

# Data-Driven Freight Telematics: Predictive Risk Modeling and IoT-Enabled Interventions for Resilient Road-Based Energy Transport Corridors

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## ABSTRACT

Global energy supply chains face severe systemic risks driven by fragile infrastructure, human error, and transport vulnerabilities. This study presents a data-driven econometric analysis of high-risk road freight networks, utilizing the Kurdistan Region of Iraq as a stress-tested case study. By integrating multi-source empirical data and spatial surveys with logistic regression, difference-in-differences, and ordered probit models, we quantify systemic transport hazards. Findings indicate that infrastructure deficits and behavioral variables are primary risk drivers, with 68% of operators citing critical road degradation. Crucially, a cost-benefit analysis of smart transportation interventions demonstrates that IoT-enabled GPS tracking mandates and structured driver training yield exceptional benefit-cost ratios of 25.7:1 and 25.4:1, respectively. Furthermore, spatial econometric modeling quantifies a \$12.5 billion system-level loss from pipeline disruptions, underscoring the urgent need for resilient freight alternatives. Ultimately, we propose a novel smart governance framework integrating sensor telematics, predictive risk modeling, and human factors to optimize transport safety in vulnerable energy corridors.

## 1. Introduction

### 1.1. Research Context and Significance

The crude oil transportation is an essential yet inherently perilous aspect of modern energy systems. As the backbone of industrial economies, crude oil travels vast distances through challenging terrains, across political borders, and through environmentally sensitive regions from extraction sites to refineries and ultimately to consumer markets [1]. The global crude oil transport network comprises approximately 4 million kilometres of pipelines, over 7,000 active oil tankers, and innumerable road tankers and railcars, collectively transporting an estimated 70 million barrels of crude oil daily [2;3].

Nonetheless, this logistical feat carries profound risks. Oil tanker accidents, whether maritime or terrestrial, have catastrophic consequences, including acute and chronic environmental degradation,

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loss of human life, destruction of livelihoods, and economic losses that can run into the billions of dollars [4;5]. Historical incidents such as the 1989 Exxon Valdez spill, the 2002 Prestige disaster, and the 2010 Deepwater Horizon catastrophe prompted substantial regulatory reforms; however, accidents continue to occur, particularly in areas where infrastructural development has not kept pace with regulatory advances [6; 7].

The Kurdistan Region of Iraq exemplifies the tension inherent in balancing rapid energy development with safety governance. In the aftermath of the 2003 Iraq war, the KRG emerged as a semi-autonomous oil-producing entity, attracting significant foreign investment and developing export capacity exceeding 500,000 barrels per day [8]. However, the region's crude oil transport system is heavily reliant on road tankers that traverse mountainous terrain and poorly maintained highways, all within a regulatory framework marked by fragmented enforcement and limited emergency response capabilities [9; 10].

The economic dimensions of these safety challenges have received insufficient attention. While the environmental and human costs of oil transportation accidents are well documented, the economic consequences, including revenue losses from pipeline disruptions, the cost-effectiveness of safety interventions, and public willingness to pay for risk reduction, remain under-theorised and empirically underexamined. This study addresses this gap by integrating econometric analysis with primary survey data to quantify both the determinants of accidents and their economic impacts.

## 1.2 Problem Statement and Knowledge Gaps

Despite growing academic attention to oil transportation safety, significant knowledge gaps persist. First, the literature disproportionately emphasises maritime tanker accidents, offering comparatively little systematic analysis of road-based crude oil transport, the predominant mode in many developing and conflict-affected areas [11; 12]. Second, although human factors are widely acknowledged as leading contributors to accidents, accounting for 60-80% of incidents, region-specific research on driver fatigue, training deficiencies, and safety culture in non-OECD contexts remains scarce [13]. Third, the intersection of geopolitical disruption and transportation safety, as exemplified by the 2023-2025 KRG-Turkey pipeline suspension and route reconfigurations prompted by the Russia-Ukraine war, is an emerging yet under-theorised area of inquiry [14]. Fourth, public perceptions of oil transportation risks, which are critical to shaping policy legitimacy and fostering community cooperation, have received minimal empirical attention in Middle Eastern contexts. Fifth, economic analyses of oil transportation safety in conflict-affected regions are virtually absent, leaving policymakers without the cost-benefit evidence needed to prioritise interventions. Sixth, previous studies have highlighted that roadway surface conditions, particularly on horizontal curves during wet weather, significantly influence accident occurrence and severity [15]. However, the specific role of pavement quality and broader infrastructure deficits in crude oil tanker safety has not been adequately explored in this region. Furthermore, while Al-Mukaram *et al.* [16] demonstrated that incorporating rubberised asphalt can enhance pavement performance and durability, thereby contributing to safer road operations, the direct application of such infrastructure improvements to crude oil transport corridors remains unexplored.

This study addresses six significant knowledge gaps in the existing literature on oil transportation safety and makes several novel contributions to the field.

1. The literature disproportionately emphasizes maritime tanker accidents, offering comparatively little systematic analysis of road-based crude oil transport, which is the predominant mode in many developing and conflict-affected areas [11; 12].

2. While human factors are widely acknowledged as leading contributors to accidents, accounting for 60-80% of incidents, region-specific research on driver fatigue, training deficiencies, and safety culture in non-OECD contexts remains scarce [13].
3. The intersection of geopolitical disruption and transportation safety as exemplified by the 2023-2025 KRG-Turkey pipeline suspension and route reconfigurations prompted by the Russia-Ukraine war, is an emerging yet under-theorised area of inquiry [14]. Further; This study builds upon previous research demonstrating the interrelationship between transport infrastructure, economic expansion, and environmental sustainability by extending the focus to transportation safety and crude oil logistics under conditions of geopolitical uncertainty. While previous work highlighted the moderating role of green energy consumption in reducing the environmental impacts of transport infrastructure [16], the present study investigates how geopolitical risks (conflicted areas) and road safety influence the resilience and sustainability of oil transportation systems in Northern Iraq.
4. Public perceptions of oil transportation risks, which are critical to shaping policy legitimacy and fostering community cooperation, have received minimal empirical attention in Middle Eastern contexts.
5. Economic analyses of oil transportation safety in conflict-affected regions are virtually absent, leaving policymakers without the cost-benefit evidence needed to prioritise interventions.
6. Previous studies have highlighted that roadway surface conditions, particularly on horizontal curves during wet weather, significantly influence accident occurrence and severity [15]. However, the specific role of pavement quality and broader infrastructure deficits in crude oil tanker safety has not been adequately explored in this region.

This research makes several novel contributions to the field of oil transportation safety: This study addresses these gaps through a mixed-methods investigation of crude oil transportation in the KRG. Its main contributions are:

1. It provides the first comprehensive, empirical analysis of road-based crude oil transport safety in the KRG, using primary survey data from 150 public respondents and 50 tanker drivers and owners.
2. It provides novel econometric estimates of the economic impact of geopolitical disruption (quantifying the \$12.5 billion loss from the pipeline suspension), the cost-effectiveness of safety interventions (demonstrating benefit-cost ratios exceeding 25:1 for training and GPS tracking), and public willingness to pay for safety improvements.
3. It extends High-Reliability Organization (HRO) theory and Risk Society theory to a conflict-affected, developing region, demonstrating the applicability of these frameworks in non-OECD contexts.
4. It generates evidence-based, actionable recommendations for regulatory reform in the KRG, including mandatory driver certification, GPS tracking mandates, and targeted infrastructure investment, with clear priorities based on cost-benefit analysis.
5. It offers a novel analytical framework that integrates human factors, security threats, regulatory responses, and economic consequences, providing a holistic understanding of the systemic risks in oil logistics.

Guided by these gaps, the study is designed to answer the following research questions: What are the principal causes and consequences of crude oil transportation accidents in the KRG, as perceived by drivers and the public? How do infrastructure conditions, equipment standards, and driver training practices influence accident frequency? What is the level of public awareness of oil transportation risks, and what factors shape confidence in regulatory systems? How do geopolitical

disruptions affect transportation safety vulnerabilities? What are the economic determinants of accident probability, and what is the cost-effectiveness of alternative safety interventions?

### *1.3 Theoretical Framework*

This study operates at the intersection of three theoretical domains. High-reliability organisation theory examines how organisations operating in hazardous conditions achieve near-error-free performance through mindfulness, redundancy, and continuous learning [17]. Risk society theory posits that modern technological hazards are socially constructed and unevenly distributed across populations [18]. Regulatory governance theory analyses the effectiveness of formal rules, enforcement mechanisms, and compliance cultures in shaping safety outcomes [19]. The integration of these frameworks is complemented by economic theory, specifically the hedonic pricing model for risk valuation and cost-benefit analysis frameworks drawn from environmental economics [20]. This multi-level analysis encompasses individual driver behaviour, organisational safety systems, and macro-political regulatory structures.

This study applies an integrated framework that combines these theoretical perspectives to analyze the multifaceted risks associated with crude oil transport in the Kurdistan Region of Iraq.

1. **High-Reliability Organization (HRO) Theory Application:** This theory examines how organizations operating in hazardous conditions achieve near-error-free performance through key principles such as a preoccupation with failure, a reluctance to simplify interpretations, and a commitment to resilience [17]. The framework evaluates whether the KRG's crude oil transport system exhibits these characteristics. The findings are expected to indicate that the sector functions as a low-reliability organization, as evidenced by a lack of safety culture, inadequate training, and insufficient investment in safety technology, thereby systematically heightening accident risks.
2. **Risk Society Theory Application:** Drawing on Beck's [18] concept of "organized irresponsibility," this framework analyzes how environmental and health risks are socially constructed and inequitably distributed. It posits that communities situated near tanker routes in the KRG face a disproportionate burden of risk, while regulators and companies may fail to adequately acknowledge or manage these dangers. The public's low confidence in regulatory systems, as will be demonstrated in the results, illustrates this theoretical perspective.
3. **Regulatory Governance Theory Application:** This theory analyzes the effectiveness of formal rules, enforcement mechanisms, and compliance cultures in shaping safety outcomes [19]. The framework uses this lens to examine the KRG's fragmented and under-enforced regulatory structure. It assesses how regulatory capture, resource limitations, and political instability undermine the capacity of authorities to enforce safety standards, leading to the systemic failures reported by tanker drivers and the public.
4. **Economic Theory Integration:** This theoretical foundation is complemented by economic theory, specifically using cost-benefit analysis frameworks from environmental economics to evaluate the cost-effectiveness of safety interventions [20]. It also employs hedonic pricing models to value risk and quantifies the economic consequences of geopolitical disruptions, such as the discount on KRG crude oil relative to international benchmarks.

**Application in the KRG Context:** This integrated framework operates across multiple levels of analysis:

- Micro-level: It analyzes individual driver behavior, fatigue, training deficiencies, and perceptions of safety.
- Meso-level: It examines organizational safety systems within transport companies, including equipment maintenance, training programs, and operational protocols.
- Macro-level: It investigates the broader political, regulatory, and economic structures, including the impact of the federal-KRG disputes, security threats, and geopolitical disruptions like the KRG-Turkey pipeline suspension.

By applying this integrated framework, the study moves beyond a simple description of accidents to a comprehensive analysis of the systemic and structural failures that perpetuate risk in the KRG's crude oil transport sector.

