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Enhancing Island–Mainland Connectivity in Estonia: Organizational and Sustainability Challenges

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ABSTRACT: In this paper we analyse ferry connectivity between Estonia's mainland and major islands, focusing on structural drivers of service performance, costs, and sustainability. Using operational data and institutional analysis, we show that outcomes are shaped primarily by route characteristics, seasonality, vessel requirements, and infrastructure lock-in rather than operational efficiency alone. The current reliance on uniform large ice-class ferries and terminals tailored to existing vessels has reduced system flexibility and constrained decarbonisation. Drawing on selected international practices with relevance to Estonia, the analysis identifies four strategic priorities—measurable service levels, clearer institutional responsibility, more flexible funding, and diversified fleet deployment—and demonstrates that right-sized vessels and modular capacity can improve utilisation, reduce energy demand at terminals, enhance resilience to variable water levels, and support phased electrification. Strengthening island connectivity therefore requires integrated planning of services, vessels, and infrastructure under clear governance frameworks.

1 INTRODUCTION

Ferry services are lifelines for island and coastal populations, providing essential links that sustain both economic stability and social cohesion in the absence of fixed connections [1]. In systems serving inhabited islands, operators must balance reliability, affordability, and adequate service frequency while coping with pronounced seasonal demand fluctuations and harsh operating conditions[2] [3]. These services play a critical role in mitigating structural disadvantages such as limited labour markets and restricted access to essential services in peripheral regions [4].

At the same time, ferry systems face growing pressure to reduce greenhouse gas emissions and improve energy efficiency. The International Maritime Organization has set a target of cutting shipping emissions by at least 50% by 2050, supported by short-term efficiency measures and pathways toward low- and zero-carbon technologies [3] [4]. In Europe, the Sustainable and Smart Mobility Strategy and the 'Fit for 55' package call for substantial decarbonisation of maritime transport by mid-century, with zero-emission vessels expected to enter regular service during the 2030s [5] [6].

In this context, this paper pursues three objectives. First, it assesses the strengths and weaknesses of Estonia's island–mainland connectivity system, covering both the major routes serving Saaremaa and Hiiumaa and the smaller island links. Second, it draws on selected international experiences to contextualise Estonia's governance arrangements, service provision, and sustainability challenges. Third, it proposes pathways for improving ferry services by integrating international lessons with national policy priorities and

European climate objectives. The analysis uses multiple sources. Operational data from the largest ferry operator TS Laevad covering the period 2017–2023 provide insight into traffic volumes, route performance, and contractual compliance. Procurement documents from the Estonian National Register are reviewed to identify recurrent issues such as delays and unclear requirements including ambiguities in technical specifications, environmental criteria, and responsibility allocation.

2 ISLAND CONNECTIVITY IN ESTONIA

2.1 *Governance and Service Provision in Estonia*

It can be argued that Estonia's ferry connections to the main islands are currently stable, flexible, and user-friendly, providing a solid foundation for future development. The fleet includes four modern ice-class ferries Leiger, Tõll, Piret and Tiiu delivered in 2016 and 2017 [7] as well as smaller vessels Ormsö, Kihnu Virve, and Soela, delivered between 2015 and 2017 [8], that serve smaller islands under separate contracts. These vessels ensure resilience across seasonal weather conditions. Two reserve ships are available to cover peak demand during the busy summer months, as well as to substitute vessels during maintenance periods and technical failures.

Operational data from two main operators (TS Laevad OÜ and Kihnu Veeteed AS) show that passenger and vehicle numbers have steadily increased across all routes between 2017 and 2023. This growing demand reflects the wider socio-economic role of ferries, with tourism and commuting being actively promoted, and the maintenance of the viability of island communities requiring the integration of certain services with the mainland. During high-demand periods, reserve capacity helps reduce congestion, maintaining service reliability and strengthening confidence in the network. Ticketing has also become more accessible and flexible. The digital platform praamid.ee [9] allows people (for both passengers and vehicles) to make reservations in advance, and to modify bookings without cost or use the same ticket for a later departure, reducing waiting times at ports and improving the overall passenger experience. Taken together, these operational strengths demonstrate that Estonia has achieved reliability and accessibility on a par with leading ferry-dependent nations. However, we argue that this success rests on a fragile foundation. Without clearer governance and long-term fleet planning, inefficiencies and limited transparency threaten to erode the service. Moreover, the absence of a long-term strategy for vessel replacement or low-emission technologies means that, despite the fleet's relatively young age, renewal and decarbonisation pathways remain uncertain.

Despite the central role of the ferry network, Estonia's regulatory and institutional framework remains fragmented (Figure 1). Ferries are formally classified as public transport under the Public Transport Act [10], but they also function as maritime infrastructure directly linked to the national road system. This dual classification has created overlapping responsibilities with vessel procurement and operation falling under the Ministry of Climate and its agencies, while port infrastructure is managed separately by the state-owned company Saarte Liinid AS. Overall service provision is coordinated by the Ministry of Regional Affairs and Agriculture through the Public Transport Department. The result is a system whereby procurement, infrastructure investment, and service planning are poorly aligned, making it difficult to implement coherent long-term strategies. No single authority is responsible for integrating these elements, and transparent monitoring mechanisms remain limited.

