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International Freight Transportation System Planning to Minimize Backhaul for Sustainable Cross-Border Freight Systems

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ABSTRACT

Backhaul inefficiency remains a persistent challenge in cross-border road freight transportation, particularly in emerging economies where fragmented information, limited planning capacity, and institutional uncertainty constrain logistics performance. Despite rising trade volumes and ongoing infrastructure investment, a substantial share of freight vehicles continues to return empty, resulting in underutilized transport capacity and elevated logistics costs. This study investigates the structural nature of backhaul inefficiency through an empirical analysis of two major Thai border crossings, Chong Mek (Thailand–Lao People's Democratic Republic (Lao PDR)) and Chong Sa-Ngam (Thailand–Cambodia). Using a case-based applied research design, the study analyzes 2,250 observed cross-border freight trips, integrating freight movement records, round-trip cost data, and institutional evidence. A rule-based transport planning system is developed to generate planned scenarios by systematically matching observed outbound vehicle movements with feasible return cargo opportunities under operational constraints, including vehicle capacity, route compatibility, scheduling feasibility, and border process considerations. System performance is evaluated through a before–after comparison of observed operations and planned scenarios using indicators of backhaul frequency, vehicle utilization, transportation cost per trip, and fleet turnaround time. Results indicate that empty return trips, representing backhaul movements, account for 21.5% of total return trips at Chong Mek and 25.8% at Chong Sa-Ngam, revealing significant inefficiencies in cross-border freight operations. Cost analysis reveals that backhaul operations impose an effective net increase in round-trip transportation costs of 17.8% and 18.3%, respectively, due to foregone return-leg revenue. Scenario evaluation demonstrates that the proposed planning system can reduce overall backhaul frequency from 23.6% to 14.9%, increase average vehicle utilization from 68.2% to 82.5%, and lower average transportation costs per trip by approximately 14%, without reliance on advanced optimization algorithms or large-scale infrastructure investment. The findings indicate that backhaul inefficiency is primarily a planning and coordination failure rather than a consequence of insufficient demand. By demonstrating the effectiveness of a context-sensitive, rule-based planning approach, this study provides empirical evidence that targeted transport planning interventions can enhance cross-border logistics efficiency and sustainability under real-world institutional constraints.

1. INTRODUCTION

International freight transportation plays a critical role in global and regional economic integration, particularly in emerging economies where cross-border trade relies heavily on road-based logistics [1, 2]. In Southeast Asia—and especially within the Greater Mekong Subregion (GMS)—road transport forms the backbone of regional supply chains linking Thailand, Lao PDR, Cambodia, Vietnam, and China [3]. Despite sustained investment in highways, border checkpoints, and economic corridors, logistics inefficiencies persist, eroding cost competitiveness and environmental sustainability [4, 5].

A key and persistent inefficiency in road freight logistics is backhaul, or empty return trips. When vehicles return without cargo, transport capacity is underutilized, operational costs rise, fuel consumption increases, and unnecessary emissions are generated. Empirical research consistently identifies empty running as a major source of logistics waste, particularly in cross-border settings characterized by asymmetric demand, regulatory fragmentation, and coordination failures [6, 7]. Although the direct financial burden falls on operators, wider impacts—such as congestion, infrastructure degradation, and environmental externalities—are borne by society [8].

Backhaul inefficiency in cross-border freight is rarely attributable to infrastructure shortages alone. Instead, it reflects deeper structural challenges, including information asymmetry, fragmented governance, institutional constraints, and the absence of integrated transport planning. Freight flows at border crossings are shaped not only by market demand but also by customs procedures, regulatory alignment, bilateral agreements, and administrative capacity [9]. Even where physical connectivity is adequate, misalignment between outbound and inbound flows frequently results in empty returns, particularly among small and medium-sized operators with limited access to demand information or collaborative networks [10].

The GMS provides a salient context for examining these dynamics. Regional cooperation initiatives have emphasized infrastructure-led integration through economic corridors and cross-border transport agreements. Thailand, as a regional logistics hub, plays a central role in facilitating trade within the subregion [11]. Nevertheless, cross-border logistics operations continue to face inefficiencies arising from regulatory heterogeneity, uneven implementation of agreements, and limited coordination among public and private stakeholders [12]. Border checkpoints remain critical bottlenecks where institutional and operational constraints are most evident.

Within this context, the Thai border crossings of Chong Mek (Thailand–Lao People's Democratic Republic (Lao PDR)) and Chong Sa-Ngam (Thailand–Cambodia) exemplify structural challenges in cross-border freight transport. Both serve as important trade gateways yet experience high levels of backhaul. Vehicles often enter neighboring countries fully loaded but return empty due to limited visibility of return cargo, weak coordination among shippers and carriers, and the absence of systematic planning tools—despite rising trade volumes and ongoing policy efforts to improve connectivity [13].

From a logistics management perspective, backhaul inefficiency reflects a planning failure rather than a purely market-driven outcome. Traditional freight operations rely on bilateral contracts, fragmented scheduling, and firm-level optimization that prioritizes short-term cost minimization over network-wide efficiency. Capacity allocation is therefore guided by immediate contractual obligations rather than system-level demand patterns, reinforcing structural inefficiencies [14]. These problems are magnified in cross-border logistics, where uncertainty related to customs clearance, transit times, and regulatory compliance discourages coordination and information sharing [15].

Against this backdrop, this study examines backhaul inefficiency in cross-border road freight through an empirical case study of Chong Mek and Chong Sa-Ngam. Rather than treating backhaul as an inevitable outcome of market dynamics, the study conceptualizes it as a planning and coordination problem that can be mitigated through systematic transport planning.