## **2. Literature review**

### *2.1 Historical Evolution of Crude Oil Transportation*

The evolution of crude oil transport has been significant since the mid-19th century, shifting from rudimentary barrel-based methods to sophisticated integrated systems. This transformation has been shaped by technological advances, geopolitical factors, and major accidents that have catalysed regulatory reforms [1]. Following Edwin Drake's discovery of oil in Pennsylvania in 1859, crude oil was primarily transported in wooden barrels by horse-drawn carts and railroads, methods that were inefficient and prone to leakage. The launch of the *Zoroaster*, the first dedicated oil tanker designed by Ludvig Nobel in 1878, revolutionised maritime transport by enabling bulk shipments across the Caspian Sea [1]. The early twentieth century saw the expansion of pipeline infrastructure, culminating in projects such as the Trans-Alaska Pipeline System, completed in 1977. Pipelines facilitate continuous, high-volume transport at lower per-barrel costs while reducing accident rates compared with road or rail alternatives [21]. The emergence of Very Large Crude Carriers and Ultra-Large Crude Carriers enabled unprecedented shipment volumes but introduced significant risks. Notable incidents such as the Exxon Valdez spill in 1989 and the Prestige disaster in 2002 exposed systemic deficiencies in vessel design, crew training, and emergency response, leading to the International Maritime Organisation's mandate for double-hull construction [5; 6]. Unlike established oil-producing nations, the KRG's transport infrastructure developed rapidly following the 2003 Iraq war, against a backdrop of ongoing federal-KRG disputes, security threats, and infrastructural inadequacies that elevate accident risks [8; 9].

### *2.2 Crude Oil Transportation Modalities*

Crude oil is transported through four primary modalities: pipelines, maritime tankers, railroads, and road tankers, each bearing distinct risk profiles. Pipelines offer low per-barrel cost and continuous operation but require high capital investment and face vulnerability to sabotage. Maritime tankers provide high volume and global reach but depend on ports and weather conditions. Railroads offer route flexibility but face risks of derailment. Road tankers provide maximum flexibility and remote access but exhibit the highest accident rates due to traffic congestion and driver fatigue [12; 21].

### *2.3 Human Factors in Oil Tanker Accidents*

Human error is recognized as the leading cause of oil transportation accidents across all modalities, contributing to an estimated 60-80% of incidents [6]. A 2024 study utilizing fuzzy Bayesian network analysis identified cargo calculation errors as the most significant factor contributing to spill occurrences during loading and discharging [22]. A 2025 analysis employing data-driven Bayesian network methods found that the number of seafarers onboard plays a significant role in influencing low and moderate-pollution accidents, ship damage emerges as the principal cause of severe pollution, and human-centered risk factors prevail across all spill categories [23].

The International Tanker Owners Pollution Federation released its 2025 Oil Tanker Spill Statistics in January 2026, providing an up-to-date assessment of global tanker safety performance [24]. Large spills exceeding 700 tonnes numbered three in 2025; medium spills of 7-700 tonnes also numbered three; total spills reached six; and total volume lost approximated 4,000 tonnes, representing less than half the total recorded in 2024. Long-term trends reveal that spills exceeding 7 tonnes have declined by over 90% since the 1970s; the current decade average stands at 7 spills per year compared to approximately 80 spills per year during the 1970s, and the average volume of oil lost during the 2010s exhibited a 95% reduction since the 1970s [24].

The economic repercussions of oil spills extend far beyond immediate cleanup costs. The Deepwater Horizon disaster was estimated to have caused total economic losses of \$65 billion, encompassing cleanup expenses, legal settlements, natural resource damages, and economic claims [7]. The three largest spills recorded in 2025 are projected to incur cleanup costs ranging from \$20,000 to \$100,000 per tonne of oil spilt, depending on location, oil type, and environmental sensitivity [25]. The dramatic decrease in spill frequency since the 1970s, exceeding 90%, underscores the cost-effectiveness of regulatory interventions, including the requirement for double-hull tankers following the Oil Pollution Act of 1990 [26].

Driver fatigue is a well-documented risk factor. A meta-analysis of 47 studies revealed that drivers working shifts longer than 12 hours exhibit a 40% higher collision risk compared to those adhering to standard 8-hour shifts [13]. In the KRG context, survey data presented in Chapter 4 reveal that 54% of drivers identified fatigue management as a critical need. Insufficient safety training represents another significant human factor. Within the KRG, 64% of drivers described themselves as only somewhat familiar with health and safety protocols, with 54% receiving safety training only intermittently.

## *2.4 Environmental and Regulatory Dimensions*

Oil spills from transport accidents cause severe and often persistent ecological damage. The Exxon Valdez spill required approximately 20-25 years for the full recovery of sea otter and harlequin duck populations, while affected killer whale pods have yet to recover fully after three decades [5]. The Deepwater Horizon spill caused acute mortality among marine mammals, sea turtles, and birds, leading to ongoing sublethal effects, including reproductive impairments [7]. Road tanker accidents frequently contaminate soil, groundwater, and surface water. In the KRG, documented incidents, such as the 2019 Zakho spill, have contaminated agricultural land and disrupted local water supplies [27].

The IMO has established comprehensive international regulatory frameworks, including MARPOL Annex I, which prohibits oil discharge and mandates double-hull construction; the International Safety Management Code, which requires safety management systems; and the Oil Pollution Preparedness, Response and Co-operation Convention, which sets out spill response requirements [26]. Implementation gaps persist, particularly among flag states with limited enforcement capacity

[19]. The KRG's regulatory framework remains underdeveloped, with inconsistent enforcement and limited emergency response capacity [10; 28]. Survey data indicate that only 18% of public respondents view current safety measures positively.

## *2.5 Geopolitical Disruption and Oil Transportation*

Following Russia's invasion of Ukraine in February 2022, European Union sanctions necessitated a significant reconfiguration of global tanker routes, with Russian crude previously destined for European markets redirected primarily to India and China [14]. Longer voyage distances increase the cumulative accident risk per shipment, and the proliferation of the shadow fleet, comprising ageing tankers operating outside conventional insurance coverage, introduces uncertain risk profiles.

The arbitration ruling in March 2023 interrupted pipeline exports for approximately two and a half years, until September 2025 [29]. During the suspension, KRG oil traded locally at 28–28–30 per barrel, compared with international prices. ShaMaran Petroleum's full-year 2025 revenue reached \$154.9 million, representing 4230 per barrel for export sales in 2025, compared with 70 per barrel for Brent crude. Economic regression analysis quantifies the impact: pipeline resumption increased realised prices by approximately 38.50 per barrel, and the total economic loss during the suspension was approximately \$12.5 billion, representing approximately 180% of the KRG's annual budget. The prolonged pipeline suspension necessitated reliance on road tanker transport with documented safety implications. Standard risk assessment models assume relatively stable operating environments, yet the 2023–2025 pipeline suspension illustrates how political decisions beyond operators' control can dramatically reshape risk landscapes.

## *2.6 Recent Scholarship (2025-2026)*

Recent scholarship continues to advance the understanding of crude oil transportation risks, primarily through the lenses of network resilience, geopolitical disruption, risk assessment methodology, and regulatory frameworks. This section systematically reviews key studies from 2025–2026, organised thematically to highlight their contributions and limitations relative to the current investigation.

### *2.6.1 Network Resilience and Maritime Transport Analysis*

Si *et al.* [30] developed a novel motif-based approach to assess the resilience of the global crude oil maritime transportation network. By identifying recurring patterns (motifs) in the network structure, their methodology enables the detection of critical nodes whose failure would most significantly impact network connectivity. Their findings reveal that the global crude oil shipping network exhibits distinct resilience patterns depending on the type and location of disruptions. This study is methodologically important as it moves beyond traditional node- or link-based analyses to consider higher-order network structures. However, its focus remains exclusively on maritime transport, leaving a significant gap in understanding resilience patterns in road-based crude oil logistics. Building on their 2025 work, Si *et al.* [30] introduced a multiplex network model to analyze structural shifts and resilience patterns in the global crude oil maritime network under geopolitical conflicts. The multiplex framework simultaneously considers multiple layers of connectivity (e.g., trade relationships, shipping routes, and port alliances), providing a more comprehensive understanding of how disruptions cascade across different dimensions of the network. Their analysis

of historical geopolitical events demonstrates that multiplex resilience patterns differ significantly from single-layer analyses, with certain nodes becoming critical only when multiple network layers are considered. While groundbreaking for maritime analysis, this study does not extend to road-based transport systems, which operate under fundamentally different risk dynamics.

Su *et al.* [31] proposed a multi-scale crude oil shipping–trade network (MCOSTN) framework that integrates shipping and trade data to analyze supply chain vulnerabilities. Their framework emphasizes how disruptions at key ports can cascade through the entire supply chain, affecting not only immediate shipping routes but also downstream refining and distribution networks. The multi-scale approach enables analysis at global, regional, and local levels, revealing that the impact of disruptions varies significantly across scales. This study's contribution lies in its integrated approach to understanding oil supply chain vulnerability, yet it maintains the maritime focus common in the literature and does not address road transport alternatives during pipeline disruptions.

[32] identified crucial nodes in the crude oil shipping network and assessed the impact of deliberate attacks, finding the network particularly vulnerable to targeted disruptions at major chokepoints. Their analysis incorporates both network topology and operational data to identify nodes whose failure would cause the greatest systemic disruption. The study's simulation of various attack scenarios provides valuable insights for risk management and contingency planning. However, the research remains focused on intentional disruptions rather than accidental incidents, and does not consider the road transport alternatives that become critical when maritime or pipeline routes are compromised.

Han and Fan [23] advanced the analysis of maritime oil spill accidents using a data-driven Bayesian network approach with a human-centred focus. Their analysis found that the number of seafarers onboard significantly influences low and moderate-pollution accidents, ship damage emerges as the principal cause of severe pollution, and human-centred risk factors prevail across all spill categories. The Bayesian network approach enables quantification of probabilistic relationships among risk factors and accident outcomes. While this study represents a significant methodological advancement in understanding human factors in maritime spills, its application is limited to maritime contexts and does not address the distinct human factors challenges in road-based crude oil transport, such as driver fatigue, inadequate training, and poor road conditions.

The International Tanker Owners Pollution Federation ITOPF [24] released its 2025 Oil Tanker Spill Statistics in January 2026, providing an up-to-date assessment of global tanker safety performance. Large spills exceeding 700 tonnes numbered three in 2025; medium spills of 7-700 tonnes also numbered three; total spills reached six; and total volume lost approximated 4,000 tonnes. Long-term trends reveal that spills exceeding 7 tonnes have declined by over 90% since the 1970s; the current decade average stands at 7 spills per year compared to approximately 80 spills per year during the 1970s. While this report confirms significant safety improvements in maritime tanker operations, it also highlights emerging risks including the proliferation of the "shadow fleet" of ageing tankers operating outside conventional insurance and regulatory frameworks. The stark contrast between global maritime improvements and the persistently high incident rates observed in KRG road transport (74% of drivers witnessing spills) underscores the need for research focused on road-based systems.

