

NEW CONCEPTS AND ADVANCED STUDIES IN CIVIL ENGINEERING



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Editor

Assist. Prof. Dr. SERDAR KORKMAZ





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Fish Passages in Water Structures

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ABSTRACT

The migration of aquatic organisms is vital for key biological functions such as reproduction, feeding, and seasonal adaptation. However, hydraulic structures like dams, commonly built for energy generation, flood control, and irrigation, disrupt natural river dynamics and obstruct migratory routes. This disruption creates significant ecological challenges, threatening both target species and the integrity of entire aquatic ecosystems. This study, titled Fish Passes in Hydraulic Structures, presents a comparative evaluation of six different fish pass types: pool passes, vertical slot passes, Denil passes, eel ladders, fish locks, and fish elevators. These structures are analyzed based on their design elements, functionality, and performance under varying hydraulic and ecological conditions. The advantages and limitations of each system are discussed in relation to species-specific swimming abilities, stream morphology, and flow characteristics.

The results highlight that the ecological success of fish pass systems depends not only on engineering efficiency but also on environmental factors such as water temperature, dissolved oxygen levels, flow velocity, and seasonal flow variations. Failure to consider these parameters can render technically sound solutions ineffective from an ecological perspective. In conclusion, the study emphasizes the need for site-specific designs that reflect the unique ecological and hydraulic conditions of each location. Integrating engineering solutions with ecological and biological insights is essential for maintaining species continuity and achieving sustainable water resource management.

Keywords – Aquatic migration, Ecosystem connectivity, Fish passes, Hydraulic structures

INTRODUCTION

Endemic fish species found in various regions of Turkey face multiple threats during their migrations, which are a crucial part of their life cycles. The lack of adequate protection and safeguards in watercourses used by fish during migration-especially during spawning seasons-leads to significant population declines. Catadromous species (which migrate to the sea to spawn) and anadromous species (which migrate to freshwater to spawn) are at risk of extinction due to physical obstacles on their migration routes such as hydroelectric power plants (HPP) and similar water structures. This puts important fish species, such as salmon, eel, and sturgeon, in danger of extinction. To prevent these issues and ensure the continuity of aquatic ecosystems, fish passages have become essential in riverine structures.

Proper and suitable design of fish passages in dams constructed in recent years addresses this need. Article 22 of Fisheries Law No. 1380, currently in effect in Turkey, mandates the construction of fish passages. This protects fishes' natural migration routes and helps maintain ecological balance. Turkey's geopolitical location and diverse geographic features necessitate consideration of regional differences in fish-pass design. Factors such as river morphology, water regime, climate conditions, and the biological characteristics of local fish species must be carefully evaluated to ensure that fish-passage projects provide unique and sustainable solutions. In this context, developing fish-pass designs tailored to the specific conditions of each region is critical both for preserving biodiversity and for minimizing the environmental impact of water infrastructure (Oner and Sorgucu, 2016:169)

Status of Aquatic Animals in Dams and Hydroelectric Power Plants

After a dam is completed, the flow conditions downstream vary depending on the operational regime of the dam. These flow conditions also influence when aquatic organisms perform vital activities, such as migration. Observations show that the behaviour and mobility of aquatic wildlife change in dammed rivers compared to pre-construction conditions (Berkun et al., 2008:43)

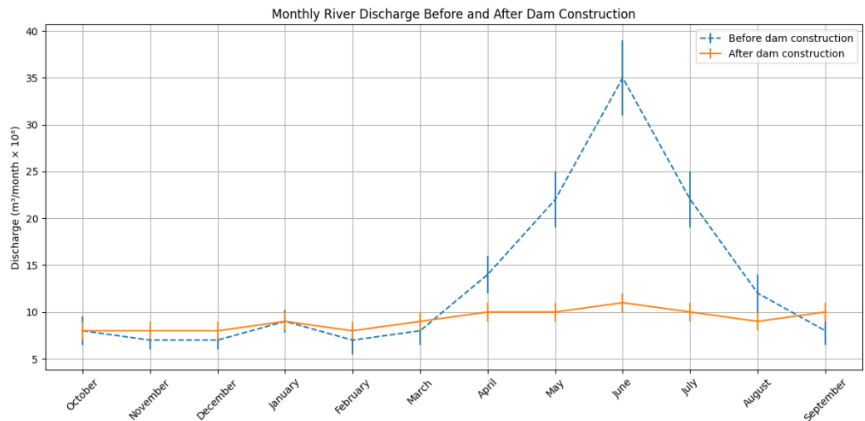


Figure 1: Change in water flow rate in the Colorado (USA) River (Berkun et al., 2008:43)