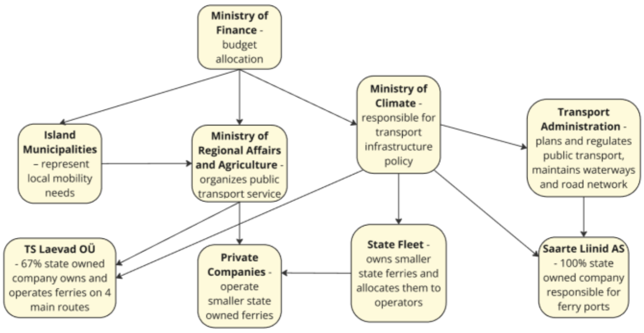

Figure 1. Institutional structure of ferry service governance in Estonia. Arrows indicate funding flows, regulatory responsibilities, and operational relationships between government bodies, state-owned entities, municipalities, and ferry operators.

Unlike in some other countries such as Scotland (discussed in section 3) where performance audits and strategic documents are publicly available, Estonia lacks an accessible and transparent framework for monitoring service quality and contract compliance. Indicators for these parameters remain few and ambiguous, a shortcoming that has been highlighted in recent studies [11]. Comparable dilemmas have been recognised in Finland, where policymakers have concluded that it is politically impossible to simultaneously increase competition, maintain service levels, and reduce public expenditure without major institutional reforms [12].

Service provision is organised through public service contracts. On the two main routes (Virtsu–Kuivastu and Rohuküla–Heltermaa [13]), contracts typically run for seven years, while smaller routes such as Ruhnu, Munalaid-Kihnu, and Sõru–Triigi routes, are tendered for five years [14]. Estonia's small market restricts competition: only a handful of operators are capable of bidding, with tender documents often presupposing that bidders already own suitable vessels. This ensures continuity but reduces the scope for innovation or alternative solutions. The relatively short contract durations (7 years for main lines and 5 years for small islands) limit the horizon for strategic planning, since major fleet investments usually require a 15–20-year amortization period. As a result, procurement processes structurally favour operators with existing fleets and constrain the development of a coherent long-term fleet renewal strategy.

The service model is highly car-oriented, with ferry capacity and timetables optimised for vehicle transport rather than for public transport integration. Alternative modes, such as coordinated bus services or cycling infrastructure, remain underdeveloped, while the needs of passengers with reduced mobility are insufficiently addressed. Contract specifications define vessel parameters and frequency but omit systematic CO_2 accounting or binding emission-reduction targets. Compared with countries such as Norway, where environmental requirements are embedded in contracts and have accelerated the adoption of hybrid and electric ferries [15], Estonia's model remains focused on basic accessibility and short-term cost control. Technological choices must also be evaluated against both environmental and economic criteria. Without integrated consideration of these parameters, Estonia risks high fuel consumption, stranded assets, and missed opportunities to align ferry operations with climate policy [16]. Ticketing processes demonstrate similar integration constraints. For the main routes, the praamid.ee system offers flexible and user-friendly booking options, while smaller island services remain fragmented, with tickets sold through four separate providers. This reflects the broader lack of a unified framework for service delivery and underscores the institutional divisions that complicate governance.

Fleet ownership further illustrates these structural weaknesses. In 2014, the government brought the main island routes under direct state control by commissioning four new ferries through the fully state-owned company AS Port of Tallinn, ending long-term cooperation with AS Saaremaa Laevakompanii. A new subsidiary of AS Port of Tallinn, OÜ TS Laevad, was established to operate them [17] [7]. The ships entered service in 2016–2017, not because the previous fleet was obsolete, but to secure strategic state ownership. In 2018, the AS Port of Tallinn was partially privatised, leaving ferries procured as state assets tied to a company with private shareholders [18]. This hybrid model blurred responsibilities, reduced transparency, and complicated accountability for fleet renewal.

Ongoing disputes over a planned fifth vessel highlight these problems. Intended initially as a hydrogen-powered ferry, the project was adjusted after funding constraints, but tenders in both 2024 and 2025 failed to attract bids [19] [20]. As a result, no vessel has been procured to date. Although the aim was to replace an ageing reserve vessel, the absence of a coherent renewal strategy left procurement criteria misaligned with environmental targets. The result is a system where strategic policy goals and tendering practice pull in different directions.

Finally, Estonia's monitoring framework remains narrowly focused on passenger volumes and frequency, offering little information on fuel use, emissions, or efficiency. This absence of systematic performance data makes it difficult to assess whether public investments are meeting decarbonisation and accessibility goals. By contrast, international practice shows that transparent monitoring frameworks are essential for balancing affordability with environmental and social objectives. Italy's National Strategy for Inner Areas, for example, links transport planning with wider socio-economic development strategies, underlining that accessibility in peripheral regions cannot be secured through infrastructure investment alone [1]. Procurement processes for new ferries have been marked by delays and disputes, highlighting the need for clearer contractual frameworks and accountability mechanisms.

