recommended Risk Mitigation Measures

7.1 Engineering controls

Engineering controls should be selected through a documented assessment of the actual installation. Important considerations include suitable equipment design, protection against mechanical damage, leak prevention, appropriate ventilation, gas detection, emergency isolation, and fire protection.

For facilities within its scope, the applicable PNGRB regulations and relevant OISD standards should be consulted to determine requirements for layout, equipment, inspection, and safeguards.

7.2 Operational controls

Operating procedures should cover normal operation, start-up, shutdown, abnormal conditions, maintenance, and emergency response.

A suitable permit-to-work system should control hazardous maintenance activities, including hot work where relevant. Isolation, gas testing, and other precautions should be established through site-specific procedures and applicable requirements.

7.3 Environmental controls

Environmental protection measures should include appropriate monitoring, review of potential off-site effects, maintenance of drainage arrangements, and evaluation of secondary contamination following a fire or release.

Where credible accident scenarios could affect neighbouring facilities or communities, emergency planning should account for off-site receptors and communication with relevant response agencies.

7.4 Training and emergency preparedness

Personnel should receive task-specific training covering LPG hazards, recognition of abnormal conditions, alarm response, evacuation, reporting, and their authorised emergency duties.

Emergency drills should be evaluated for response time, communication, access, accountability, and coordination. Personnel should not be expected to undertake hazardous intervention outside their training, equipment, or assigned responsibilities.

7.5 Management systems and periodic review

A formal safety management system should incorporate inspection, incident investigation, corrective-action tracking, competency assurance, management of change, and periodic audit.

The PNGRB framework emphasises these elements as part of safe LPG facility operation.

8. Results and Discussion

Because no facility-specific observations, measurements, or incident records were supplied, this paper presents a proposed evaluation framework rather than empirical findings.

The framework is expected to support three main functions.

First, integrated hazard identification: It provides a common structure for evaluating LPG leakage, fire and explosion scenarios, worker safety, and environmental consequences. This may improve the completeness of the assessment when compared with an uncoordinated review of separate hazards.

Second, risk-based prioritisation: A consistent risk register and documented rating criteria can help identify where additional investigation or corrective action is needed. However, the aggregate score must not override statutory requirements or critical hazards.

Third, systematic verification: Reassessment after corrective measures can help determine whether equipment conditions, exposure levels, safeguard performance, or other relevant risk indicators have improved.

The effectiveness of these functions should be evaluated using actual plant data. It would be inappropriate to claim a percentage reduction in accidents, environmental impact, or occupational risk without a documented baseline and post-intervention evidence.

8.1 Proposed performance indicators

Indicator	Purpose
Number of identified LPG leak points	Monitor equipment integrity and leak-prevention performance
Percentage of scheduled inspections completed	Evaluate maintenance and inspection compliance
Gas detection and alarm test results	Verify detection-system availability

Number of overdue high-priority actions	Monitor corrective-action management
Emergency drill performance	Evaluate preparedness and response capability
Number and severity of LPG-related incidents	Track safety outcomes over an appropriate period
Environmental monitoring results	Evaluate relevant emissions and incident-related impacts
Percentage of critical safeguards verified	Confirm the operational status of essential protections

These indicators should be interpreted in context. For example, an increase in reported near misses may indicate improved reporting rather than worsening safety. Similarly, a high inspection-completion rate does not prove that all hazards are adequately controlled.

9. Limitations and Future Research

The proposed framework has several limitations.

First, risk scores depend on the quality of available data and the consistency of assessor judgement. Second, environmental consequence models may produce uncertain estimates because release conditions, weather, ignition, and physical obstructions can vary. Third, the framework has not been calibrated against actual accident frequencies or independently validated against occupational and environmental outcomes.

Future research should include:

- Field assessment of LPG installations across multiple automotive manufacturing plants.
- Statistical analysis of incident, near-miss, maintenance, and inspection records.
- CFD-based modelling of selected LPG dispersion scenarios where justified.
- Quantitative fire and explosion consequence analysis using validated methods.
- Comparative evaluation of risk scores before and after engineering improvements.
- Development of a digital risk register or decision-support tool for monitoring LPG safety indicators.

These investigations would provide evidence about the framework's reliability, transferability, and practical value.

10. Conclusion

This study proposes an integrated framework for evaluating environmental hazards and occupational safety risks in LPG handling facilities of automotive industries. The approach combines systematic hazard identification, environmental consequence assessment, occupational risk evaluation, risk ranking, and verification of preventive and mitigating controls.

The framework addresses major concerns such as gas leakage, atmospheric dispersion, fire and explosion, equipment failure, unsafe maintenance, and emergency preparedness. It also provides a structure for evaluating environmental effects and establishing corrective-action priorities.

The proposed methodology is intended to complement applicable Indian regulations and technical standards rather than replace them. Its final configuration must reflect the specific LPG installation, applicable legal requirements, and the hazards identified at the facility.

The framework's effectiveness remains to be established through empirical testing. Field observations, environmental measurements, equipment inspection data, incident records, and post-intervention assessments are required to determine whether the proposed methodology improves risk identification and safety management in automotive manufacturing environments.

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