Hydroelectric power plant turbines are thought to affect oxygen levels in the water. After using the already oxygen-poor bottom waters in the dam

reservoir for power generation, the water downstream becomes even more depleted in oxygen. Conversely, the dam's spillways aerate the water, causing excessive dissolved oxygen (DO) saturation in the downstream section. Saturation of atmospheric nitrogen in both upstream and downstream waters-even beyond natural levels-can be fatal to aquatic organisms. All these variations contribute to the complex structure of the river and affect its dynamics. Dams that block migration routes of migratory fish species limit fluvial habitat. Fish that enter intake channels and pass through turbines suffer significant losses-on the order of 22% on average-resulting in a very different habitat situation downstream compared to historical conditions. To minimize these losses, intake areas are secured with screens and wire mesh. However, these measures cause a noticeable decrease in flow rate. In addition to such measures, efforts are made to minimize damage to fish during migration by technical modifications of turbines (for example, changes in blade design and operation). Another method is to schedule power plant operations so they do not overlap with fish migration periods, a practice used in the United States among other places (Berkun et al., 2008:44)

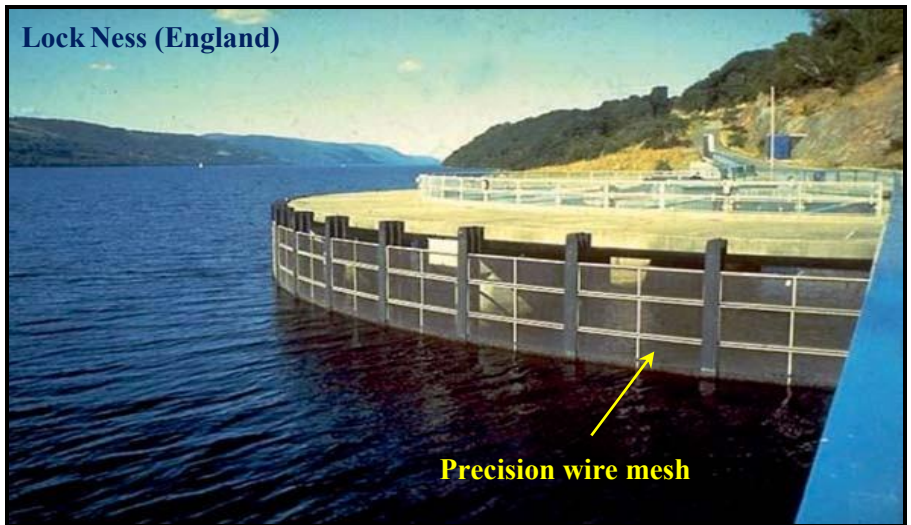


Figure 2: Surrounding the entrance section of the hydroelectric power station with a delicate wire mesh (Berkun et al., 2008:45).

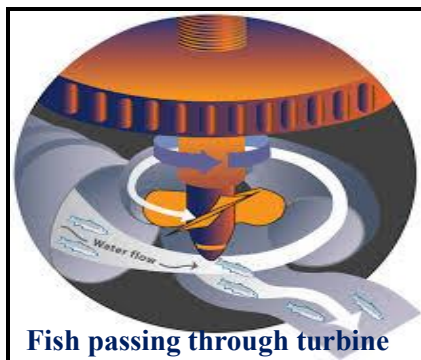


Figure 3. Fish passages in turbines, grilles prevent fish migration (Berkun et al., 2008:44).