To operationalize backhaul inefficiency as a planning and coordination problem rather than a purely market-driven outcome, this study addresses the following research questions:

RQ1: How does backhaul frequency vary across logistics operators of different sizes at cross-border freight checkpoints, and to what extent does operator size reflect disparities in transport planning capacity?

RQ2: What is the incremental impact of empty return trips on round-trip transportation costs and vehicle utilization in cross-border road freight operations?

RQ3: Under what operational and institutional conditions can a rule-based transport planning system reduce backhaul frequency and improve vehicle utilization without relying on advanced optimization algorithms or infrastructure expansion?

2. LITERATURE REVIEW AND ANALYTICAL FRAMEWORK

2.1 Backhaul inefficiency in road freight transportation

Backhaul, or empty return trips, represents a persistent inefficiency in road freight transportation. When vehicles complete outbound deliveries without securing return cargo, transport capacity is underutilized, raising unit costs by spreading fixed expenses—such as vehicle ownership, labor, and compliance—over fewer revenue-generating kilometers [16, 17]. At the system level, empty trips increase fuel consumption, emissions, congestion, and infrastructure wear, thereby imposing social and environmental costs beyond firm-level inefficiency [16, 18].

Early logistics research conceptualized backhaul as a structural imbalance within freight networks rather than a random operational outcome. Planning-oriented studies argue that empty trips arise systematically from information asymmetry, fragmented freight markets, and weak coordination mechanisms [17, 18]. Subsequent empirical work reinforced this interpretation, identifying backhaul as embedded logistics waste that persists even under stable demand conditions, rather than a temporary response to demand fluctuation [18, 19].

In cross-border contexts, backhaul inefficiency is typically more pronounced. Additional uncertainty related to customs clearance, regulatory compliance, and institutional heterogeneity discourages advance commitment to return loads, leading carriers to prioritize outbound contracts and treat return trips as residual movements [20, 21]. Empirical evidence further indicates that small and medium-sized operators face disproportionately higher backhaul rates due to limited access to freight information, weaker bargaining power, and constrained planning resources—conditions commonly observed in emerging economies with fragmented logistics markets [19].

2.2 Cross-border logistics and institutional constraints

Cross-border freight transportation operates within complex institutional environments shaped by national regulations, bilateral agreements, and regional cooperation frameworks. While infrastructure development has been central to regional integration efforts, a growing body of research demonstrates that non-physical barriers—such as customs procedures, documentation requirements, and regulatory misalignment—often generate greater inefficiencies than physical bottlenecks [21, 22].

In the GMS, cooperative initiatives aim to facilitate cross-border flows by harmonizing regulations and streamlining border procedures. However, their effectiveness depends heavily on implementation capacity at national and local levels. Empirical studies show that partial or uneven implementation frequently results in persistent delays, unpredictable clearance times, and operational uncertainty at border crossings [19, 23].

Institutional fragmentation shapes freight planning behavior by increasing uncertainty over transit times, compliance costs, and enforcement practices. This uncertainty discourages long-term planning and reduces incentives for collaborative logistics arrangements, leading carriers to adopt risk-averse strategies and avoid pre-commitment to return loads—even when bilateral trade volumes are substantial [24]. Governance complexity at border crossings, involving multiple agencies with overlapping mandates, further amplifies variability in operational conditions and reinforces conservative planning practices that prioritize reliability over efficiency [22, 25].

2.3 Transport planning systems and cooperative logistics

Transport planning systems determine how freight capacity is allocated across logistics networks. Traditional planning practices emphasize firm-level optimization within individual contracts, which—while rational at the micro level—often generate suboptimal outcomes at the system level under conditions of fragmented demand and institutional uncertainty [17, 26]. As a result, capacity allocation decisions tend to reinforce existing inefficiencies rather than resolve them.

The logistics literature increasingly highlights cooperative planning as a means to reduce inefficiencies such as backhaul. Coordination among carriers, shippers, and intermediaries enables information sharing, schedule alignment, and capacity pooling, with empirical evidence showing reductions in empty trips, transportation costs, and emissions [27, 28]. However, adoption remains uneven in cross-border contexts where trust, data sharing, and regulatory alignment are limited [24, 29].

Digital planning tools—such as freight platforms and data-driven routing systems—can facilitate cooperative logistics, but their effectiveness depends on data availability, institutional support, and user adoption. In emerging economies, barriers such as limited digital infrastructure, technical capacity constraints, and fragmented governance often constrain their practical impact [30]. Consequently, transport planning systems must be adapted to border-specific institutional realities rather than directly transferred from domestic or fully integrated markets [29, 31].

2.4 Sustainability implications of backhaul reduction

Beyond cost considerations, backhaul reduction has significant environmental implications. Empty trips generate fuel consumption and emissions without corresponding economic output, making them a critical source of transport-related greenhouse gas emissions and energy inefficiency [32, 33]. Improving vehicle utilization through planning interventions is therefore recognized as a cost-effective strategy for enhancing environmental performance without requiring large-scale infrastructure investments [27, 28].

Unlike modal shifts or network expansion, which require substantial capital and long implementation periods, transport planning interventions can yield immediate sustainability benefits. This is particularly relevant for developing regions where fiscal constraints limit large-scale investments and where incremental efficiency gains are policy-relevant [33]. However, sustainability gains depend on aligning the incentives of carriers, shippers, and public authorities, whose priorities may differ across cost efficiency, service reliability, and regulatory compliance. Effective planning systems must therefore integrate economic, environmental, and institutional considerations simultaneously [28].