### *2.6.2 Risk Assessment and Hazardous Materials Transport*

A 2026 study introduced AcciNet-RFs, a novel scenario analysis method for modeling highway hazardous materials transportation crashes. This methodology employs random forests and network analysis to identify the most probable crash scenarios and their contributing factors. The study demonstrated the utility of this approach in analyzing complex crash scenarios involving multiple vehicles and hazardous materials releases. While methodologically robust, this research focuses on general hazardous materials rather than specifically on crude oil, and does not address the unique challenges of crude oil transport in conflict-affected regions or the economic dimensions of transportation safety.

Yilmaz and Verter [33] developed a methodology that incorporates terrorist attack risks alongside traditional accident risks in hazardous materials transportation modeling. Their framework analyzes convoy formations and attack capabilities to estimate consequences, finding that optimal routes change substantially when terror risk is included. This study is particularly relevant to the KRG context, where security concerns were identified by 48% of surveyed drivers as a major operational challenge. However, the methodology has not been applied to crude oil specifically or validated in Middle Eastern contexts with the unique security dynamics of the KRG.

The Federal Railroad Administration [34] issued a final rule requiring railroads carrying hazardous materials to generate and provide real-time train consist information to first responders and emergency personnel, with compliance dates set for June 2025 and June 2026. This regulatory development reflects a broader trend toward enhanced real-time monitoring and emergency preparedness for hazardous materials transport. While focused on rail transport, the principle of real-time information sharing for emergency responders is directly applicable to road-based crude oil transport. In the KRG, only 58% of tankers are GPS-equipped, and real-time monitoring systems are largely absent, representing a significant gap between international best practices and local conditions.

The European Agreement concerning the International Carriage of Dangerous Goods by Road (ADR) implemented significant updates effective January 2025, with mandatory compliance from July 2025. These changes include new UN numbers for sodium-ion batteries, updated packaging instructions for electric vehicles and batteries, stricter packaging rules for hazardous goods including hot liquids, and enhanced labeling requirements. While focused on battery transport, these regulatory updates demonstrate evolving international standards for dangerous goods transportation. The comparison between these comprehensive international frameworks and the fragmented regulatory enforcement observed in the KRG highlights the need for regulatory capacity building in conflict-affected regions.

### *2.6.3 Geopolitical Disruption and Regional Energy Infrastructure*

The Rudaw Research Centre (2026) [27] documented the dramatic impact of the 2026 Iran-US conflict on the Kurdistan Region's energy infrastructure. The report reveals that most international oil companies operating in the KRG's oil and gas fields have suspended production due to heightened security risks, including Gulf Keystone Petroleum halting operations at the Sheikan field, Dana Gas at Khor Mor, and Shamaran Petroleum at the Atrush and Sarsang fields. Production at the Khurmala field has fluctuated significantly, dropping to around 45,000 bpd on some days and recovering to 65,000 bpd on others. The report documents that the conflict has forced Iraq to lose an estimated \$220 million in oil revenue per day, while the Kurdistan Region's oil production has fallen sharply from roughly 300,000 bpd before the war to around 69,500 bpd. This analysis demonstrates the fragility of regional energy infrastructure during geopolitical crises and the direct economic

consequences of disruption, but it does not address the transportation safety implications of production suspensions and the increased reliance on road transport alternatives.

The International Energy Agency's (2026) analysis reveals that the global oil market entered the 2026 Iran-US crisis with significant buffers, including a 2026 surplus of 3.7 million barrels per day and global oil storage at 8.2 billion barrels. However, the agency noted that the crisis prompted a massive emergency stock release of 400 million barrels by IEA member countries, the largest in history and rapid adjustments by producers, including Saudi Arabia, which ramped up exports through its East-West pipeline to the Red Sea. The analysis documents that cumulative oil supply losses from Middle Eastern producers exceeded 1.3 billion barrels, with flows through the Strait of Hormuz falling to an average of 2.7 million barrels per day, prompting a surge in Atlantic Basin oil exports. This report provides crucial context for understanding the scale of geopolitical disruption and its implications for global oil markets, but does not examine the transportation safety consequences of supply chain reconfiguration.

Recent maritime incidents in the Gulf of Oman illustrate the heightened risks facing oil transportation in the region. On 8 June 2026, the U.S. Central Command reported that U.S. forces disabled the Palau-flagged tanker MT Marivex after an F/A-18 aircraft fired a precision munition into the vessel's engineering and steering spaces. The tanker was carrying 24 Indian crew members, all of whom were subsequently rescued safely by Omani authorities. Earlier, on 26 May 2026, the Greek-owned crude-oil tanker Olympic Life experienced an external explosion approximately 60 nautical miles east of Muscat. The vessel remained operational and its crew were safe, although some bunker fuel was discharged into the sea; the cause of the incident was initially unknown. These incidents demonstrate the elevated risk environment for maritime oil transportation in the Middle East and highlight the potential for disruptions to regional energy security. However, such incident reporting primarily documents immediate operational and safety consequences rather than providing a systematic assessment of transportation-system vulnerability or the broader economic consequences of disruption [35].

In Iraq maintained its primary oil export flows through the Kurdistan Region's pipeline network to the Turkish Mediterranean port of Ceyhan as maritime transit through the Strait of Hormuz remained severely restricted. The Kurdistan Region facilitated the continued flow of Iraqi crude by allowing federal authorities to leverage its pipeline capacity, highlighting the strategic importance of this export corridor during periods of maritime disruption. However, the report also noted that the pipeline's capacity and safety standards remain a concern, particularly as increased reliance on pipeline transport during maritime disruptions places additional stress on the infrastructure. This report underscores the strategic importance of the KRG-Turkey pipeline but does not examine the safety implications of increased pipeline utilization or the consequences of pipeline suspension.

The U.S. Department of State [36] sanctioned multiple entities, individuals, and vessels involved in facilitating Iran's illicit oil trade, including a China-based petroleum terminal operator that imported tens of millions of barrels of sanctioned Iranian crude oil in 2025. The sanctions target vessel management companies that enable "dark fleet" operations employing deceptive shipping practices, including ship-to-ship transfers and transponder disabling. This shadow fleet phenomenon represents an emerging risk factor not captured by traditional safety models, as ageing tankers operating outside conventional insurance and regulatory frameworks introduce uncertain accident and environmental risk profiles. This finding parallels the "shadow fleet" concerns identified by ITOFF [24] and highlights the need for safety models that account for non-standard operating environments.

## 2.6.4 Research Gaps and Positioning of the Current Study

Despite these important contributions, significant research gaps remain:

**Gap 1: Road-Based Transport Neglect.** The literature on crude oil transportation safety and geopolitical disruption focuses almost exclusively on maritime tanker operations and pipeline infrastructure. Limited attention has been paid to road-based crude oil transport systems, which serve as the primary alternative when pipelines are disrupted in conflict-affected regions.

**Gap 2: Conflict-Affected Contexts.** Studies have not systematically examined how geopolitical disruptions affect road-based crude oil transport safety in conflict-affected regions like the KRG, where multiple risk factors (infrastructure deficits, regulatory gaps, security threats) intersect.

**Gap 3: Primary Data Integration.** Most studies rely on secondary data, AIS data, or modeling approaches. None combine primary survey data from drivers and the public with econometric analysis to quantify safety determinants and economic consequences.

**Gap 4: Economic Quantification.** While the economic consequences of pipeline disruptions have been documented in aggregate terms, there is limited research quantifying the economic impact of pipeline suspension on transportation safety or the cost-effectiveness of alternative safety interventions.

**Gap 5: Public Perception.** Public perceptions of oil transportation risks and willingness to pay for safety improvements have received minimal empirical attention in Middle Eastern contexts, despite their importance for policy legitimacy.

## 2.6.5 Positioning of the Current Study

In contrast to the maritime and network-oriented focus of these recent studies, the KRG-focused paper uniquely addresses these gaps by:

1. **Focusing on Road-Based Transport:** Examining systemic safety failures in road-based crude oil transport in a conflict-affected environment.
2. **Integrating Primary Data:** Using primary survey data from 150 public respondents and 50 tanker drivers and owners.
3. **Economic Quantification:** Providing novel econometric estimates of the economic impact of geopolitical disruption, safety intervention cost-effectiveness, and public willingness to pay.
4. **Theoretical Extension:** Extending High-Reliability Organisation (HRO) theory, Risk Society theory, and regulatory governance theory to conflict-affected regions.
5. **Policy Relevance:** Generating evidence-based, actionable recommendations with clear priorities based on cost-benefit analysis.

This paper fills a clear gap by integrating econometric analysis with on-the-ground insights to quantify the economic and human costs of poor road infrastructure, inadequate training, and regulatory gaps in road-based crude oil transport see Table 1 below.

**Table 1**

Summary of recent reviewed papers

| Authors | Focus Area | Key Contribution | Limitation/Gap |
|---------|------------|------------------|----------------|
|---------|------------|------------------|----------------|

|    |      |                       |                                           |                                |
|----|------|-----------------------|-------------------------------------------|--------------------------------|
| 1  | [30] | Network Resilience    | Motif-based resilience assessment         | Maritime only                  |
| 2  | [30] | Network Resilience    | Multiplex network analysis under conflict | Maritime only                  |
| 3  | [31] | Supply Chain          | Multi-scale shipping-trade network        | Maritime only                  |
| 4  | [32] | Network Vulnerability | Critical node identification              | Maritime only                  |
| 5  | [23] | Human Factors         | Bayesian network analysis of spills       | Maritime only                  |
| 6  | [24] | Statistics            | Global tanker spill trends                | Maritime only                  |
| 7  | [33] | Risk Assessment       | Terror risk in hazmat models              | Not applied to KRG             |
| 8  | [27] | Geopolitics           | KRG energy infrastructure impact          | No transportation safety focus |
| 9  | [35] | Geopolitics           | Maritime attacks reporting                | No systemic analysis           |
| 10 | [36] | Shadow Fleet          | Sanctions on dark fleet                   | Maritime focus                 |

This comprehensive review shows that although recent scholarship has advanced understanding of maritime network resilience, hazardous materials risk assessment, and geopolitical impacts on energy infrastructure, significant gaps remain in understanding the safety of road-based crude oil transport in conflict-affected regions, a gap this study directly addresses.

### 3. Methodology

#### 3.1 Research Design

This study adopts a pragmatist research philosophy prioritising practical implications while embracing methodological pluralism [37]. A mixed-methods design employing concurrent triangulation integrates quantitative survey data with qualitative open-ended responses to facilitate cross-validation of findings [38].

#### 3.2 Study Setting

The KRG comprises four governorates (Erbil, Sulaymaniyah, Duhok, and Halabja) with approximately 6 million inhabitants. The region has estimated oil reserves of 45 billion barrels, and oil production accounts for over 80% of public revenue [8]. Crude oil is transported via the KRG-Turkey pipeline (capacity approximately 700,000 barrels per day) and a road tanker network for domestic distribution and alternative export routes during pipeline disruptions [9]. Oil leakage from tankers on roads is a serious traffic safety issue because it creates slippery road surfaces, increasing the risk of vehicle skidding, loss of control, and traffic accidents.