The sturgeon, currently facing extinction, encounters barriers imposed by dams in Turkey during their spawning migrations. These fish, upon entering migration season, strive to access freshwater environments; however, due to restricted access, pollution, and obstruction of their natural routes by dam reservoirs, they are now on the brink of extinction. Research indicates that the prioritization of electricity generation in dam development, combined with the absence of natural spawning habitat conditions, has severely diminished the natural sturgeon populations in Turkey. Although species differ, these fish historically migrate 200–250 km inland from the river's mouth to deposit their eggs. For example, the migration routes in the Geyve Strait within Sakarya Province, which extend toward Eskisehir, have been obstructed by dams constructed across the river. This phenomenon is also prevalent in the Kizilirmak and Yesilirmak basins. In the Yesilirmak River, dams located 40 km or even 60 km inland impede further migration. To allow economically valuable sturgeon to spawn on riverbeds, fish passages or bypass channels have needed to be constructed along their routes. Unable to advance inland from the river mouth to spawn, the fish have progressively abandoned these regions. Overfishing and pollution have further contributed to their decline. Early intervention measures are therefore critical for their ongoing survival. Adult sturgeon-economically important-attain large sizes and may weigh between 80 and 100 kilograms. Naturally, passageways must be proportionally wide to accommodate individuals of such size. However, most dams have been designed with fish passages intended for smaller species, leaving openings insufficient for sturgeon. Empirical studies confirm that adult sturgeon require substantially wider

passage corridors than those typically provided. The absence of adequate dams or insufficient mitigation measures endangers not only sturgeon but also trout species (Ustundag, 2005:5-7; Berkun et al., 2008:45; Ucuncu ve Altindag, 2010:50; Tiril and Memis, 2013:136-137; Ak, 2017:1).

Hydrological impacts manifest through alterations to flow regimes and chemical parameters. As water evaporates from the reservoir, concentrations of salts and other dissolved minerals increase. In the transition from riverbed to reservoir, diffusion, water velocity, and the medium's oxygen-carrying capacity decline, rendering the reservoir less pristine and predisposed to eutrophication. As water quality within the reservoir shifts, the continuity of aquatic life is disrupted. Because anthropogenic dams, in their structural design, often fail to accommodate ecological cycles, they sever migratory corridors for both terrestrial and aquatic organisms, and inundate natural habitats beneath reservoir waters. Such alterations imperil species in the riverine surroundings. However, mitigation measures intended to sustain vital life processes of these species can sometimes cause unintended harm. For instance, fish passages constructed upstream may inflict more damage than downstream structures: low flow in upstream reaches can interfere with fishes' ability to detect passage entrances, undermining their ability to navigate toward them. Moreover, if fish cannot regulate swimming velocity within the passage, improved designs may prove ineffective and pose significant challenges. Accordingly, fish passages should be sited such that they do not impede natural habitat or swimming behaviour. Where feasible, the passage should align with natural migration routes without altering fishes' inherent balance. Further, during fish-pass design, it is imperative to account for potential use by diverse species, ensuring adequate and favourable flow conditions. As a rough estimate, a fish passage constructed for a 25 m tailwater head might cost approximately \$4 million. In contrast, the 135 m-high, 15 km-long Ilisu Dam project on the Tigris River is estimated to require approximately \$43 million (Berkun et al., 2008:45-46).