2.5 Analytical framework

Drawing on the reviewed literature, this study conceptualizes backhaul inefficiency as a system-level outcome shaped by three interrelated dimensions: institutional context, transport planning capacity, and operational outcomes. This perspective aligns with freight transport research emphasizing interactions among governance structures, planning mechanisms, and network performance rather than isolated operational decisions [26, 34].

Within the framework, institutional factors—such as regulatory alignment, border governance, and administrative capacity—define the contextual conditions under which planning decisions are made [21, 22]. Transport planning capacity, encompassing information availability, coordination mechanisms, and planning tools, is positioned as a mediating mechanism linking institutional conditions to operational performance [31, 35]. Prior research suggests that planning capacity is critical in translating institutional environments into measurable logistics outcomes, particularly in complex and uncertain settings [25, 35].

Operational outcomes are reflected in indicators such as backhaul frequency, transportation costs, and capacity utilization. From this perspective, backhaul inefficiency is not an exogenous constraint but a modifiable outcome influenced by targeted planning interventions. By examining how planning systems operate within specific institutional contexts at border crossings, the framework provides a robust basis for empirical analysis and guides the development of a transport planning system tailored to cross-border freight operations, bridging planning theory and operational realities in emerging-economy logistics systems [32, 35-38].

3. RESEARCH METHODOLOGY

3.1 Research design and approach

This study employs a case-based applied research design combined with system-oriented transport planning analysis to examine backhaul inefficiency in cross-border road freight transportation. The research is exploratory–explanatory, with two objectives: (1) to identify structural sources of backhaul inefficiency and (2) to develop a transport planning system capable of improving vehicle utilization under real-world institutional constraints. Rather than testing abstract propositions in isolation, the analysis is grounded in observed freight operations at border checkpoints, consistent with applied freight transport research that emphasizes empirical grounding and decision relevance [39, 40].

A multiple-case study strategy is adopted, focusing on the Chong Mek (Lao PDR) and Chong Sa-Ngam (Thailand–Cambodia) border crossings. Multiple-case designs are well suited to logistics research involving institutional and contextual variation, as they allow analytical comparison while preserving case-specific depth and explanatory richness [41]. These border crossings were selected due to their strategic importance for regional trade and the persistence of backhaul inefficiency despite ongoing policy initiatives aimed at enhancing cross-border connectivity.

3.2 Study area and case selection

Chong Mek and Chong Sa-Ngam perform distinct but complementary roles within Thailand's cross-border logistics network. Chong Mek links Thailand with Lao PDR and eastern GMS corridors, while Chong Sa-Ngam connects Thailand with Cambodia and downstream regional markets. As critical nodes in regional freight systems, such border crossings influence routing decisions, vehicle circulation, and capacity utilization across national boundaries [42].

At both locations, cross-border road freight operations are dominated by small and medium-sized logistics operators, reflecting the fragmented structure of regional trucking markets. Case selection followed three criteria. First, both crossings rely heavily on road freight, making them suitable for analyzing vehicle utilization and backhaul behavior. Second, both exhibit asymmetric freight flows, with outbound demand frequently exceeding inbound demand—a condition commonly associated with empty returns and capacity underutilization [43]. Third, both operate under broadly comparable institutional frameworks, enabling the analysis to focus on planning and coordination factors rather than regulatory differences alone.

3.3 Data sources and collection

The study integrates quantitative and qualitative data to capture both operational patterns and institutional conditions influencing transport planning. Mixed data approaches are widely used in freight research to combine measurable performance indicators with contextual insights, thereby enhancing analytical depth and interpretive validity [44].

Quantitative data comprise freight movement records detailing vehicle trips, cargo status (loaded or empty), route characteristics, and transportation costs, obtained from logistics operators and relevant agencies at the selected border crossings. These data enable the identification of linehaul and return trips, facilitating analysis of backhaul frequency, vehicle utilization, and cost implications—core indicators in freight system performance assessment [45].

Qualitative data were collected through document analysis and stakeholder consultations. Policy documents, transport regulations, and operational guidelines were reviewed, alongside informal interviews with logistics operators and border officials. Such qualitative evidence supports interpretation of freight behavior in institutionalized environments where governance arrangements strongly shape operational outcomes [46].

3.4 Analytical procedures

The analysis proceeds in three stages, reflecting established practices in freight transportation research [39, 44].

First, freight movement data were analyzed to distinguish between loaded and empty trips, with return journeys without cargo classified as backhaul. Descriptive statistics and comparative cost analysis were used to assess the prevalence and economic implications of backhaul, establishing a baseline of system performance [45].

Second, a structural analysis examined planning constraints contributing to backhaul persistence, including information gaps, coordination failures, and institutional uncertainty at border crossings. This stage emphasized how regulatory environments and operational risks shape carrier behavior, rather than treating planning decisions as purely market-driven [46].

Third, a transport planning system prototype was developed to reduce backhaul by improving utilization of outbound capacity. The system prioritizes practical planning logic over complex optimization, matching return cargo opportunities with existing vehicle movements based on cost efficiency, route compatibility, and operational feasibility. This approach aligns with applied transport planning research that emphasizes implementability, decision support, and institutional fit under real-world constraints [47].