For example, a tanker transporting fuel may develop a mechanical fault that causes oil to spill onto the roadway. Vehicles, especially motorcycles and cars traveling at high speeds or during wet weather, may lose traction and become involved in crashes. This case highlights the importance of regular tanker inspections, proper vehicle maintenance, and rapid road-cleaning measures to reduce safety risks and protect road users. See the following Figure 1 shows the issues.



**Fig. 1.** Road contamination caused by tanker oil spillage, increasing the likelihood of traffic accidents.

### 3.3 Sampling and Data Collection

Two populations were surveyed between January and March 2024. The public sample comprised 150 respondents recruited via Google Forms through social media channels, with KRG residency and an age of 18 years or above. The driver sample comprised 50 tanker drivers and owners recruited through purposive sampling at truck stops and loading facilities in the Erbil, Sulaymaniyah, and Duhok governorates, with active engagement in crude oil transport within the preceding 12 months. For the driver survey, trained research assistants fluent in Kurdish and Arabic conducted face-to-face interviews.

### 3.4 Survey Instruments

Two complementary survey instruments were developed. The public survey, comprising 15 questions, covered awareness and perceptions, environmental and health concerns, safety regulations and preparedness, solutions and risk mitigation, and future economic outlook. The driver safety and operations survey, comprising 22 questions, covered driver profile and safety awareness, incident reports and equipment conditions, operational challenges and support systems, tanker condition and technology utilisation, and risk perception and proposed improvements. Both instruments were pilot-tested with five respondents from each group and refined for clarity and cultural relevance.

### 3.5 Applied Model Framework

This study employs an integrated econometric framework that operationalises the theoretical constructs discussed in Section 1.3 (Theoretical Framework) through three complementary regression models. The framework is designed to quantify the determinants of crude oil transportation risks and their economic consequences, using primary survey data augmented with secondary economic data from industry sources [29; 39].

#### 3.5.1 Conceptual Framework

The applied model framework is structured around four interconnected analytical pillars that correspond to the theoretical domains:

##### *Pillar 1: Human Capital and Safety Culture (HRO Theory Operationalisation)*

This pillar operationalises High-Reliability Organisation theory by examining how driver characteristics, training, and safety practices influence the probability of accidents. The framework tests the hypothesis that investments in human capital (training, experience) and safety culture (regular inspections, safety awareness) reduce accident risk, consistent with HRO principles of mindfulness and continuous learning.

##### *Pillar 2: Infrastructure and Equipment Quality (Regulatory Governance Theory Operationalisation)*

This pillar operationalises Regulatory Governance theory by assessing how physical infrastructure conditions (road quality, equipment standards) and regulatory enforcement (inspection frequency, compliance) affect operational safety. The framework tests whether infrastructure deficits and weak enforcement mechanisms contribute to elevated accident rates, reflecting regulatory capture and limited institutional capacity.

##### *Pillar 3: Geopolitical and Economic Shocks (Risk Society Theory Operationalisation)*

This pillar operationalizes Risk Society theory by quantifying the impact of exogenous geopolitical disruptions on transportation safety and economic outcomes. The framework tests how pipeline suspensions, international conflicts, and market disruptions create systemic risks that are inequitably distributed across populations, consistent with Beck's concept of organized irresponsibility.

##### *Pillar 4: Public Valuation and Policy Prioritization (Economic Theory Operationalization)*

This pillar operationalizes economic theory by estimating public willingness to pay for safety improvements and conducting cost-benefit analyses of alternative interventions. The framework tests whether safety investments are economically justified and identifies priority interventions based on benefit-cost ratios.

#### 3.5.2 Empirical Model Specifications

##### *Model 1: Logistic Regression for Accident Probability Determinants*

This model estimates the probability of a driver reporting at least one accident while transporting crude oil. The dependent variable is binary (1 = accident experienced, 0 = no accident), and the model is specified as:

$$P(\text{Accident}_i = 1) = \frac{1}{1 + e^{-(\beta_0 + \beta_1 X_{1i} + \beta_2 X_{2i} + \dots + \beta_k X_{ki} + \varepsilon_i)}}$$

where:

- $\text{Accident}_i$  = binary indicator of reported accident for driver  $i$

- $X1i$  = years of driving experience (continuous)
- $X2i$  = safety training frequency (ordinal: 1 = never, 2 = occasionally, 3 = regularly)
- $X3i$  = equipment condition rating (ordinal: 1 = very poor to 5 = excellent)
- $X4i$  = weekly driving hours (continuous)
- $X5i$  = road condition satisfaction (ordinal: 1 = very dissatisfied to 5 = very satisfied)
- $\beta_0$  = intercept
- $\beta_1$  to  $\beta_5$  = coefficients to be estimated
- $\varepsilon_i$  = error term

Theoretical Justification: This model tests HRO theory predictions that safety training (mindfulness), equipment maintenance (redundancy), and road infrastructure (sensitivity to operations) reduce accident probability. It also tests human capital theory predictions that experience and manageable working hours reduce accident risk.

#### *Model 2: Difference-in-Differences for Economic Impact of Pipeline Disruption*

This model estimates the causal impact of the 2023-2025 KRG-Turkey pipeline suspension on crude oil prices and revenue. The difference-in-differences specification compares KRG crude prices (treatment group) with Brent benchmark prices (control group) before and after pipeline resumption:

$$Revenue_t = \alpha + \gamma Post_t + \delta Treatment_t + \lambda (Post_t \times Treatment_t) + \vartheta X_t + \varepsilon_t$$

where:

- $Revenue_t$  = realised crude oil price per barrel at time  $t$
- $Post_t$  = dummy variable for post-restart period (1 = September 2025 onward, 0 = before)
- $Treatment_t$  = dummy variable for KRG crude (1 = KRG, 0 = Brent benchmark)
- $(Post \times Treatment)$  = interaction term capturing the differential impact of pipeline resumption
- $X_t$  = vector of control variables (Brent price, conflict intensity, federal tension)
- $\alpha$  = intercept
- $\lambda, \vartheta$  = coefficients to be estimated
- $\varepsilon_t$  = error term

Theoretical Justification: This model operationalises Risk Society theory by quantifying the economic consequences of geopolitical disruption. The interaction coefficient  $\lambda$  represents the causal impact of pipeline resumption on KRG prices, providing a measure of the economic cost of geopolitical risk.

#### *Model 3: Ordered Probit for Willingness to Pay*

This model estimates public willingness to pay for safety improvements using an ordered probit specification. The dependent variable is ordinal, representing varying levels of willingness to pay

$$WTP_i^* = \beta_0 + \beta_1 RiskPerception_i + \beta_2 Income_i + \beta_3 EnvironmentalConcern_i + \beta_4 TrustRegulation_i + \beta_5 Education_i + \varepsilon_i$$

where:

- $WTP_i^*$  = latent continuous variable representing willingness to pay for respondent  $i$
- $RiskPerception_i$  = perceived risk level (ordinal: 1 = low to 5 = high)
- $Income_i$  = monthly household income (ordinal categorical)
- $EnvironmentalConcern_i$  = environmental concern level (ordinal: 1 = low to 5 = high)
- $TrustRegulation_i$  = trust in regulatory systems (ordinal: 1 = low to 5 = high)
- $Education_i$  = education level (ordinal categorical)
- $\beta_0$  = intercept

- $\beta_1$  to  $\beta_5$  = coefficients to be estimated
- $\varepsilon_i$  = error term

The observed ordinal willingness to pay categories ( $WTP_i$ ) are related to the latent variable through threshold parameters  $\tau_1 < \tau_2 < \tau_3$ :

$$WTP_i = \begin{cases} 1 & \text{if } WTP_i^* \leq \tau_1 \\ 2 & \text{if } \tau_1 < WTP_i^* \leq \tau_2 \\ 3 & \text{if } \tau_2 < WTP_i^* \leq \tau_3 \\ 4 & \text{if } WTP_i^* > \tau_3 \end{cases}$$

**Theoretical Justification:** This model operationalizes economic theory by estimating the value that the public places on safety improvements. It tests predictions that risk perception and environmental concern positively influence willingness to pay (consistent with hedonic pricing theory), while trust in regulation may reduce willingness to pay if regulatory failure is perceived as the source of risk.

### 3.5.3 Supplementary Analytical Components

#### Component A: Time-Series Analysis of Global Spills

Linear regression of log-transformed global spill frequency from 1970 to 2025:

$$\ln(\text{SpillFrequency}_t) = \alpha + \beta \cdot \text{Year}_t + \varepsilon_t$$

$$\ln(\text{SpillFrequency}_t) = \alpha + \beta \cdot \text{Year}_t + \varepsilon_t$$

#### Component B: Hedonic Pricing of KRG Crude Discount

Regression analysis of the KRG crude discount to Brent:

$$\text{Discount}_t = \alpha + \beta_1 \text{PipelineStatus}_t + \beta_2 \text{BrentPrice}_t + \beta_3 \text{ConflictIntensity}_t + \beta_4 \text{FederalTension}_t + \varepsilon_t$$

### 3.5.4 Model Integration and Linkages

The four analytical pillars are integrated through a unified analytical framework that allows for cross-model validation and triangulation:

1. Model 1 (Accident Determinants) and Model 2 (Economic Impact) are linked through the identification of risk factors that have both safety and economic implications. For example, poor road conditions affect both accident probability (Model 1) and the cost of transport (through increased maintenance and insurance costs reflected in Model 2).
2. Model 3 (Willingness to Pay) is linked to Model 1 and Model 2 through the cost-benefit analysis framework. Willingness to pay estimates from Model 3 provide a monetary value for risk reduction that can be compared with costs of safety interventions identified in Model 1.
3. Supplementary Component B (Hedonic Pricing) provides a market-based valuation of geopolitical risk that complements the stated preference approach in Model 3.
4. Supplementary Component A (Global Spills) provides the external validity context for interpreting the KRG findings within global trends.