While the current operational model delivers reliable day-to-day service, it is largely oriented toward short-term continuity rather than long-term system optimisation.

2.2 *Service Performance and Demand Trends*

Service performance is defined by passenger numbers, vehicle traffic, and seasonal demand. These patterns reveal whether capacity is sufficient and how well services meet the mobility needs of island communities. Estonia's island–mainland ferry network is dominated by a small number of major routes alongside medium-scale and lifeline routes. Importantly, route lengths vary substantially across the network, ranging from short crossings of only a few kilometres to open-sea connections exceeding 100 km (Figure 2). The two major routes are Virtsu-Kuivastu (7 km) and Rohuküla-Heltermaa (22 km), which carry the vast majority of passengers.

Medium-scale routes include Rohuküla–Sviby (10 km), Munalaid–Kihnu (16.5 km), and Triigi–Sõru (16.5 km), which provides a direct Saaremaa–Hiiumaa connection. Beyond the two main routes, Estonia's ferry network thus comprises two distinct categories of smaller routes: medium-scale inhabited island routes (Kihnu, Vormsi and the Sõru–Triigi link) and very low-volume lifeline services to micro-islands such as Abruka, Manija and Ruhnu, which differ fundamentally in demand, operational conditions, and service objectives.

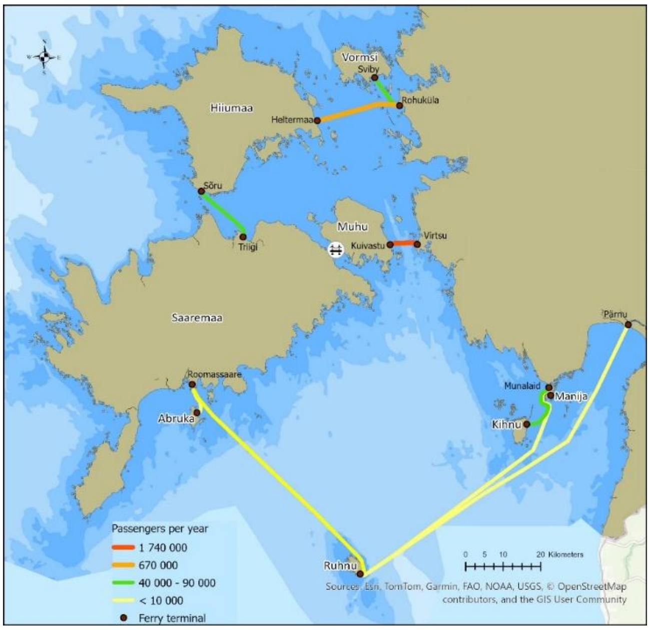

Figure 2. Main island–mainland ferry connections in Estonia. Annual passenger volumes for each route in 2023 are shown. Muhu and Saaremaa are connected by a permanent road link, so the Virtsu–Kuivastu ferry effectively provides access to both islands. Passenger volumes on the Roomassaare–Abruka and Munalaid–Manija routes are very low and are therefore not considered in the subsequent quantitative analysis.

Among the lifeline routes, Ruhnu maintains very low but socially critical traffic volumes and is accessible by ferry only during the summer season, with services operating on a rotating basis from Munalaid (66 km), Pärnu (103 km), and Roomassaare (77 km). During winter, access is provided exclusively by air transport. Roomassaare–Abruka (7 km) and Munalaid–Manija (0.8 km), by contrast, are served year-round by water.

Between 2017 and 2023, passenger and vehicle numbers have risen on all the routes. On the Virtsu–Kuivastu route, traffic increased steadily for both passengers and vehicles (Figure 3). The Rohuküla–Heltermaa route shows a similar trend, with total passenger traffic up by 28%, vehicle transport by 49%, and resident ticket sales by 81%. A comparable upward trend was also observed across all medium-scale and lifeline routes

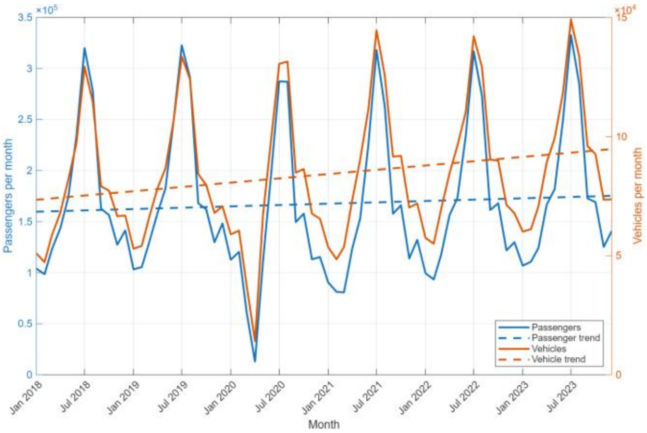

Figure 3. Monthly passenger and vehicle volumes on the Virtsu–Kuivastu route (2018–2023). Passenger numbers range from approximately 100 000 in winter to over 300 000 during summer peaks, while vehicle volumes increase from about 50 000 to nearly 150 000 per month. Dashed lines show linear trends fitted to monthly data. The sharp decline in 2020 reflects reduced travel demand during the COVID-19 pandemic.