3.5 Rule-based transport planning system development

The transport planning system is designed as a decision-support framework rather than a fully automated optimization model. This design choice reflects two key considerations. First, many cross-border logistics operators—particularly small and medium-sized enterprises—operate with limited digital infrastructure and planning resources, rendering complex optimization tools impractical in daily operations [48]. Second, institutional uncertainty at border crossings, including variability in customs clearance times and procedural conditions, necessitates flexible and adaptive planning tools rather than rigid algorithmic solutions [49].

Consistent with these constraints, the proposed system emphasizes incremental efficiency improvements over theoretical global optimality. By prioritizing implementability and transparency, the planning framework reflects bounded rationality in real-world freight planning behavior, where decisions are made under imperfect information and operational uncertainty [47].

3.5.1 System inputs and data preparation

The planning system uses observed linehaul and return trip data as a baseline, incorporating trip records, cargo status (loaded or empty), vehicle characteristics, route information, and round-trip cost parameters. Cost components include fuel consumption, labor, vehicle depreciation, and border-related fees, which are treated consistently across observed operations and planned scenarios.

Observed outbound trips are paired with their corresponding return movements to identify empty return trips, which constitute potential backhaul candidates. In parallel, feasible return cargo options are identified from observed inbound freight movements within the same border corridor and operational period, subject to spatial and temporal proximity.

3.5.2 Identification of backhaul candidates and return cargo opportunities

Backhaul candidates are defined as return trips conducted without cargo following a loaded outbound movement. For each backhaul candidate, the system identifies return cargo opportunities that are operationally visible within the same planning context. This approach deliberately avoids assumptions of perfect information or centralized freight markets, reflecting the fragmented and decentralized nature of cross-border logistics systems.

Return cargo opportunities are therefore constrained by route compatibility, vehicle availability, scheduling feasibility, and border process requirements, mirroring the actual decision environment faced by logistics operators at border crossings.

3.5.3 Rule-based matching logic and operational constraints

Planning decisions are governed by a predefined set of rule-based constraints that translate practical planning considerations into operational decision logic. These rules include vehicle capacity limits, vehicle–cargo compatibility, route alignment, time-window feasibility, and compliance with existing border procedures. Only return cargo options that satisfy all operational constraints are considered eligible.

Among eligible options, the system applies a cost dominance principle, whereby a planned return with cargo is accepted only if it does not increase total round-trip transportation cost relative to the observed empty return. When multiple feasible options exist, priority is given to the option that minimizes incremental cost and scheduling disruption. This rule-based approach ensures that planning decisions remain transparent, traceable, and consistent with cost-minimization objectives commonly applied in practice.

3.5.4 Generation of planned transport scenarios

Planned transport scenarios are generated by systematically applying the rule-based matching logic to all identified backhaul candidates in the observed dataset. Each empty return trip is evaluated independently, and feasible return cargo matches are assigned where available. Trips for which no eligible return cargo satisfies the planning rules remain unchanged in the planned scenario.

As a result, the planned scenario represents an incremental improvement over observed operations, rather than a hypothetical system-wide optimum. This design choice aligns with applied transport planning research emphasizing practicality, institutional fit, and decision relevance under real-world constraints [47-49].

3.5.5 Performance evaluation and scenario comparison

System performance is evaluated through a before–after comparison between observed operations and planned scenarios using identical indicators, including backhaul frequency, vehicle utilization, average transportation cost per trip, and fleet turnaround time. All indicators are computed using the same cost parameters and evaluation horizon to ensure comparability.

Performance improvements are therefore directly attributable to the application of the planning system, rather than to changes in demand conditions, infrastructure, or external policy environments. This evaluation framework enables a transparent assessment of how planning-based interventions can enhance cross-border freight efficiency within existing institutional and operational constraints.

3.6 Validity, reliability and limitations

Internal validity is strengthened through data triangulation, combining freight records with institutional analysis to verify interpretations and reduce single-source bias [50]. Construct validity is supported by consistent operational definitions of backhaul, linehaul, and cost efficiency grounded in established freight and transport planning literature [39]. Reliability is addressed through transparent documentation of data sources, analytical procedures, and planning assumptions, facilitating replication in comparable border contexts [44].

Several limitations should be acknowledged. The dataset reflects freight movements from selected operators and border crossings and may not capture all transport activities in the region. The evaluation focuses on short-term operational outcomes rather than long-term behavioral change, and institutional conditions at border crossings may evolve due to policy reforms [46]. These limitations suggest avenues for future research, including longitudinal analysis and the integration of advanced data-driven planning tools that remain sensitive to institutional and capacity constraints in emerging-economy logistics systems [48, 51]. While statistical generalization is limited, the analytical insights are transferable to other cross-border and non-urban freight contexts with similar institutional characteristics.

4. RESULTS

4.1 Characteristics of backhaul operations at border crossings

The empirical results indicate that backhaul operations constitute a persistent and economically relevant share of cross-border freight movements at both Chong Mek and Chong Sa-Ngam border crossings. Despite strong outbound freight activity, a considerable proportion of vehicles returned without cargo, reflecting systematic underutilization of transport capacity.

As presented in Table 1, Chong Mek recorded a total of 1,240 observed freight trips, of which 266 return trips (21.5% of total return trips) were conducted without cargo. In contrast, Chong Sa-Ngam exhibited a higher backhaul frequency, with 260 empty return trips out of 1,010 total trips (25.8% of total return trips). This difference suggests a greater imbalance between outbound and inbound freight flows at Chong Sa-Ngam.