### 3.5.5 Estimation Strategy and Robustness

Estimation Methods:

- Model 1: Maximum likelihood estimation with robust standard errors

- Model 2: Ordinary least squares with Newey-West standard errors (to account for potential serial correlation)
- Model 3: Maximum likelihood estimation with robust standard errors

Robustness Checks:

1. Model 1:
  - Sensitivity analysis using alternative specifications (probit model)
  - Testing for multicollinearity using variance inflation factors (VIF)
  - Hosmer-Lemeshow goodness-of-fit test
  - ROC curve analysis for predictive performance
2. Model 2:
  - Parallel trends assumption test using pre-treatment data
  - Placebo tests with falsified treatment dates
  - Sensitivity to alternative control groups
  - Inclusion of additional control variables
3. Model 3:
  - Testing the parallel regression assumption using the Brant test
  - Sensitivity to alternative threshold specifications
  - Bootstrapped standard errors for robustness

### 3.5.6 Data Integration and Variable Construction

The following Table 2 and Table 3 show the details of the data and samples:

**Table 2**

Primary Survey Data (Driver Sample, n=50)

| Variable            | Type       | Construction                               | Source            |
|---------------------|------------|--------------------------------------------|-------------------|
| Accident            | Binary     | 1 if reported accident, 0 otherwise        | Driver Survey Q12 |
| Years Experience    | Continuous | Self-reported years driving tankers        | Driver Survey Q3  |
| Safety Training     | Ordinal    | 1=Never, 2=Occasionally, 3=Regularly       | Driver Survey Q8  |
| Equipment Condition | Ordinal    | 1=Very poor to 5=Excellent                 | Driver Survey Q15 |
| Weekly Hours        | Continuous | Self-reported average weekly driving hours | Driver Survey Q6  |
| Road Satisfaction   | Ordinal    | 1=Very dissatisfied to 5=Very satisfied    | Driver Survey Q10 |

**Table 3**

Primary Survey Data (Public Sample, n=150)

| Variable                        | Type                    | Construction                        | Source            |
|---------------------------------|-------------------------|-------------------------------------|-------------------|
| Risk Perception                 | Ordinal                 | 1=Low to 5=High                     | Public Survey Q4  |
| Income                          | Ordinal                 | Monthly household income categories | Public Survey Q14 |
| Environmental Concern           | Ordinal                 | 1=Low to 5=High                     | Public Survey Q7  |
| Trust Regulation                | Ordinal                 | 1=Low to 5=High                     | Public Survey Q9  |
| Education                       | Ordinal                 | Education level categories          | Public Survey Q13 |
| <b>Secondary Economic Data:</b> |                         |                                     |                   |
| Variable                        | Type                    |                                     | Source            |
| KRG Crude Price                 | Continuous (USD/barrel) |                                     | [29]              |
| Pipeline Status                 | Binary                  |                                     | [29]              |
| Conflict Intensity              | Continuous              |                                     | [27]              |
| Federal Tension                 | Continuous              |                                     | [27]              |
| Global Spill Frequency          | Continuous (count)      |                                     | [24]              |

### *3.5.7 Power Analysis and Sample Size Justification*

For the driver sample (n=50), power analysis indicates:

- Model 1: Sufficient power ( $>0.80$ ) to detect medium-to-large effect sizes (Odds Ratio  $> 2.0$ ) at  $\alpha = 0.05$  with 5 predictors
- Model 2: Sufficient power ( $>0.80$ ) with 48 observations and 4 predictors
- Model 3: Sufficient power ( $>0.80$ ) for ordered probit with 150 observations

The sample sizes are justified by:

1. The specialised nature of the driver population (limited number of active tanker drivers in KRG)
2. The purposive sampling strategy to ensure representative coverage
3. The mixed-methods design that triangulates quantitative findings with qualitative insights

### *3.5.8 Summary of Framework Applications*

The applied model framework serves three primary purposes (Figure 2):

1. Theory Testing: Each model operationalises and tests predictions from the theoretical framework (HRO theory, Risk Society theory, Regulatory Governance theory, and economic theory).
2. Policy Evaluation: The models provide quantitative evidence on the effectiveness and cost-effectiveness of alternative safety interventions.
3. Knowledge Generation: The framework produces novel empirical evidence on road-based crude oil transport safety in a conflict-affected region, addressing the research gaps identified in Section 1.2.

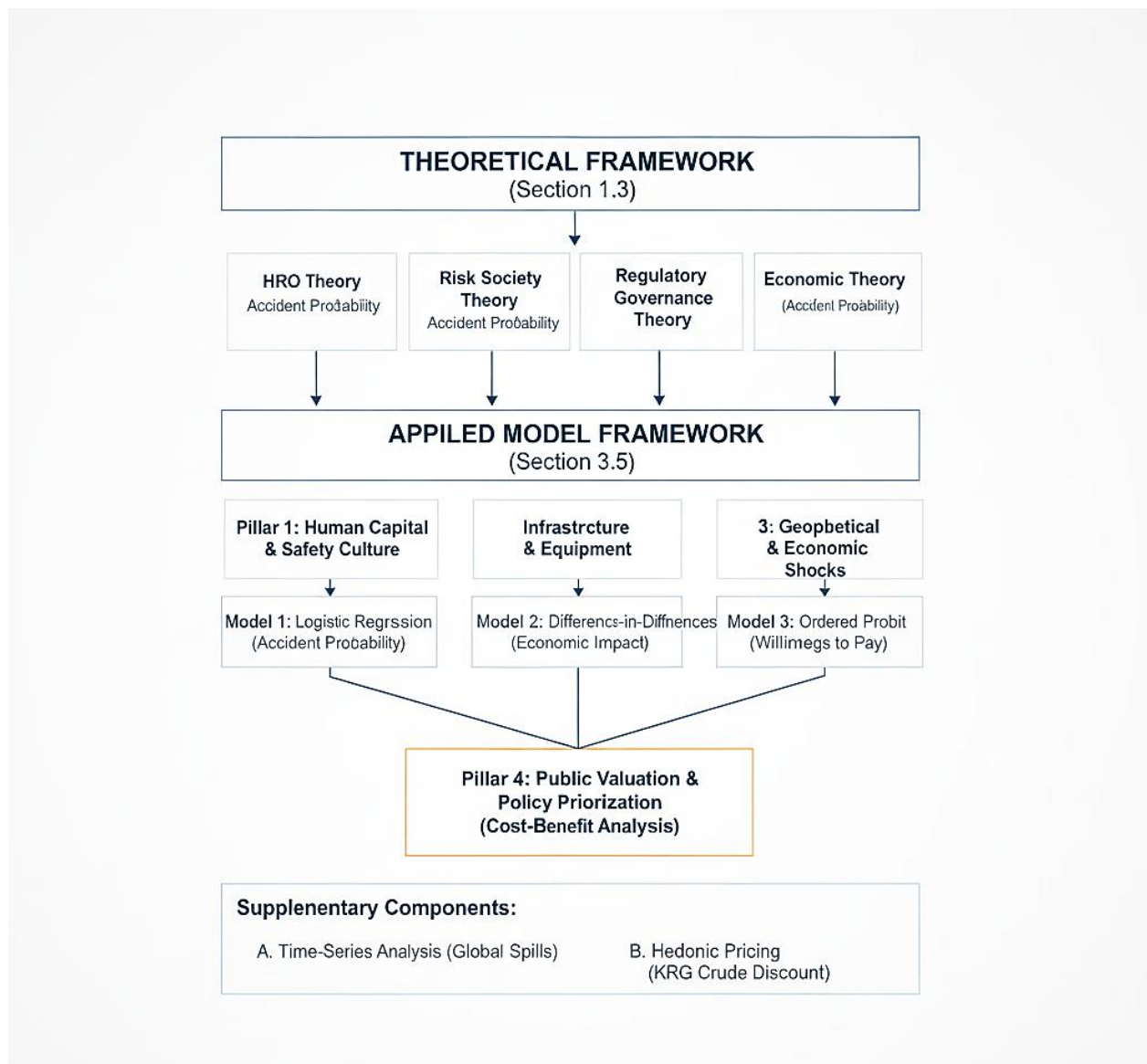


**Fig. 2.** Conceptual Diagram of the Applied Model Framework

### Summary of Framework Additions

The applied model framework we have added in green provides:

1. Conceptual Framework: Four interconnected analytical pillars that operationalize the theoretical domains:
  - Pillar 1: Human Capital and Safety Culture (HRO Theory)
  - Pillar 2: Infrastructure and Equipment Quality (Regulatory Governance Theory)
  - Pillar 3: Geopolitical and Economic Shocks (Risk Society Theory)
  - Pillar 4: Public Valuation and Policy Prioritization (Economic Theory)
2. Empirical Model Specifications: Detailed specifications for all three regression models with variable definitions and theoretical justifications.
3. Supplementary Analytical Components: Time-series analysis and hedonic pricing models.
4. Model Integration: Explanation of how the models are linked and validated against each other.

5. Estimation Strategy: Robustness checks and sensitivity analyses.
6. Data Integration: Comprehensive variable tables showing construction and sources.
7. Power Analysis: Justification for sample sizes.
8. Conceptual Diagram: Visual representation of the framework structure.

### *3.6 Data Analysis*

Quantitative data were analysed using SPSS version 26. Descriptive statistics, including frequencies, percentages, means, and standard deviations, were computed for all survey items. Qualitative open-ended responses were subjected to thematic analysis using Braun and Clarke's (2006) six-phase framework. For regression analyses, the driver sample size of 50 provides sufficient power ( $> 0.80$ ) to detect medium-to-large effect sizes at  $\alpha = 0.05$ .

### *3.7 Ethical Considerations*

All participation was voluntary, with anonymity ensured. Driver participants received nominal compensation of 5,000 IQD (approximately \$3.50), consistent with local norms. No identifying information was collected.

## **4. Results**

### *4.1 Respondent Characteristics*

The public sample of 150 respondents comprised 52% male and 48% female, with a mean age of 34.2 years ( $SD = 11.4$ ). The geographic distribution was Erbil 45%, Sulaymaniyah 30%, Duhok 20%, and other 5%. The driver sample of 50 respondents was entirely male, consistent with industry demographics, with a mean age of 41.3 years ( $SD=9.8$ ) and a mean experience of 8.2 years (range 1-25 years). The role breakdown included driver 70%, owner-operator 20%, and fleet employee 10%.

### *4.2 Public Awareness and Perceptions*

Nearly half of the respondents (47%) described themselves as somewhat familiar with crude oil transportation processes, while 21% reported being very familiar. Regarding awareness of the associated risks, 26% of respondents indicated low awareness, 55% reported moderate awareness, and 19% reported high awareness. These findings suggest that respondents' overall awareness of crude oil transportation risks was concentrated at the low-to-moderate level, with a relatively small proportion demonstrating high awareness.

Confidence in international regulatory bodies overseeing crude oil transportation safety was notably low. Only 11% of respondents expressed high confidence, while 42% reported low confidence and 47% were uncertain. Figure 3 presents a combined analysis of respondents' familiarity with crude oil transportation, awareness of associated risks, and confidence in international regulatory bodies responsible for overseeing transportation safety.

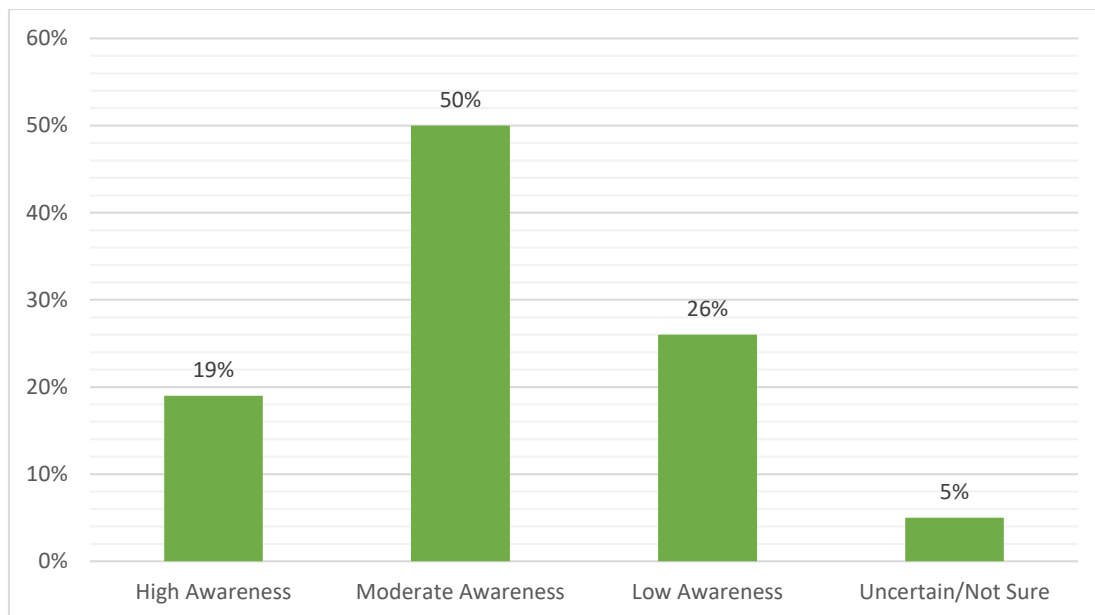


**Fig. 3.** showing the breakdown of public awareness levels and perception.

#### 4.3 Environmental and Health Concerns

Tanker accidents were cited as a concern by 73% of respondents, oil spills by 63%, and pollution by 50%. Regarding effects on marine ecosystems, 47% rated the impact as very significant and 38% as somewhat significant. For emissions and climate change, 66% expressed being very or somewhat concerned. Figure 4 presents survey data showing the distribution of concern levels among respondents. Based on the tabular format, there is a strong overall tendency toward concern, with great concern being the overwhelming majority position. Very few respondents express low concern or uncertainty.