Despite overall growth, demand remains highly seasonal. Summer peaks push vessels to near full capacity on all routes while winter traffic drops sharply, leaving large ice-class ferries underutilised. This mismatch results in higher costs per passenger in winter raising questions about the efficiency of operating large vessels year-round when such capacity is only required for a few months annually. Weekly and daily variations are also highly variable. On the Rohuküla–Heltermaa route (Figure 4), departures concentrate on Fridays and returns on Sundays. Comparable weekend peaks are also seen on other routes.

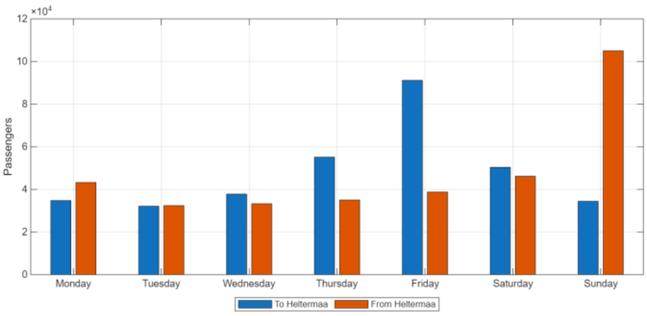

Figure 4. Total passenger volumes by weekday and travel direction in 2023. Higher inbound volumes on Fridays and outbound volumes on Sundays reflect typical weekend travel patterns between the mainland and all the islands.

Overall, these demand patterns show that capacity utilisation fluctuates considerably over time. Consequently, unit costs are influenced not only by operational efficiency but also by structural factors such as route length, vessel characteristics, and demand variability. This interaction is illustrated in the combined cost-per-passenger analysis presented in Figure 5.

There are significant cost and revenue differences between the two main routes, largely driven by their contrasting lengths and operating conditions. Virtsu–Kuivastu is a short crossing with high service frequency and consistently strong demand, generating relatively high ticket revenues and lower unit costs. By contrast, the Rohuküla–Heltermaa connection spans a much longer distance and requires larger ice-class vessels to ensure year-round operation, resulting in substantially higher costs per passenger. Although both routes rely on state subsidies to remain affordable, this comparison illustrates in simple terms how route length and operating conditions directly influence financial sustainability.

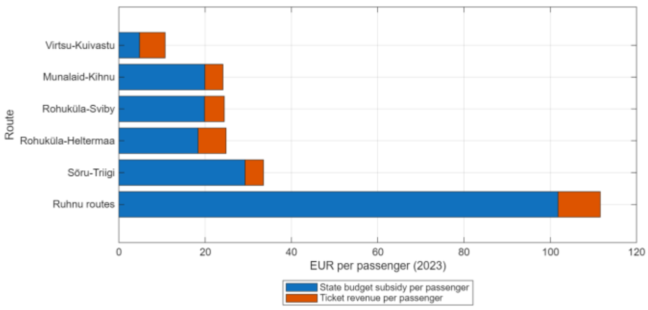

Figure 5. Total operating cost per ferry route in 2023, showing the proportion of costs covered by ticket revenue and the proportion financed through state budget subsidies (€).

On the smaller island routes, ticket revenues cover only a very small proportion of operating costs, indicating that these services function primarily as lifeline connections rather than market-based transport. Ruhnu represents an extreme case, with minimal demand and very high cost per passenger. By contrast, although passenger numbers on the Rohuküla–Heltermaa route have increased, unit costs remain significantly higher than on Virtsu–Kuivastu due to the longer crossing distance. This disparity is further accentuated by seasonal underutilisation, where large vessels operate at low occupancy in winter, while summer peaks briefly push capacity to its limits.

Smaller connections such as Munalaid–Kihnu, Rohuküla–Sviby, Ruhnu routes, and Sõru–Triigi operate at much lower passenger volumes, functioning primarily as lifeline services for local residents. Their operation under shorter, five-year public service contracts reflects higher vulnerability: limited demand reduces financial viability and places these routes lower in policy prioritisation. While they rely on smaller vessels adapted to local port conditions, service speeds are broadly aligned with the wider network. As vessel speed is a primary determinant of fuel consumption, operating at these speeds under low occupancy leads to disproportionately higher costs and emissions per passenger. This contrast highlights a broader challenge for Estonia's ferry system: whether fleet strategies can be diversified to balance efficiency and resilience across routes of very different scale.

The growth in vehicle transport has been steeper than passenger growth, pointing to a service model that primarily accommodates cars. Vehicle decks are often fully booked in summer, while passenger spaces remain underutilised. This autocentric focus reinforces dependence on private cars, partly because integration with bus and rail services remains weak. For people without cars—including those with reduced mobility—the accessibility of ferry travel is more limited, underscoring the need for stronger intermodal connections and inclusive design. International experience shows that ferry systems aligned with public transport networks can reduce car dependence and improve accessibility for all users [21] [22].