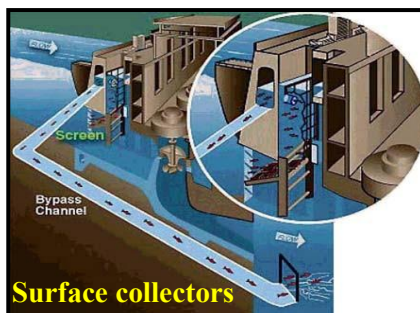
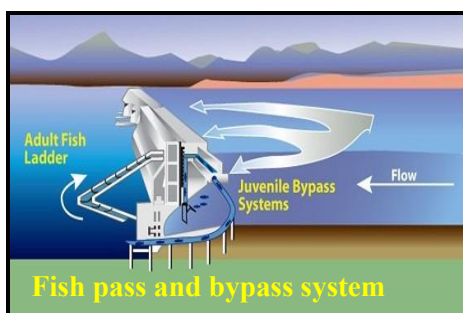
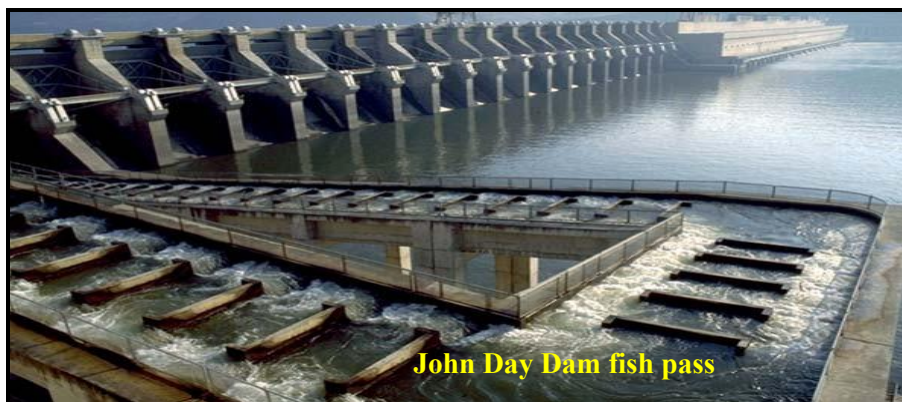


Figure 4. John Day Dam fish pass (NWP, 2025), downstream fish pass for large fish and bypass systems for small fish, surface collectors (FWEE, 2025).

Fish Pass Types

Fish passes are categorized under six principal types (Ekren, 2015:9). These types are:

- a) Pool passes
- b) Slot passes
- c) Denil passes
- d) Eel ladders
- e) Fish locks
- f) Fish elevators.

a) Pool Passages

The key element of a pool pass is the division of the entire channel between the upstream and downstream ends using curtain walls, which create a series of pools. Water primarily flows through orifices in these curtain walls, gradually reducing the potential energy of the water within the pools. Fish migrate from one pool to the next by passing through openings located either at the bottom (submerged orifice) or the top (notch) of the curtain wall.

During migration, fish encounter high flow velocities only at these orifices; the pools themselves, characterized by lower flow velocities, provide areas for resting and shelter. Substrate roughness is essential to allow bottom-dwelling organisms to traverse the pool pass effectively (Sever, 2014:15). A longitudinal section of a typical pool pass is shown below.

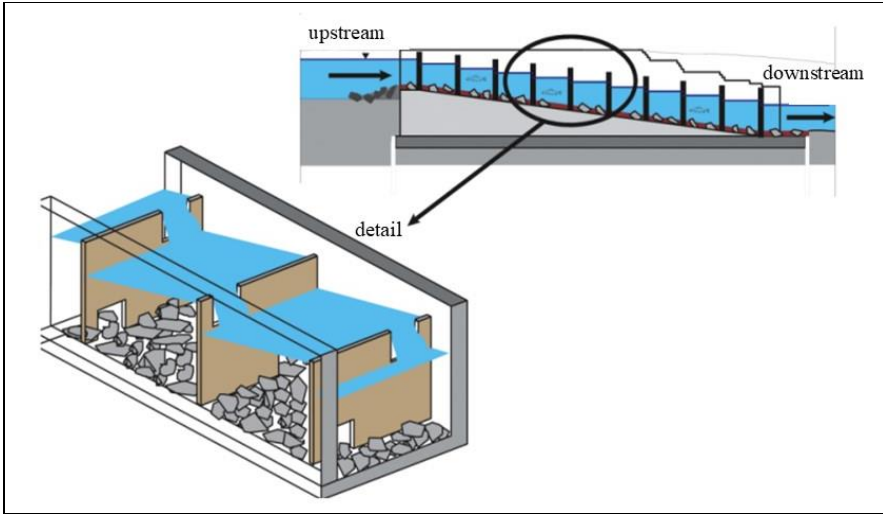


Figure 5. Structure and detail of a pool passage (Ucuncu and Altindag, 2012:51; Senturk, 2025:1).

b) Slotted Passages

The vertical slotted passage, or slotted passage, which has survived from the 1950s to the present day, was developed in the northern United States. Slotted passages have also become common in Germany recently. Slotted passages are a similar design to pooled passages (Ucuncu and Altindag, 2012:52).