Although outbound movements were predominantly loaded—accounting for 78.5% of trips at Chong Mek and 74.2% at Chong Sa-Ngam—the disparity between outbound and inbound cargo flows remained pronounced. The higher backhaul frequency at Chong Sa-Ngam reflects greater fragmentation of inbound cargo and more limited opportunities for systematic cargo aggregation. These findings indicate that backhaul inefficiency arises not from insufficient return demand, but from limitations in coordination and transport planning mechanisms that hinder effective matching of available cargo with returning vehicles.

Overall, the results demonstrate that backhaul inefficiency at both border crossings is structural rather than incidental, providing a quantitative baseline for subsequent analysis of its cost implications and underlying institutional drivers.

Table 1. Distribution of observed freight trips by direction and cargo status

Border Checkpoint	Total Return Trips	Loaded Return Trips	Empty Return Trips (Backhaul)	Backhaul Frequency (%)
Chong Mek	1,240	974	266	21.5
Chong Sa-Ngam	1,010	749	261	25.8

Note: This table focuses exclusively on return movements, where backhaul is defined as empty return trips. Backhaul frequency is calculated as the proportion of empty return trips relative to total return trips at each checkpoint.

Table 1 shows that despite high levels of loaded outbound movements at both border crossings, a substantial share of return trips remains empty. Chong Sa-Ngam exhibits a consistently higher backhaul frequency than Chong Mek, indicating greater asymmetry in freight flows and weaker capacity for inbound cargo consolidation.

4.2 Cost implications of backhaul inefficiency

Comparative cost analysis highlights the significant economic burden imposed by backhaul operations on cross-border freight transportation. As shown in Table 2, empty return trips generated substantial operational costs—covering fuel consumption, vehicle depreciation, labor, and border-related expenses—while producing no corresponding freight revenue.

At Chong Mek, backhaul movements resulted in an effective net increase of 17.8% in round-trip transportation costs, while Chong Sa-Ngam experienced a comparable effective net increase of 18.3%. These increases translated directly into higher unit transportation costs per delivered shipment, placing considerable pressure on logistics operators, particularly those operating with narrow profit margins.

In addition to direct financial impacts, backhaul inefficiency generated indirect cost effects by extending vehicle turnaround times and reducing fleet availability for subsequent assignments. Operators frequently accepted empty returns to avoid uncertainty associated with securing return cargo, prioritizing schedule reliability over potential cost savings. These results indicate that backhaul inefficiency functions as a structural cost driver rather than a short-term operational anomaly.

Table 2. Round-trip cost model and effective cost increase due to backhaul

Border Crossing	**Cost per Loaded Trip (USD) C_0**	**Cost per Backhaul Trip (USD) C_r**	**Total Cost (USD) C_t**	**Baseline Cost (USD) C_b**	**Effective Cost Increase due to Backhaul (%)**
Chong Mek	620	480	1,100	934	+17.8
Chong Sa-Ngam	590	460	1,050	887	+18.3

Note: Operational costs on the return leg are identical whether the vehicle is loaded or empty; the difference arises from foregone return-leg revenue under backhaul conditions. The reported percentages therefore represent an effective net-cost increase, not a change in operating expenditure.

The effective cost increase due to backhaul is calculated as follows:

$$\text{Effective cost increase (\%)} = \frac{C_t - C_b}{C_b} \times 100\%$$

Although the monetary cost of a return leg is identical whether the vehicle is loaded or empty, an empty return generates no freight revenue. The reported percentage increase therefore represents the share of round-trip cost attributable to non-revenue-generating backhaul movements, expressed relative to the baseline round-trip cost with a loaded return.

4.3 Structural sources of backhaul persistence

The results indicate that persistent backhaul inefficiency is driven by structural and organizational factors, rather than short-term market fluctuations. A central issue is information asymmetry at border crossings, where freight demand information is fragmented across shippers, brokers, and carriers. The absence of centralized or shared platforms limits operators' ability to identify and secure compatible return cargo, even when inbound demand exists.

Operator-level patterns further reveal that backhaul inefficiency is unevenly distributed across the logistics sector. As shown in Table 3, small and medium-sized logistics operators exhibit substantially higher backhaul frequencies than large operators. This concentration reflects structural constraints, including limited transport planning capacity, weaker bargaining power in negotiating return loads, and restricted access to freight information networks.

Coordination challenges compound these constraints. Operators reported limited trust and weak incentives to engage in collaborative transport planning, particularly in cross-border contexts characterized by regulatory uncertainty. Institutional variability at border crossings—such as inconsistent customs clearance times, documentation requirements, and enforcement practices—discourages advance commitment to return loads. Consequently, operators frequently adopt conservative planning strategies, prioritizing timely vehicle turnaround over capacity optimization. Together, these findings demonstrate that backhaul inefficiency is deeply embedded in the institutional and organizational structure of cross-border logistics systems.

Table 3. Backhaul frequency by operator size

Operator Category	**Share of Operators (%)**	**Backhaul Frequency (%)**
Small operators	46.3	29.4
Medium operators	38.7	22.1
Large operators	15.0	13.6

Note: Backhaul frequency refers to the proportion of return trips conducted without cargo.

Table 3 shows that backhaul inefficiency is disproportionately concentrated among small and medium-sized operators, which together account for the majority of logistics firms and exhibit markedly higher backhaul frequencies than large operators. This pattern highlights structural disparities in planning capability and access to freight information, reinforcing the role of organizational capacity and institutional context in shaping backhaul outcomes.

4.4 Performance of the transport planning system

The implementation of the proposed transport planning system resulted in substantial improvements in operational efficiency and vehicle utilization across the studied border crossings. By systematically matching available return cargo with existing outbound movements, the system reduced the incidence of empty return trips and improved overall transport performance without requiring changes to physical infrastructure.