Overall, Estonia's ferry network demonstrates rising demand and strong user reliance, but also inefficiencies caused by seasonality, high operating costs, and car-dominated travel. Figure 3 and Figure 4 illustrate how daily and seasonal variations generate mismatches between capacity and actual demand, increasing fuel consumption and cost per passenger. While large ice-class vessels guarantee winter resilience, they sail with significant unused capacity outside the summer peak. In summer, demand exceeds vehicle deck capacity and requires reserve vessels, but in winter the same ships operate with low occupancy and high fixed costs. This imbalance undermines cost-effectiveness and highlights the need for long-term planning that better aligns vessel deployment with seasonal demand, while also integrating accessibility and environmental performance into procurement criteria. Together, these results suggest that observed cost differences are driven mainly by structural conditions rather than operational choices, providing the basis for the fleet and infrastructure challenges discussed in the following section.

2.3 *Fleet and infrastructure challenges*

Research in the Baltic context indicates that battery-electric ferries are best suited to short routes with adequate charging infrastructure, while diesel-electric hybrid vessels provide a practical transitional solution on routes where full electrification is not feasible [23]. Ferries powered by fuels such as LNG, hydrogen, or ammonia face significant technical and regulatory barriers [24]. These studies also highlight that electrification is most effective when combined with right-sized vessels and flexible deployment patterns, allowing smaller ferries to operate efficiently during off-peak periods while enabling higher service frequency during peak demand through modular capacity [25] [26]. Research in the context of the Baltic Sea indicates that fully electric and diesel-electric hybrid vessels are currently the most feasible alternatives to large diesel-powered ice-class ferries [27]. Smaller, right-sized vessels can reduce peak power requirements at terminals, making electrification more achievable in constrained grid environments and reinforcing the case for modular fleet configurations. Evidence from comparable island ferry systems further indicates that service configuration can be as important as vessel technology in reducing emissions: smaller vessels operated at higher frequency can achieve substantially lower CO_2 emissions per passenger and vehicle than larger ferries on the same connections, highlighting the potential of right-sized fleet deployment even within existing route structures [28].

Although TS Laevad introduced hybrid technology by converting the ferry Tõll in 2020 [29] operating on the Virtsu-Kuivastu route, the initiative has not been extended to other vessels. Empirical studies of in-port and island ferry services show that hybrid diesel-electric vessels achieve approximately 10–12% higher energy efficiency and corresponding CO_2 reductions compared with conventional full-diesel ferries, confirming the potential of hybrid retrofits as an effective interim decarbonisation measure [30]. The retrofit of Tõll demonstrated tangible benefits, including reported fuel savings of around 20% under typical operating conditions, yet this experience has not translated into a broader decarbonisation pathway. To date, neither the state nor operators have adopted a long-term fleet renewal strategy, leaving vessel replacement and decarbonisation largely reactive rather than planned.

Port infrastructure has similarly been adapted reactively to the existing vessels rather than on the basis of long-term planning. Most terminals have been rebuilt or modified to accommodate the current ferries, ensuring compatibility with the existing fleet but making it more difficult and costly to accommodate different vessel types in the future. Operational constraints further illustrate the limitations of the current fleet configuration: periodic low water levels on the Rohuküla-Heltermaa connection already affect service reliability, highlighting the vulnerability of deep-draft vessels and the potential advantages of smaller ferries with reduced draught, which would offer greater flexibility under variable water levels. As a result, investments in vessels and ports have not been strategically aligned, reinforcing the short-term and fragmented nature of Estonia's connectivity system.

3 STRATEGIES FOR IMPROVING ISLAND CONNECTIVITY

3.1 *Establish a National Framework for Measurable Service Levels*

Currently, Estonia lacks a unified strategy that addresses ferry service levels, fleet renewal, and environmental targets in a coherent manner. Implementing a national strategy would consolidate existing initiatives under a common framework, ensuring that operational objectives align with broader transport policy goals and sustainability commitments under the Fit for 55 initiative [5]. This strategy should also include clear service level agreements (SLAs) that define measurable quality standards, such as punctuality, vessel capacity, and emission reduction targets [31]

International experience shows that measurable service levels are central to ensuring consistency and transparency. In Norway, ferry service levels are determined using a structured framework that considers factors such as traffic intensity, vehicle waiting times, and route length [32]. In Sweden, ferry services are formally integrated into the road network, with Trafikverket's subsidiary Färjerederiet operating 40 routes nationwide. In the Stockholm archipelago, services are procured by Region Stockholm, which bundles more than 30 routes into long-term contracts; while price remains important, environmental and service quality requirements are gaining influence, including provisions for electrification [23]. In Scotland, service quality is systematically monitored through contractual reporting [33], with CalMac's performance data on punctuality, reliability and user satisfaction made publicly available [34]. These examples demonstrate how measurable frameworks allow policymakers to monitor outcomes and hold operators accountable, while giving users confidence in the reliability of services.