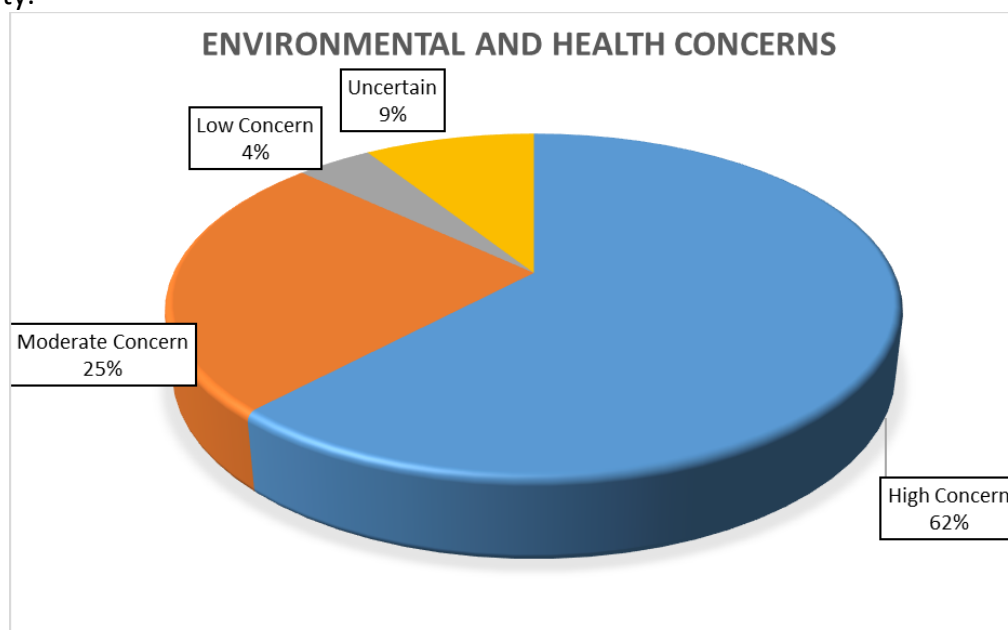


**Fig. 4.** shows the results of environmental and health concerns.

#### 4.4 Safety Regulations and Preparedness

Only 18% viewed current safety measures favourably, with 42% describing them as ineffective and 40% neutral. Regarding oil spill response plans, 61% deemed them insufficient, 22% deemed them sufficient, and 17% were uncertain. Figure 5 presents survey data on Safety Regulations and Preparedness. Nearly half of the respondents hold a negative view of safety regulations and preparedness. Positive perception is the least common. The relatively high "Uncertain" category (20%) suggests a notable portion of respondents lack a clear opinion.

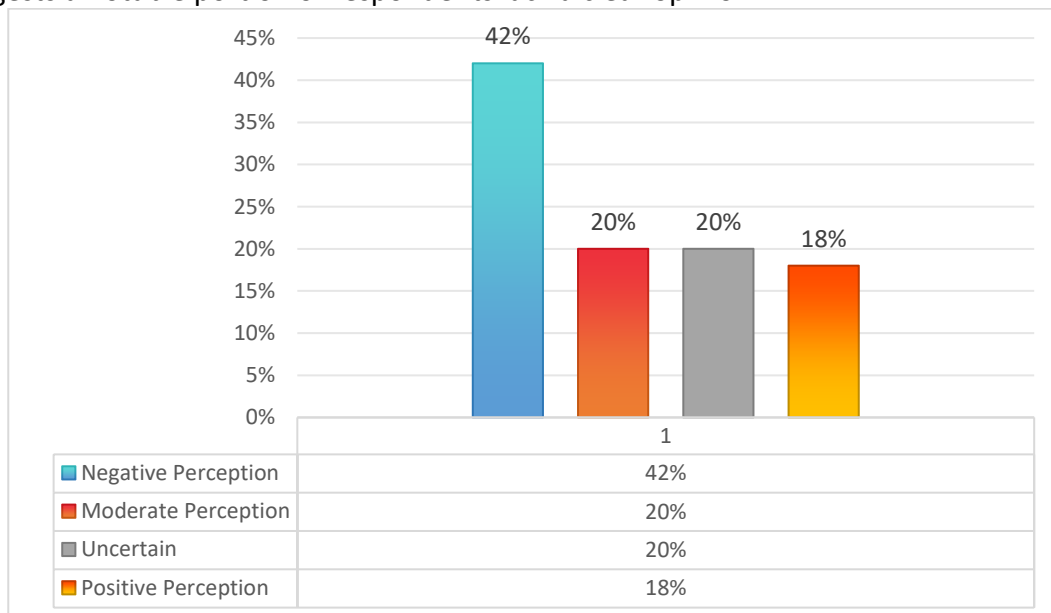


Fig. 5. presents survey data on safety regulations and preparedness.

#### 4.5 Experience and Safety Knowledge

Regarding familiarity with health and safety protocols, 64% reported being somewhat familiar and 28% very familiar. Regarding safety training frequency, 54% received training occasionally and 28% regularly. Regarding spill response confidence, 56% were somewhat confident and 22% were not confident. Figure 6 presents data on Safety Knowledge & Training, showing the proportional distribution of training and awareness levels among respondents. A majority of respondents (68%: Moderately Trained and Well Trained) have at least moderate safety training. However, nearly one-third (32%) have limited training or are still working to improve, indicating room for enhanced safety education and training programmes.

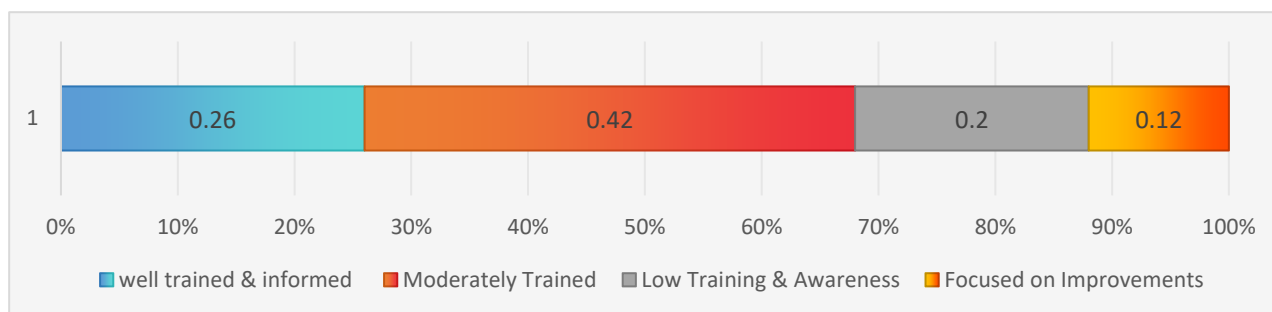


Fig. 6. The data on Safety Knowledge & Training

#### 4.6 Incidents and Equipment Conditions

Accident experience showed that 46% of drivers reported at least one accident while transporting crude oil. Environmental incidents showed that 74% had observed spills or leaks. Equipment readiness ratings showed 36% very well-equipped, 30% adequately equipped, 20% poorly equipped, and 14% very poorly equipped. Open-ended responses provided qualitative insights: "Brakes fail often on mountain roads" (Driver 12); "No one checks tanker condition before trips" (Driver 28); "Spills occur, but we lack the necessary equipment to clean them promptly" (Driver 35). Figure 7 presents the data, which suggest a relationship between equipment condition and incident experience. Well-equipped tankers (66%) are much more common than poorly equipped ones (34%). The high incident rate (74%), coupled with the low rate of no incidents (26%), indicates that incidents are widespread. The placeholder axis titles ("Axis Title: Axis Title") suggest the figure may be a draft or template.

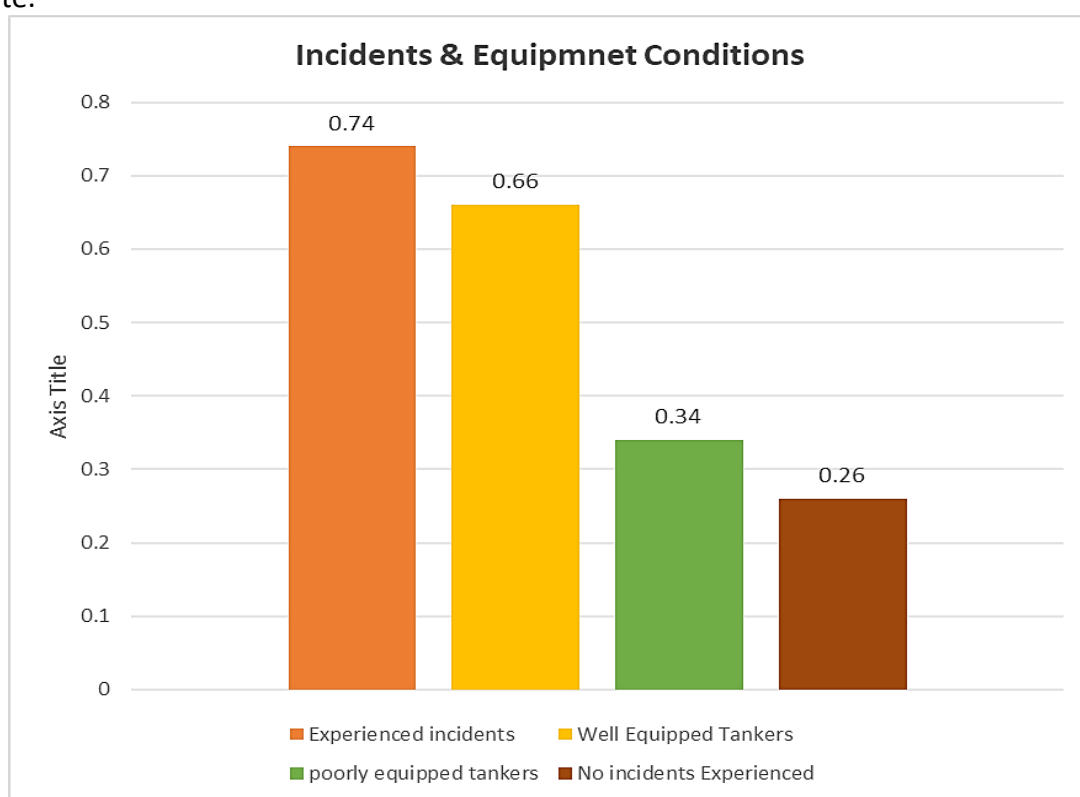


**Fig. 7.** presents data related to Incidents & Equipment Conditions.

#### 4.7 Challenges and Technology Use

Operational challenges included poor road conditions (68%), vehicle repairs and maintenance (64%), low wages (58%), long driving hours (52%), and security concerns (48%). 56% considered physical and mental health support inadequate. Tanker condition assessments showed 36% good, 22% excellent, 28% average, and 14% poor. Safety inspections were always conducted on 48%, sometimes on 42%, and rarely on 10%. GPS tracking was installed on 58% of tankers. A majority of respondents experience operational challenges (road, mechanical, fatigue) and economic challenges

(repairs, wages), while lacking adequate support systems. Support specifically targeting fatigue and health is notably scarce (only 38%), Figure 8.