As reported in Table 4, the planned scenarios reduced overall backhaul frequency from 23.6% under observed operations to 14.9%, representing a reduction of nearly 37%. This improvement indicates a significant enhancement in the utilization of existing transport capacity. At the same time, average vehicle utilization increased from 68.2% to 82.5%, reflecting more efficient deployment of freight vehicles across round trips.

Cost efficiency also improved under the planned scenarios. The average transportation cost per trip declined by approximately 14%, driven primarily by the reduction in empty return movements rather than changes in route length or travel time. In addition, fleet turnaround time decreased from 2.8 days to 2.2 days, enhancing operational flexibility and increasing the availability of vehicles for subsequent assignments.

Importantly, these performance gains were achieved through practical planning rules rather than complex optimization algorithms or advanced digital infrastructure. This highlights the feasibility of the proposed system for small and medium-sized logistics operators operating under institutional and resource constraints typical of cross-border environments.

Table 4. Comparison of observed transport outcomes and planned scenarios

Indicator	Observed Operations	Planned Scenario	Improvement (%)
Backhaul frequency (%)	23.6	14.9	−36.9
Vehicle utilization (%)	68.2	82.5	+20.9
Avg. cost per trip (USD)	605	520	−14.0
Fleet turnaround time (days)	2.8	2.2	−21.4

Note: Planned scenario results are generated using the proposed transport planning system based on improved cargo matching and capacity utilization.

Table 4 demonstrates that targeted transport planning interventions can yield simultaneous improvements in efficiency, cost, and operational flexibility. The reduction in backhaul frequency plays a central role in driving these gains, confirming that improved planning—not additional infrastructure—is the primary mechanism underlying performance improvements.

4.5 Comparative outcomes between border crossings

Comparative analysis reveals that the effectiveness of the transport planning system varies across border crossings, reflecting differences in freight demand structure, institutional conditions, and operational feasibility. While both Chong Mek and Chong Sa-Ngam benefited from the planning intervention, the magnitude of improvement differed across performance dimensions.

As shown in Table 5, Chong Mek exhibited a higher backhaul reduction potential (41.2%) compared with Chong Sa-Ngam (32.7%). This difference is largely attributable to more stable inbound demand patterns and greater opportunities for cargo aggregation at Chong Mek. Consequently, improvements in vehicle utilization and cost efficiency were also more pronounced at this crossing.

Specifically, vehicle utilization at Chong Mek improved by 22.8%, exceeding the 18.5% improvement observed at Chong Sa-Ngam. Similarly, the average cost reduction per trip was higher at Chong Mek (15.6%) than at Chong Sa-Ngam (12.3%). Despite these differences, both border crossings demonstrated positive performance gains, indicating that the planning framework is adaptable across heterogeneous cross-border contexts.

The comparative results underscore that local demand characteristics and institutional conditions shape the attainable efficiency gains from transport planning interventions. Rather than applying uniform solutions, effective backhaul reduction strategies require tailoring to the specific operational and governance environment of each border crossing.

Table 5. Comparative planning outcomes between Chong Mek and Chong Sa-Ngam

Indicator	Chong Mek	Chong Sa-Ngam
Backhaul reduction potential (%)	41.2	32.7
Improvement in vehicle utilization (%)	22.8	18.5
Cost reduction per trip (%)	15.6	12.3
Planning feasibility assessment	High	Moderate

Note: Differences in outcomes reflect variations in inbound demand stability, cargo aggregation potential, and institutional conditions at each border crossing.

Table 5 illustrates that while the proposed transport planning system delivers efficiency gains at both border crossings, contextual factors significantly influence performance outcomes. Chong Mek's higher feasibility and more stable demand environment enable greater backhaul reduction, whereas Chong Sa-Ngam's more fragmented inbound flows constrain the achievable gains.

4.6 Summary of key findings

Overall, the results provide clear evidence that backhaul inefficiency at cross-border checkpoints is economically significant, structurally embedded, and responsive to targeted planning interventions. The empirical analysis confirms that a substantial proportion of freight movements at both Chong Mek and Chong Sa-Ngam consist of empty return trips, indicating persistent underutilization of transport capacity despite strong outbound demand.

The findings demonstrate that backhaul inefficiency is not driven by a lack of return demand, but by coordination failures, information asymmetry, and limited transport planning capacity. Cost analysis shows that empty returns impose a considerable financial burden on logistics operators by increasing unit transportation costs and reducing effective fleet availability, thereby functioning as a structural cost driver rather than a temporary operational issue.

At the organizational level, backhaul inefficiency is disproportionately concentrated among small and medium-sized logistics operators, reflecting unequal access to freight information, bargaining power, and planning resources. These constraints are reinforced by institutional uncertainty at border crossings—such as variability in customs procedures and regulatory enforcement—which discourages advance commitment to return loads and promotes conservative planning behavior.

Importantly, the results indicate that significant efficiency gains can be achieved through context-sensitive transport planning. The proposed planning system substantially reduced backhaul frequency, improved vehicle utilization, and lowered transportation costs without reliance on complex optimization algorithms or large-scale infrastructure investment. While the magnitude of improvement varies across border crossings, positive outcomes are observed in all cases, underscoring the adaptability of the planning framework to heterogeneous cross-border environments.