By contrast, Estonia has no uniform framework to define or monitor service performance. The absence of binding standards makes service planning reactive, fragmented, and difficult to evaluate. In Scotland, systematic performance audits have informed reforms in ferry governance and procurement, demonstrating the value of transparent monitoring frameworks for publicly funded services [22] [35]. An official and publicly accessible framework would prevent ad hoc decisions and support strategic planning across all publicly funded ferry routes.

Institutional fragmentation further complicates the situation. Previous research has shown that fragmented governance structures and weak inter-agency coordination hinder the development of systemic transport solutions [36] [37]. This insight also applies to Estonia, where overlapping responsibilities between ministries and operators make long-term planning difficult. Service level governance should therefore be clearly assigned to one lead body or supported through formal coordination mechanisms, ensuring that responsibilities are transparent and decisions consistent.

The national framework should also be directly linked to public procurement contracts and service delivery monitoring. Without predefined quality standards, it is difficult to compare services across different islands or evaluate operator performance. Clear expectations would help align operational outcomes with contractual obligations, reducing disputes and ensuring accountability. To make the framework meaningful, it must include measurable indicators such as minimum departure frequencies, maximum waiting times, seasonal coverage, punctuality thresholds, and user satisfaction metrics. Regular monitoring and public reporting would ensure accountability and allow adjustments based on actual performance. Service level definitions should be applied equitably, while still accounting for the specific needs of different islands. Categorising routes—for example, distinguishing between major islands and small or remote islands—could help tailor expectations without compromising comparability. A structured, transparent system would promote fairness across regions and support informed policy development.

In summary, Estonia should move from an ad hoc and fragmented system towards a national framework that establishes binding, measurable, and transparent service levels. Drawing on international examples from Norway, Sweden, and Scotland, such a framework would help align ferry operations with national transport policy, strengthen accountability, and provide island communities with more reliable and equitable connectivity. Unlike in these countries, however, Estonia also operates routes to very small islands with only a handful of permanent residents. For such cases, international best practice offers limited guidance, and Estonia needs to develop its own context-specific minimum service standards to ensure fair and sustainable access. Recent research has already proposed an operational model for defining service levels for Estonian small islands, including differentiated categories such as daily, scheduled, invitation-only, and tourism-based services, which could provide a practical basis for national policy development [11]. Implementing defined service levels in practice requires procurement and contract structures that actively incentivise service quality and efficient asset utilisation, reinforcing the need for analysis-led rather than reactive decision-making.

3.2 *Reduce Institutional Fragmentation and Clarify Responsibilities*

A broader OECD International Transport Forum (ITF) review of Estonia's transport sector, including island ferry connectivity, similarly concludes that infrastructure decisions are often taken before systematic analysis, reinforcing reactive investment patterns and weakening long-term strategic planning capacity [38]. The division of responsibilities between the Ministry of Climate, the Ministry of Regional Affairs and Agriculture, and various state-owned companies complicates strategic planning and investment coordination in Estonia. As highlighted in previous sections, the absence of a unified framework for service levels makes it difficult to align operational outcomes with national policy goals. Without clear institutional leadership, planning remains vulnerable to overlapping mandates and inconsistent priorities.

In several countries, ferry routes are formally integrated into the national transport network, enabling more coherent planning, stable funding, and clearer institutional responsibility [2] [27] [39]. International practice demonstrates that strong institutional coordination is a precondition for reliable and sustainable ferry services. Evidence from the Finnish archipelago further shows that ferry services are treated as a public service obligation rather than a market-based activity, with long-term state support enabling stable planning and sustained accessibility for remote islands. This institutional commitment has been identified as a key factor behind the relatively well-functioning ferry network in Pargas, Finland, despite low population densities and high operating costs [40]. In Norway, ferry governance is consolidated under the Norwegian Public Roads Administration, which sets clear service level requirements and ensures that procurement aligns with both accessibility and environmental objectives [41]. Sweden has adopted a dual approach: Trafikverket manages the national road-ferry network directly through its subsidiary Färjerederiet, while Region Stockholm procures archipelago services through bundled long-term contracts that increasingly emphasize environmental criteria such as electrification [23]. Beyond Europe, similar governance challenges have been identified in North America. A review by the Michigan Department of Transportation concludes that ferry access for island residents must be treated as a public service obligation requiring sustained state-level responsibility, rather than fragmented local arrangements [42]. Overall, these examples reinforce the need for a clear institutional owner of island–mainland connectivity in Estonia, with defined accountability for long-term service performance and investment planning. This approach would also facilitate the implementation of sustainable procurement criteria, promoting the acquisition of hybrid or electric vessels to reduce greenhouse gas emissions, as demonstrated by recent initiatives in Scotland and Sweden [43] [44].