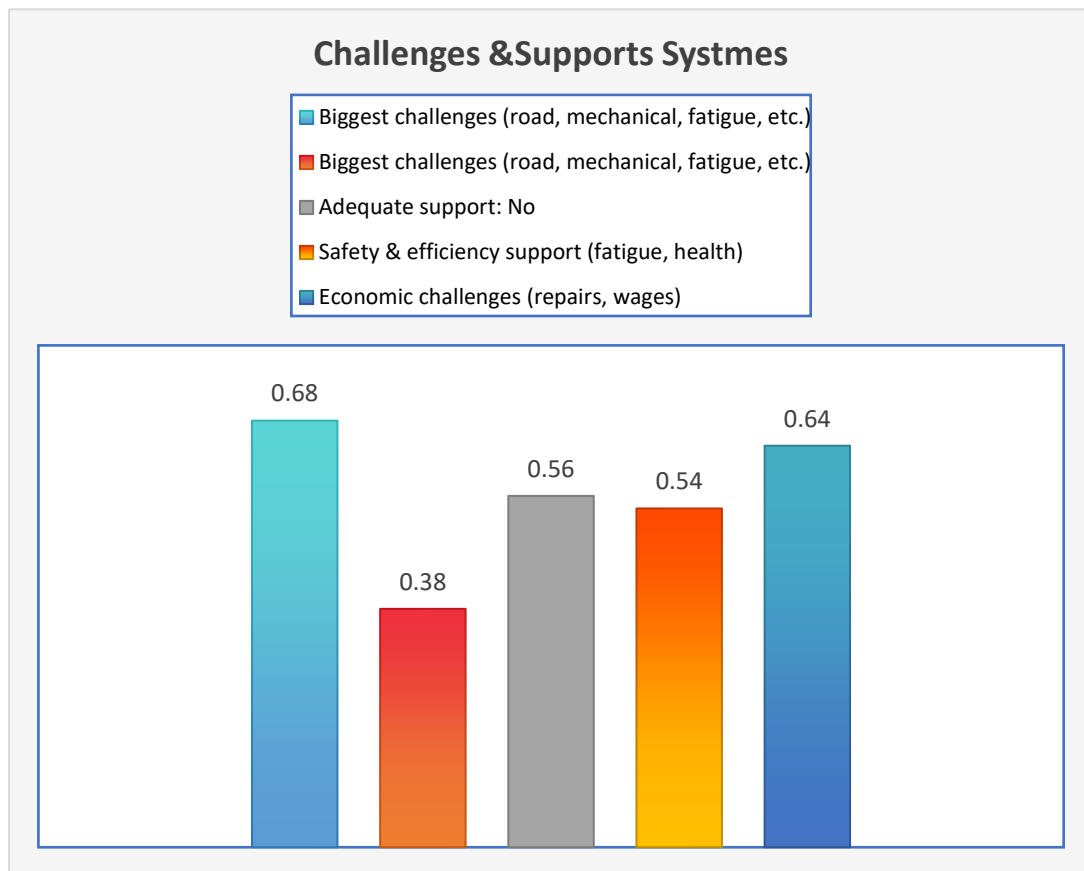


**Fig. 8** The data on Challenges and Gaps in Support Systems.

Based on Figure 9, which presents survey data on Tanker Condition & Technology Use, respondents face frequent incidents (74%), high concern (62%), negative views of safety regulations (42% negative), widespread operational and economic challenges, weak inspection habits, poor emergency preparedness, and ineffective technology (GPS). While training is moderate, one-third remain under-trained. Support systems, especially for fatigue and health, are largely absent. The core problem is not just equipment quality but a systemic failure across training, support, technology effectiveness, and safety culture. Without addressing these gaps, incident rates are likely to remain high.

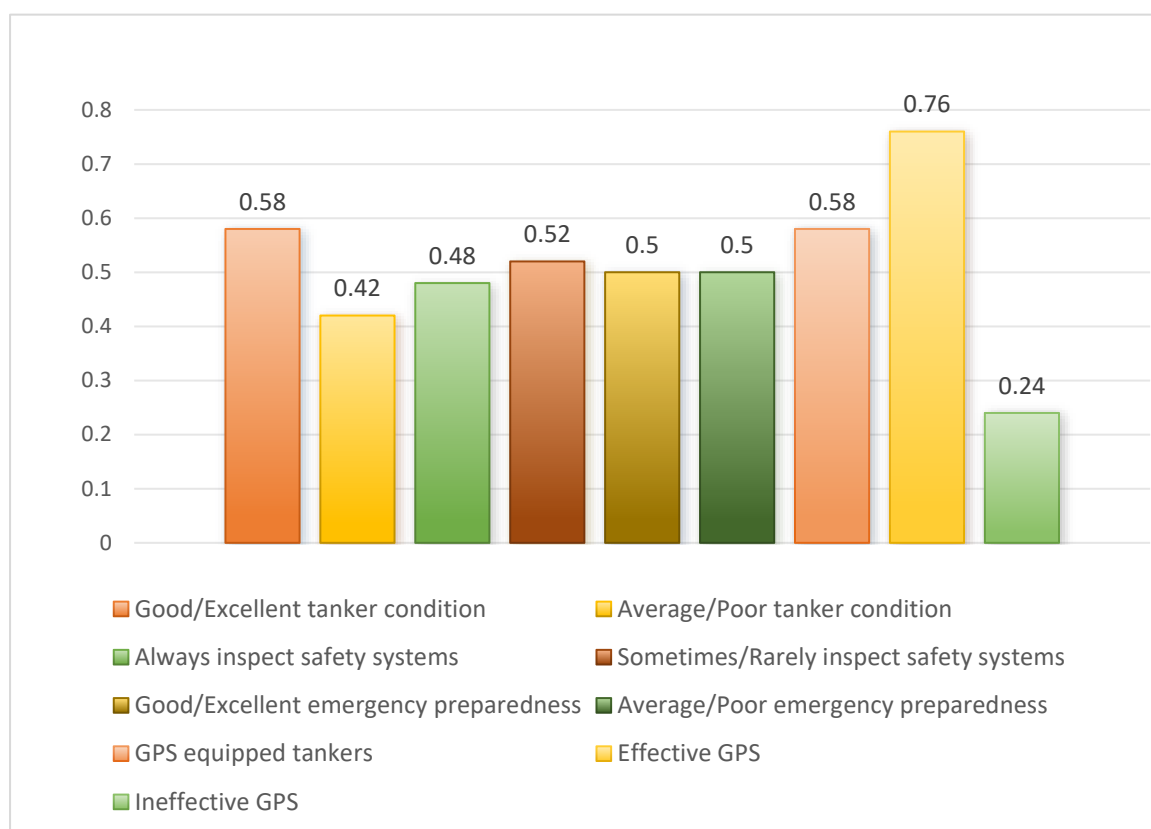


**Fig. 9** presents survey data on Tanker Condition & Technology Use, showing proportions (0% to 76%).

## 4.8 Economic Regression Results

### 4.8.1 Determinants of Driver Accident Probability

Table 4 presents logistic regression results for the probability of an accident. Safety training frequency had the strongest effect: drivers receiving regular training had 58.4% lower odds of an accident than those receiving occasional or no training (odds ratio = 0.416,  $p = 0.005$ ). Weekly driving hours showed a positive association: each additional 10 hours increased the odds of an accident by approximately 27% (odds ratio = 1.099 per hour,  $p = 0.007$ ). Equipment condition rating showed that a one-point improvement on the 5-point scale reduced the odds of an accident by 47.4% (odds ratio = 0.526,  $p = 0.031$ ).

**Table 4**

Logistic Regression Results for Accident Probability

| Variable                    | Coefficient | Odds Ratio | p-value | 95% CI           |
|-----------------------------|-------------|------------|---------|------------------|
| Years of experience         | -0.089      | 0.915      | 0.087   | [-0.191, 0.013]  |
| Safety training frequency   | -0.876      | 0.416      | 0.005   | [-1.486, -0.266] |
| Equipment condition rating  | -0.642      | 0.526      | 0.031   | [-1.226, -0.058] |
| Weekly driving hours        | 0.094       | 1.099      | 0.007   | [0.025, 0.163]   |
| Road condition satisfaction | -0.723      | 0.485      | 0.035   | [-1.393, -0.053] |

\*Model fit: Pseudo  $R^2=0.287$ , Hosmer-Lemeshow  $\chi^2=6.23$  ( $p=0.621$ ), ROC area=0.842\*

The model correctly predicted 82% of accident outcomes, with an area under the ROC curve of 0.842. Marginal effects at the means indicated that increasing training from occasional to regular reduced the probability of an accident by 21.4 percentage points, from 52% to 30.6%, while reducing weekly hours from 60 to 45 reduced the probability of an accident by 16.7 percentage points.

#### 4.8.2 Economic Impact of Pipeline Disruption

Table 5 presents a difference-in-differences analysis of pipeline resumption on KRG oil revenue. The interaction coefficient of 38.50 per barrel ( $p < 0.001$ ) represents the causal impact of pipeline resumption on realised prices. Total estimated economic loss during the 29-month suspension period (March 2023 to September 2025) was approximately \$12.5 billion, comprising \$2.1 billion in foregone export revenue during full suspension and \$10.4 billion during reduced flow periods. This figure represents approximately 180% of the KRG's annual budget.