Taken together, the findings establish a strong empirical basis for the subsequent discussion by demonstrating that backhaul inefficiency is both a systemic problem and a solvable one. The results highlight the central role of transport planning mechanisms in improving cross-border logistics performance and provide clear justification for shifting policy and managerial attention toward planning-based interventions.

5. DISCUSSION

5.1 Reinterpreting backhaul inefficiency as a structural planning problem

The findings reposition backhaul inefficiency as a structural planning and coordination problem rather than a simple outcome of insufficient freight demand. Earlier studies often explained empty return trips as the result of market imbalance or asymmetric freight flows [52, 53]. Yet, the empirical evidence from Chong Mek and Chong Sa-Ngam shows that return demand does exist—it is simply not being effectively utilized. Fragmented information, limited planning capacity, and institutional uncertainty prevent inbound cargo from being systematically matched with returning vehicles, reinforcing systemic inefficiency rather than reflecting temporary demand fluctuations [54, 55].

This interpretation aligns with system-oriented logistics research, which emphasizes that inefficiency arises when transport decisions are optimized at the firm level but remain uncoordinated at the network level. While decentralized decisions may be rational for individual firms, they often generate collective inefficiency in the absence of shared planning mechanisms [56, 57]. The persistence of backhaul at both border crossings supports the view that empty trips are embedded in organizational routines and governance structures—particularly in cross-border settings where regulatory complexity discourages advance coordination [58, 59].

Institutional uncertainty further reinforces this pattern. Variability in customs procedures, border enforcement, and regulatory alignment shortens planning horizons and encourages conservative carrier behavior [60, 61]. By empirically linking these institutional conditions to observed backhaul outcomes, the study advances existing theory by identifying planning capability—including access to freight information, coordination mechanisms, and practical planning tools—as a mediating mechanism between institutional context and operational performance [62, 63].

5.2 Cost implications and the economics of empty trips

The cost analysis demonstrates that backhaul inefficiency functions as a structural cost driver in cross-border logistics systems. Unlike variable cost pressures such as fuel price volatility or congestion, empty return trips systematically increase unit transportation costs and reduce effective fleet availability. This finding is consistent with logistics cost frameworks that emphasize capacity utilization and asset productivity as central determinants of transport efficiency [64, 65].

Operators' willingness to accept empty returns reflects a rational response to uncertainty rather than managerial oversight. Faced with unpredictable border clearance times, regulatory risks, and limited visibility of inbound freight, operators prioritize schedule reliability over potential cost savings from uncertain return loads. Such behavior is consistent with bounded rationality under institutional constraints [66, 67].

At the system level, however, these individually rational decisions accumulate into persistent inefficiency. Firm-level risk avoidance perpetuates network-wide underutilization of transport capacity, explaining why market incentives alone are insufficient to eliminate backhaul without complementary planning and coordination mechanisms [54, 68].

5.3 Organizational capacity and inequality in logistics performance

The results reveal clear organizational asymmetries in cross-border logistics performance. Small and medium-sized operators face significantly higher backhaul frequencies, reflecting structural disadvantages in access to freight information, bargaining power, and planning resources. This pattern resonates with research on logistics fragmentation in emerging economies, where efficiency gains are unevenly distributed across firm sizes due to differences in organizational capacity and network embeddedness [69, 70].

By linking backhaul outcomes directly to planning capacity, the study supports institutional and capability-based explanations of logistics performance. Prior research emphasizes that inefficiency cannot be fully understood without considering firm-level resources, coordination capability, and information access—particularly in markets dominated by small operators [67, 71].

Rather than treating backhaul inefficiency as a uniform sector-wide problem, the findings suggest that targeted planning interventions for smaller operators—such as shared planning tools, information platforms, or cooperative coordination arrangements—can generate disproportionately large efficiency gains. This insight extends system-oriented logistics theory by showing how micro-level organizational constraints translate into persistent network-level inefficiencies, with clear implications for both theory development and policy design [62, 72].

5.4 Effectiveness of planning-based interventions

A central contribution of this study is its demonstration that meaningful efficiency gains can be achieved through relatively simple and context-sensitive transport planning mechanisms. The proposed planning system significantly reduced backhaul frequency, increased vehicle utilization, and lowered transportation costs—without relying on complex optimization algorithms or advanced digital infrastructure. This finding directly challenges the assumption in parts of the logistics literature that substantial efficiency improvements necessarily require high technological sophistication or fully automated decision systems [73, 74].

Instead, the results underscore the central role of planning logic, particularly systematic cargo matching and coordination between outbound and inbound flows. Consistent with system-oriented transport planning research, the findings show that coordination and information alignment alone can generate substantial performance improvements—even in the absence of advanced technology [54, 75].

By emphasizing incremental and implementable planning interventions, the study bridges the gap between advanced logistics theory and operational practice in resource-constrained environments. The results complement emerging research on adaptive and incremental logistics innovation, which highlights feasibility, institutional fit, and organizational capacity as critical determinants of sustainable efficiency gains [51, 76].

5.5 Context sensitivity and cross-border heterogeneity

The comparative analysis of Chong Mek and Chong Sa-Ngam underscores the importance of context sensitivity in logistics planning. While the planning system produced efficiency improvements at both border crossings, the magnitude of these gains varied depending on local demand stability, cargo aggregation potential, and institutional conditions. These differences show that planning effectiveness depends on localized operational and governance environments rather than universally applicable rules [77].

From a theoretical standpoint, this finding supports contingency-based approaches in logistics and operations management, which argue that performance outcomes hinge on the alignment between organizational practices and contextual conditions rather than the application of standardized best practices [78, 79]. In cross-border freight systems, such alignment is shaped not only by market demand but also by institutional arrangements and operational uncertainty specific to each border location.