3.3 *Introduce a More Flexible and Needs-Based Funding Model*

A flexible funding model that considers seasonal demand variations and route-specific cost structures could improve both financial sustainability and operational efficiency in Estonia. The current approach, where subsidies are allocated primarily on the basis of contractual commitments, leaves little room to adjust to unexpected demand shifts or to incentivize innovation. This rigidity is particularly problematic in a context where traffic volumes fluctuate strongly between summer peaks and winter lows, and where smaller islands often face higher unit costs due to low passenger volumes.

Affordability mechanisms such as Scotland's Road Equivalent Tariff, which aligns ferry fares with comparable road travel costs, illustrate how pricing policy can improve accessibility for island residents when embedded in a wider public service framework led by Transport Scotland [45]. International experience also shows that differentiated pricing and subsidy allocation can be designed on an economic basis rather than uniform contractual rules. In Norway, Ramsey pricing principles—where higher-demand routes contribute more to subsidising socially necessary low-demand services—are used to balance affordability and efficiency across routes with very different demand levels [46]. This suggests that Estonia could similarly explore fare structures or targeted subsidies that better reflect residents' mobility needs, rather than relying solely on uniform contractual pricing.

International practice illustrates several ways in which funding design can improve outcomes. In Norway, subsidy allocation explicitly accounts for route characteristics and demand patterns, ensuring that high-cost connections to small islands remain affordable, while shorter and more heavily used routes are operated at higher frequencies [46].In Washington State, targeted capital funding has been used to accelerate the introduction of hybrid-electric ferries and terminal electrification, demonstrating how financial incentives can be linked directly to environmental objectives [47]. Both cases show that flexibility in funding models can help balance efficiency, equity, and sustainability goals. Similar findings are reflected in earlier studies, which show that targeted funding mechanisms can incentivize operators to adopt low-emission vessels and optimize service frequency to match demand fluctuations [15] [33].

For Estonia, a reformed funding model could include performance-based subsidies, rewarding operators who meet predefined targets related to service quality, punctuality, and emission reduction. At the same time, subsidies should reflect seasonal and geographic variations: major routes to Saaremaa and Hiiumaa may justify higher baseline support due to their strategic importance, while smaller island routes could be subsidized on the basis of minimum service guarantees. Such differentiation would align funding more closely with actual mobility needs, rather than relying solely on uniform contractual arrangements.

Addressing seasonality requires not only differentiated subsidies but also flexible service models and capacity management strategies that can adapt to fluctuations in demand, a challenge emphasized in international studies of island ferry systems [21] [23]. Options include using modular fleets that allow smaller vessels to operate in off-peak periods, adjusting timetables to better match passenger flows, and introducing contractual mechanisms that enable temporary increases in sailings during peak tourist months. Earlier research on archipelago transport systems shows that pronounced seasonality is a structural characteristic rather than a temporary imbalance, leading to persistent inefficiencies in capacity utilisation [25]. Consequently, seasonality requires not only adaptive service planning but also flexible resource allocation and structural responses in fleet and funding models. By embedding these principles in funding arrangements, Estonia could ensure that ferry services remain both reliable and cost-efficient year-round, while also advancing the transition toward low-emission maritime transport.

3.4 *Diversify the Fleet and Optimize Vessel Deployment*

Estonia's current reliance on four identical large ice-class ferries for year-round operations introduces structural inefficiencies. These vessels are designed to meet severe winter conditions, but their reinforced hulls and propulsion systems result in higher energy demand even during open-water operation, increasing fuel consumption and emissions irrespective of seasonal demand levels. Recent empirical analysis based on MRV data further shows that a higher ice class is directly associated with increased fuel consumption even under open-water conditions [51], reinforcing the inefficiency of operating large ice-class ferries year-round [2] [24]. A more diversified fleet structure would improve alignment between capacity and actual demand.

While Estonia's core ferry fleet is relatively modern, both reserve vessels are of advanced age and approaching the end of their economic service life. At the same time, recent attempts to procure a new vessel have not resulted in a contract award, leaving the system without a clear replacement pathway. Together, these factors expose a growing structural vulnerability in fleet resilience, particularly during peak demand and unplanned maintenance periods.

Optimisation studies of passenger ferry systems further confirm that aligning vessel size and deployment with actual demand patterns can significantly improve both economic efficiency and service performance. Fleet allocation models show that mixed and modular fleets outperform uniform vessel strategies, particularly in systems with strong seasonal variation, by reducing unit costs while maintaining required service levels [26].

International experience shows that fleet renewal is most effective when embedded in long-term strategies that link vessel procurement with climate targets and coordinated port investment, as demonstrated by Transport Scotland's Islands Connectivity Plan and Färjerederiet's Vision 2045 [44] [48] [49]. Clear, time-bound targets (such as defined shares of low-emission vessels) provide certainty for operators and enable coordinated infrastructure planning.