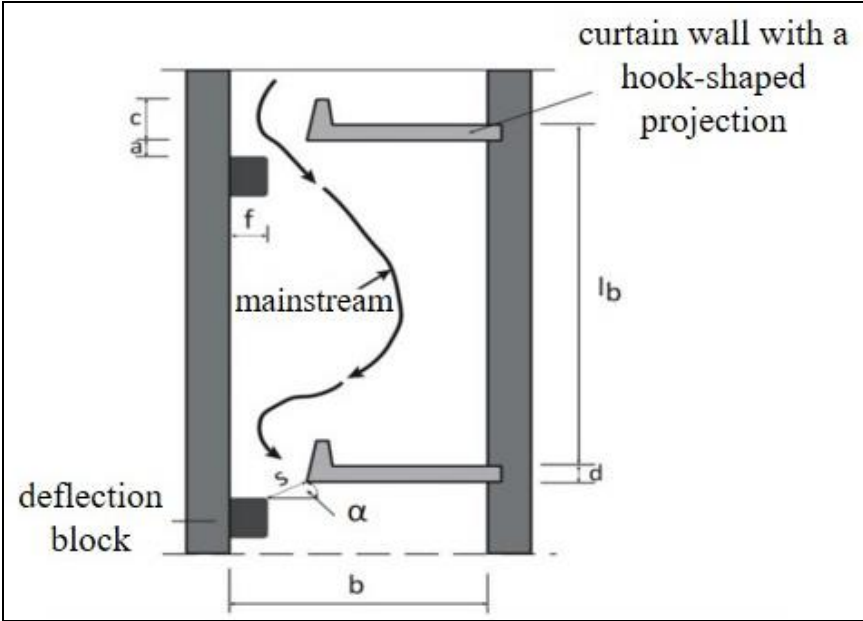


Figure 6. Single-slot fish pass section (Tufek, 2009:79; Celebi, 2014:17).

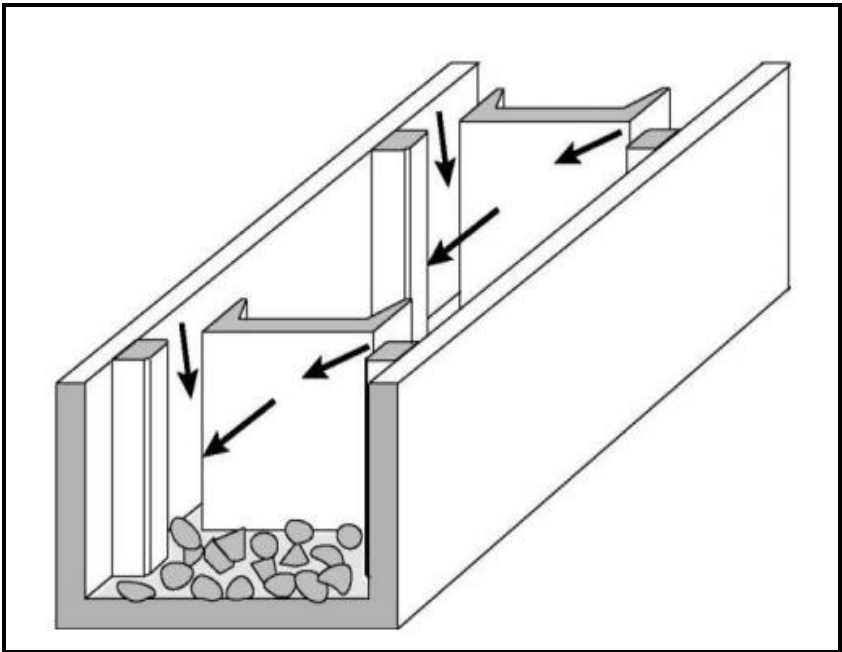


Figure 7. Double-slot fish pass section (Mese, 2019:12; Can, 2022:12).