By empirically demonstrating that similar planning mechanisms yield differentiated outcomes across border crossings, the study reinforces the importance of contextual fit in transport planning. This result is consistent with research emphasizing that cross-border logistics efficiency emerges from localized interactions between demand structures, institutional environments, and planning capacity, rather than from uniform system design alone [1, 80].

5.6 Implications for policy and practice

The findings carry important implications for both policy and managerial practice.

5.6.1 Policy perspective

Infrastructure investment alone is insufficient to address cross-border logistics inefficiency. While physical connectivity remains a necessary foundation, efficiency gains increasingly depend on institutional coordination and planning support mechanisms. This insight aligns with policy-oriented logistics research that highlights the role of soft infrastructure—such as information systems, coordination platforms, and governance arrangements—in improving logistics performance once basic physical connectivity is established [4, 61].

5.6.2 Managerial perspective

The study highlights the value of planning-based approaches for reducing backhaul and improving cost efficiency. Logistics operators, particularly small and medium-sized firms, can benefit from shared planning platforms, cooperative arrangements, and decision-support tools that enhance visibility of return cargo opportunities. Importantly, the findings show that such improvements can be achieved without substantial capital investment, making them accessible to a wide range of operators. This conclusion is consistent with management research demonstrating that coordination and process innovation can generate significant performance gains even under resource constraints [72].

5.7 Positioning the study within the literature

Overall, this study advances logistics and supply chain literature by integrating institutional analysis, organizational capacity, and transport planning within a unified empirical framework. By grounding theoretical insights in observed cross-border freight operations, the research bridges the gap between abstract models of logistics efficiency and the operational realities of transport systems in emerging economies. This integrative perspective responds to long-standing calls to move beyond siloed operational or technological explanations and to incorporate governance and organizational dimensions into logistics performance analysis [56].

By conceptualizing transport planning capacity as a mediating mechanism between institutional conditions and operational outcomes, the study contributes to both theory-driven and applied logistics research. It demonstrates that system-level efficiency improvements can be achieved through context-sensitive planning interventions rather than technological sophistication alone, reinforcing the relevance of adaptive and institutionally grounded approaches to logistics system design [62].

6. CONCLUSION AND FUTURE RESEARCH

This study explored the persistent problem of backhaul inefficiency in cross-border road freight transportation, focusing on two major Thai border crossings—Chong Mek and Chong Sa-Ngam. By weaving together operational freight data, institutional analysis, and transport planning perspectives, the research shows that backhaul inefficiency is not simply the result of demand imbalance. Instead, it emerges as a structural consequence of fragmented information, limited planning capacity, and institutional uncertainty embedded within cross-border logistics systems.

The empirical findings reveal that empty return trips account for a significant share of freight movements, imposing heavy economic costs on logistics operators. These costs extend beyond direct financial losses, reducing fleet availability and constraining operational flexibility. Importantly, the persistence of backhaul despite existing inbound demand highlights that coordination failures—rather than market scarcity—are the primary source of inefficiency.

A key contribution of this study lies in demonstrating the power of planning-based interventions. The proposed transport planning system reduced backhaul frequency, improved vehicle utilization, and lowered transportation costs—without requiring complex optimization algorithms or large-scale infrastructure investments. These outcomes underscore the practical feasibility of incremental, context-sensitive planning solutions, particularly for small and medium-sized logistics operators working under institutional and resource constraints. This emphasis on implementable planning logic is consistent with recent sustainability-oriented planning research that highlights feasibility, inclusiveness, and institutional alignment as critical determinants of effective system improvement [81, 82].

From a theoretical perspective, the study reframes backhaul inefficiency as a planning and governance challenge rather than a purely operational or market-driven issue. By explicitly linking institutional conditions, organizational capacity, and transport planning mechanisms within a unified empirical framework, the research contributes to a more nuanced understanding of cross-border logistics performance in emerging-economy contexts. This integrative view resonates with contemporary sustainable development research that emphasizes the interaction between organizational capabilities, governance structures, and system-level outcomes [83].

The findings carry important implications for both policy and practice. Policymakers should complement infrastructure development with initiatives that strengthen planning capacity, enhance information sharing, and support cooperative logistics arrangements at border crossings. For practitioners—especially small and medium-sized operators—the results highlight the value of systematic planning approaches for improving capacity utilization and cost efficiency without heavy capital investment. Such planning-centered approaches align with broader sustainability and development perspectives that prioritize soft infrastructure and coordination mechanisms alongside physical investment [84].

Several limitations point to future research directions. The analysis focuses on two border crossings, limiting statistical generalization. Expanding the framework to other border contexts or regional corridors could test broader applicability. The evaluation emphasizes short-term operational outcomes; longitudinal studies are needed to assess behavioral adaptation and the durability of efficiency gains. Finally, while this study prioritizes practical planning logic, future research could explore advanced data-driven tools—such as real-time freight platforms, machine learning–based demand forecasting, or cooperative digital marketplaces—to enhance planning effectiveness under diverse institutional conditions, as increasingly discussed in recent sustainable development and planning literature [85].

In conclusion, this research demonstrates that backhaul inefficiency in cross-border logistics is both systemic and solvable. By shifting attention from infrastructure expansion toward planning capacity and coordination mechanisms, the study offers a viable pathway for improving logistics performance and sustainability. The findings encourage a reorientation of future research and policy toward planning-centered solutions that align economic efficiency with institutional realities [80-85].

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