Earlier studies confirm that vessel size and operational patterns are decisive for both economic and environmental performance. Adjusting vessel size and speed to actual demand can significantly reduce costs and emissions [50]. Electrifying and right-sizing domestic fleets yields substantial efficiency gains and greenhouse gas reductions [51]. Ferry fleet decarbonisation strategies must integrate both economic and environmental dimensions, underscoring the need for diversified and technologically adaptive renewal [16]. Together, these findings strengthen the case for moving away from a uniform fleet model. International practice demonstrates how such approaches can be implemented in ferry systems. In Norway, vessel size and frequency are adjusted according to route length, seasonal variation, and traffic intensity, supported by contracts that encourage the use of hybrid- or fully electric ferries on less trafficked routes [32]. Scotland has introduced a small vessel replacement programme, deploying energy-efficient ships for secondary routes while reserving larger ferries for peak demand [52]. These examples illustrate how diversified fleets enhance service flexibility and reduce both fuel consumption and environmental impact.

For Estonia, adopting a mixed fleet strategy would mean deploying smaller, more fuel-efficient vessels on major routes during winter, while maintaining ice-class ships as reserve capacity and when ice conditions require their use even to maintain minimal service levels, and for peak summer operations. Integrating hybrid-electric or fully electric ferries would further reduce emissions and align national operations with EU and IMO climate objectives [3] [5]. Coordinated investment in charging infrastructure and port upgrades will be essential to support modular deployment and ensure that vessels of different sizes can be rotated between routes. A gradual transition to a diversified and modular fleet would therefore enhance both economic efficiency and environmental performance, while providing resilience against seasonal fluctuations. Such a strategy would bring Estonia closer to the flexible, low-emission ferry systems already being implemented in comparable island regions.

3.5 *Strengthen Data-Driven and Integrated Transport Planning*

Implementing digital monitoring systems that track real-time service data, including fuel consumption, CO_2 emissions, passenger volumes, and vehicle occupancy, would provide valuable insights for optimizing ferry operations and identifying areas for improvement [53]. Coupled with regular user feedback surveys, such systems would help align service provision with passenger expectations and support more adaptive operations.

These insights are also critical for improving integration with the national transport network. Aligning ferry timetables with bus and rail connections, particularly during peak and off-peak periods, would enhance intermodal connectivity and provide passengers with more reliable and convenient travel options. At present, ferries often run with high vehicle occupancy but relatively low passenger numbers, indicating a modal imbalance and limited integration with public transport [53]. Coordinated planning between ferry operators, the Public Transport Department, and local municipalities, supported by digital monitoring and user feedback, is essential to ensure seamless connections and minimize transfer waiting times [32]. Similar priorities have been emphasised in Scotland, where the Islands Connectivity Plan identifies integration across transport modes as a central objective [48]. A comprehensive transport strategy that considers both mainland and island mobility needs would further enhance accessibility, efficiency, and sustainability [1].

4 CONCLUSIONS

This study examined the organisation and performance of Estonia's island–mainland ferry system in relation to three key objectives: ensuring governance stability and transparency, improving service quality and accessibility, and aligning fleet strategies with sustainability goals.

First, analysis of governance and procurement frameworks shows that Estonia has achieved a degree of stability through long-term contracts and state involvement, ensuring reliable year-round services. Institutional fragmentation between ministries, agencies, and state-owned companies has created overlapping responsibilities and reduced transparency. In contrast, international experience shows that integrated governance models, supported by systematic monitoring and public accountability, help balance efficiency with long-term resilience.

Second, service performance indicators confirm that ferry connections are vital for island residents and visitors, with steadily rising passenger and vehicle volumes since 2017. Ticketing for the main routes has improved accessibility, yet the system remains highly vehicle-oriented, with weaker integration into other modes of public transport and insufficient adaptation to the needs of vulnerable groups. Seasonal demand fluctuations further expose inefficiencies: while ferries operate at or near capacity in summer, they remain underutilised in winter, resulting in high costs and environmental pressures. Addressing these gaps requires clearer service standards that link frequency, affordability, and accessibility with broader socio-economic goals.

Third, fleet and operational challenges highlight the tension between winter resilience and year-round efficiency. The reliance on large, ice-class ferries ensures reliability in severe conditions but increases fuel consumption and operational costs outside the winter season. International examples show that modular fleets, hybrid propulsion, and flexible deployment strategies can reduce both emissions and costs, while aligning with decarbonisation targets. Estonia's failed procurement attempts in 2024–2025 underline the need for a coherent long-term fleet renewal strategy that integrates technical, financial, and environmental considerations from the outset.

Taken together, the findings indicate that Estonia's ferry system has a solid foundation in terms of reliability but faces structural weaknesses that limit its adaptability and sustainability. Addressing these challenges requires a shift from short-term procurement and fragmented governance towards integrated, evidence-based planning that combines service quality, accessibility, and decarbonisation objectives. On this basis, the study highlights the need for measurable service levels, clearer institutional responsibility, more flexible funding, and diversified fleet deployment—while showing that right-sized vessels and modular capacity can improve utilisation, reduce energy demand at terminals, enhance resilience to variable water levels, and support phased electrification.

Such a transition would not only improve operational efficiency but also ensure that ferry services continue to function as lifeline connections supporting the wider development of Estonia's island regions.

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