The passage features curtain walls with hook-shaped projections, and opposite these walls are baffle blocks to reduce turbulence and dissipate water energy. In slotted passages, the curtain walls are notched by creating vertical slits along the entire height of the wall. Curtain walls can have one or two slits, depending on the density of the incoming water and the flow rate. In a single-slit design (in contrast to a classic pooled passage), the slits are always located in the same section (Ucuncu and Altindag, 2012:52).

c) Denil Passes

In the early 20th century, Belgian engineer G. Denil designed a type of fish pass known as a "counterflow pass" due to its operating mechanism. This design, commonly referred to in the literature as the Denil pass, consists of a channel equipped with closely spaced baffles arranged against the direction of flow. The turbulence generated by the baffles dissipates a substantial amount of energy, thereby reducing flow velocities in the lower chambers (Tufek, 2009:87).

As a result, the Denil pass can be constructed with a much steeper slope compared to other fish pass types, making it suitable for overcoming small to medium elevation differences over short distances. Its streamlined and modular structure enables prefabrication under dry conditions and allows for full on-site assembly in a single operation. Moreover, it is particularly advantageous for retrofitting existing dams that lack fish passage facilities, and for use in locations where available space is limited (Kadioglu, 2010:11-12; Baydar, 2014:11). A schematic representation of a Denil pass is shown in the figure below.

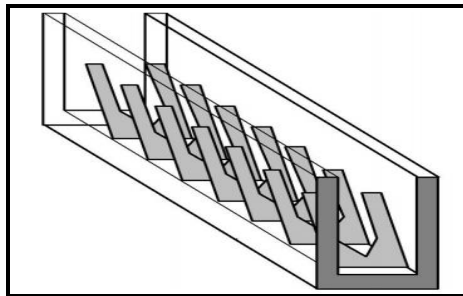


Figure 8. Denil passage section (Ucuncu and Altindag, 2012:52)

d) Eel Ladders

The eel (*Anguilla anguilla*) inhabits all still and flowing waters connected to the sea throughout its life cycle and is classified as a catadromous migratory species. It grows and matures in freshwater environments until it is ready to reproduce. Upon reaching the "silver eel" stage, it migrates from inland freshwater systems to the Sargasso Sea to spawn. It takes approximately 2–3 years for the eel larvae, known as glass eels, to drift back across the Atlantic Ocean and reach European coastlines. From there, they continue their migration upstream into inland waters. During this phase, juvenile eels-ranging in length from 7 to 25 cm-must navigate physical barriers characterized by small cracks and rough surfaces. However, immature eels exhibit limited climbing capabilities. As a result, vertically oriented devices (e.g., brush bundles) intended to assist in their ascent have shown limited effectiveness. To enhance the migratory success of glass eels, it is advisable to implement supplementary measures in addition to conventional fish passes, especially considering their scarcity at river mouths. Larger eels, in contrast, are capable of utilizing standard fish passes effectively. Therefore, the installation of separate eel ladders is generally unnecessary in such systems (Tufek, 2009:95-96; Mese, 2019:15).

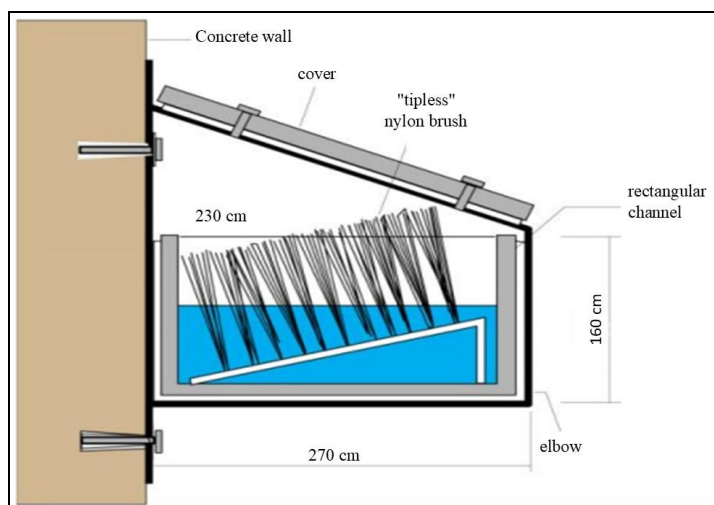


Figure 9. Example of an eel ladder in the Zeltingen dam in the Moselle River (Tufek, 2009:95-96; GDSHW, 2016:296; Mese, 2019:15).