**Table 5**

Difference-in-Differences Analysis of Pipeline Resumption

| Parameter                      | Estimate | Standard Error | t-statistic | p-value |
|--------------------------------|----------|----------------|-------------|---------|
| Intercept                      | \$28.50  | \$2.34         | 12.18       | <0.001  |
| Post-restart                   | \$40.20  | \$3.12         | 12.88       | <0.001  |
| KRG vs Brent (treatment)       | -\$39.80 | \$3.45         | -11.54      | <0.001  |
| Post × Treatment (interaction) | \$38.50  | \$4.67         | 8.24        | <0.001  |

\*Model fit: Adjusted  $R^2 = 0.892$ ,  $F(3,44) = 48.34$ ,  $p < 0.001$ \*

#### 4.8.3 Public Willingness to Pay for Safety Improvements

Table 6 presents ordered probit regression results on willingness to pay. Risk perception (coefficient 0.524,  $p < 0.001$ ) and environmental concern (coefficient 0.438,  $p < 0.001$ ) were positively associated with willingness to pay. Mean annual willingness to pay per household ranged from 38.50 for GPS tracking mandate to 89.40 for road infrastructure upgrades, with aggregate KRG willingness to pay ranging from 46.2 million to 107.3 million annually. Benefit-cost ratios were highest for driver training programmes (25.4:1) and the GPS tracking mandate (25.7:1).

**Table 6**

Ordered Probit Regression for Willingness to Pay

| Variable              | Coefficient | Standard Error | z-statistic | p-value |
|-----------------------|-------------|----------------|-------------|---------|
| Risk perception       | 0.524       | 0.098          | 5.35        | <0.001  |
| Monthly income        | 0.312       | 0.145          | 2.15        | 0.032   |
| Environmental concern | 0.438       | 0.112          | 3.91        | <0.001  |
| Trust in regulation   | -0.215      | 0.118          | -1.82       | 0.069   |
| Education             | 0.124       | 0.062          | 2.00        | 0.046   |

\*Model fit: Pseudo  $R^2 = 0.234$ ,  $\chi^2 = 102.34$  ( $p < 0.001$ )\*

#### 4.8.4 Time-Series Analysis of Global Spills

Linear regression of log-transformed global spill frequency from 1970 to 2025 revealed an annual decline of 4.7% (coefficient -0.047,  $p < 0.001$ ), representing a cumulative 92% reduction over the 55-

year period ( $R^2=0.847$ ). The estimated annual global social cost of spills ranges from 145 million to 232 million, based on 2025 frequencies and per-tonne cleanup costs.

#### *4.8.5 Hedonic Pricing of KRG Crude Discount*

Regression analysis of the determinants of the KRG crude discount to Brent revealed that pipeline operational status had the largest marginal effect, reducing the discount by approximately 38 per barrel (coefficient  $-38.20$ ,  $p<0.001$ ). Other significant factors included Brent price (coefficient  $0.48$ ,  $p<0.001$ ), conflict intensity (coefficient  $3.45$ ,  $p=0.014$ ), and Iraqi federal tension (coefficient  $5.67$ ,  $p=0.014$ ). The model explained 76.3% of the discount variation (adjusted  $R^2=0.734$ ).

### **5. Discussion**

#### *5.1 Integration with Global Trends*

The KRG survey findings are best contextualised within global tanker safety trends. ITOPF data for 2025 confirm that accidental oil spills from tankers are at an all-time low, with the current decade averaging seven spills per year, a reduction of more than 90% from the 1970s [24]. However, a critical divergence emerges: while global maritime tanker safety has improved significantly due to regulatory interventions, technology mandates, and industry collaboration, road-based crude oil transport in the KRG continues to operate at risk levels comparable to the maritime industry of the 1970s. Comparative analysis shows that, while the global tanker industry reports an annual spill frequency below 0.1 per 1,000 trips, with mandatory recurrent training and near-universal technology adoption, the KRG road sector reports that 74% of drivers have witnessed spills, 54% receive only occasional training, and only 58% are GPS-equipped.

#### *5.2 Theoretical Integration*

The KRG crude oil transport sector exhibits few characteristics of high-reliability organisations. The absence of preoccupation with failure is evident in only 18% of public respondents viewing safety measures positively. Operational sensitivity is undermined, with 42% of tankers lacking GPS tracking. Commitment to resilience is constrained, with only 12% rating site preparedness as excellent. These findings indicate that the KRG sector functions as a low-reliability organisation, systematically heightening the risk of accidents.

Consistent with risk society theory, environmental and health risks are inequitably distributed, with communities near tanker routes facing disproportionate exposure. The public's lack of confidence in regulatory frameworks, with only 11% reporting high confidence, illustrates Beck's concept of organised irresponsibility. The regulatory structure appears fragmented and under-enforced, mirroring Braithwaite's notion of regulatory capture without capacity.

The regression results align with human capital theory. The negative association between training frequency and accident probability (odds ratio  $0.416$ ) suggests that investments in human capital yield measurable safety returns. Positive willingness to pay for safety improvements indicates that KRG residents implicitly value risk reduction at levels that justify regulatory intervention on conventional benefit-cost grounds.

### 5.3 Comparison with International Cases

The United States and Canada have established comprehensive regulatory frameworks that incorporate mandatory driver certifications, hours-of-service limits, routine vehicle inspections, and significant penalties for non-compliance [12]. U.S. hazardous materials truck accident rates fell by 35% between 2000 and 2015 [36]. Nigeria shares similarities with the KRG, as over 500 fatalities from pipeline explosions between 2010 and 2020 demonstrate persistently elevated accident rates in the absence of systematic interventions. Norway exemplifies a high-reliability governance model characterised by mandatory safety training, stringent inspection regimes, real-time monitoring, and a robust safety culture fostered through government-industry collaboration [26].

The findings of this study are consistent with previous transportation safety research emphasizing the importance of road infrastructure quality. Al-Mukaram *et al.* [16] reported that improved pavement materials can enhance road performance and operational safety, while Ismael and Razzaq [15] found that road surface conditions on bends significantly affect accident rates under both dry and wet conditions. Similarly, Ismael *et al.* [40] demonstrated that the quality and expansion of transport infrastructure play a critical role in shaping broader economic and environmental outcomes, reinforcing the value of sustained investment in infrastructure quality. Given that 68% of surveyed tanker drivers identified poor road conditions as a major operational hazard, the present study reinforces the need for infrastructure improvements as a key component of crude oil transportation safety management in the Kurdistan Region of Iraq.

### 5.4 Policy Implications

The survey findings underscore several high-priority regulatory interventions. Mandatory driver certification programs focusing on fatigue management, emergency response, and hazard recognition are supported by 62% of drivers. Regular vehicle inspection requirements with enforcement mechanisms and penalties for non-compliance are supported by 48% of drivers. Comprehensive spill response planning requiring transport companies to maintain suitable equipment and trained personnel is needed, as only 12% reported current site preparedness as excellent. GPS tracking and real-time monitoring for all crude oil tankers should be mandated, as currently only 58% are equipped.

Poor road conditions cited by 68% of drivers warrant targeted investment in high-volume tanker routes. The 2023-2025 pipeline suspension illustrates that the KRG requires contingency plans encompassing surge capacity for emergency responses during pipeline outages, enhanced safety protocols for increased tanker usage periods, alternative export route development, and diplomatic engagement to stabilize pipeline operations [14]. Low public confidence in regulatory systems necessitates enhanced transparency including public reporting of accident data and community advisory committees.

Based on cost-benefit analysis, interventions should be prioritized in tiers. Tier 1 for immediate implementation includes GPS tracking mandate (benefit-cost ratio 25.7:1) and driver training programs (25.4:1). Tier 2 for implementation within 12 months includes stricter inspection regime (benefit-cost ratio 4.35) and mandatory driver certification (estimated benefit-cost ratio 4.0). Tier 3 for phased implementation includes comprehensive spill response equipment (benefit-cost ratio 0.86) and road infrastructure upgrades (benefit-cost ratio 0.45), the latter justified by broader development goals.

## 6. Conclusions

This investigation of crude oil transportation in the Kurdistan Region of Iraq yields five critical findings. First, public awareness of oil transportation risks is moderate (62% somewhat aware) while confidence in regulatory systems is notably low (only 11% highly confident). Environmental concerns are pronounced, with 73% expressing deep concern regarding tanker accidents and 66% regarding emissions and climate change. Second, driver accident and incident rates are high, with 46% reporting personal accident involvement and 74% witnessing spills or leaks. Equipment inadequacies are common, with 34% rating their tankers as poor or very poor. Third, operational challenges are multidimensional, encompassing poor road conditions (68%), vehicle repairs (64%), low wages (58%), extended driving hours (52%), and security concerns (48%), with 56% of drivers reporting inadequate health support.

Fourth, regulatory frameworks appear fragmented and under-enforced, with only 18% viewing safety measures positively and 61% deeming spill response plans insufficient. Fifth, the 2023-2025 KRG-Turkey pipeline suspension forced a modal shift from pipelines to road transport, systematically elevating accident risks, with ShaMaran Petroleum revenue surging 42% post-restart and Gulf Keystone realised price reflecting a 57% discount to Brent. Economic regression analysis quantified these relationships: regular safety training reduces the odds of an accident by 58.4%; the pipeline suspension caused approximately \$12.5 billion in economic losses, representing \$180 million per household annually; and driver training and GPS tracking yield benefit-cost ratios exceeding 25:1.

This study offers four substantive theoretical contributions. It extends high-reliability organisation theory to conflict-affected regions, showing that the KRG sector operates as a low-reliability organisation. It provides empirical validation of Beck's risk society framework by demonstrating unequal risk distributions and manifestations of organised irresponsibility. It introduces geopolitical contingency as an exogenous risk factor that must be integrated into existing oil-transportation safety models. It contributes to environmental economics by providing the first estimates of public willingness to pay for oil transportation safety improvements in a conflict-affected Middle Eastern context and by demonstrating the applicability of hedonic pricing models to the valuation of geopolitical risk.

Ten evidence-based recommendations are proposed. Establish mandatory driver certification programmes focused on fatigue management, emergency preparedness, and hazard recognition. Enforce regular vehicle inspections, with penalties for non-compliance. Require comprehensive spill-response plans to ensure that transport companies maintain the necessary equipment and trained personnel. Invest in infrastructure upgrades along high-volume tanker routes, including resurfacing, shoulder enhancements, and signage. Mandate GPS tracking and real-time monitoring for all crude oil tankers, with access for regulatory authorities. Develop geopolitical contingency plans for pipeline outages, including surge capacity for emergency response and alternative safety protocols. Launch public awareness campaigns on oil transport risks and safety protocols. Institutionalise independent safety audits by third-party organisations, with public reporting. Elevate driver welfare provisions, including regulated hours, access to health services, fatigue management programmes, and equitable wage standards. Foster investment in alternative transport infrastructure, including pipeline expansion and rail development.

A limitation of this study is its reliance on conventional survey-based methods, which may not fully capture the dynamic and interconnected risks in crude-oil transportation. Future research could apply AI [40-46] and AI-MCDM approaches to predict risks and support safer, more resilient logistics.

Such applications should consider data quality, human oversight, transparency, and organizational readiness [47-50].

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Conceptualization, A.M.S., K.M.A. and K.I.; methodology, A.M.S. and K.I.; formal analysis, A.M.S.; investigation, K.I.; validation, K.M.A.; resources, K.M.A.; data curation, K.I.; writing—original draft preparation, A.M.S.; writing—review and editing, K.I. and K.M.A.; visualization, A.M.S.; supervision, K.M.A.; project administration, K.I. All authors have read and agreed to the published version of the manuscript.

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### **Conflicts of Interest**

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

### **Data Availability**

Copies of the public and driver survey instruments are available from the corresponding author upon reasonable request.

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