e) Fish Locks

Fish locks have been employed as a fish passage solution for many years in countries such as Scotland, Russia, the Netherlands, and Ireland. They are also present on the Sieg and Saar Rivers in Germany. Structurally, fish locks are similar to ship locks, sharing a common design element: a lock chamber equipped with a closure system at both the lower entrance and the upper exit. Despite these structural similarities, there are several key differences between fish locks and ship locks. Ship locks are not designed to accommodate fish migration and, therefore, are generally unsuitable for use as fish passages. Specifically, factors such as the absence of a continuous flow, the short duration of gate openings, high water turbulence within the chamber during filling, and the positioning of the lock within the weir complex significantly hinder fish movement through ship locks. Nonetheless, during peak migration periods of certain species, such as salmonids and glass eels, temporary operational modifications to ship locks may be considered to facilitate upstream fish passage (Tufek, 2009:96-97; Sever, 2014:28-31). The operational scheme of a fish lock is illustrated in the figure below.

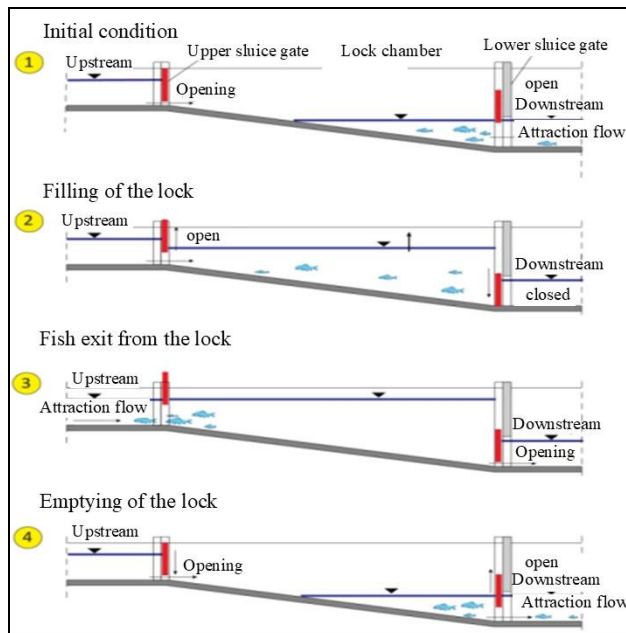


Figure 10. How the fish lock works (Sever, 2014:28-31)

f) Fish Elevator

When available water resources are limited and the elevation difference is considerable (typically between 6–10 meters), the application of conventional fish passes becomes constrained due to spatial requirements, the physical limitations of the fish, and their migratory performance. In cases where the height of the obstacle is too great for fish to overcome naturally, several fish elevator systems have been developed as an alternative solution. These systems generally involve transporting fish using a specially designed boat or container. The fish can be transferred either by tilting the boat or through a retractable discharge hatch. This hatch is embedded in the bottom of the structure when the boat is positioned at the lower level, and fish are directed toward the elevator via a guiding flow current. A foldable and sliding grate-like hatch, located at the front of the elevator, guides the fish into the elevator and subsequently into the transport vessel. At regular intervals, the lower hatch of the elevator closes to prevent the fish from escaping. The fish, once inside the boat, are unable to move freely and are transported upstream as the boat ascends. Upon reaching the upper level, the boat may either discharge the fish directly into the upstream waterbody or establish a watertight connection between the boat and the upper channel. The fish then move into the upper reach using the water contained within the vessel. A clear and directed flow must also be present in the upper channel to encourage fish movement (Tufek, 2009:100; Ucuncu and Altindag, 2012:53).

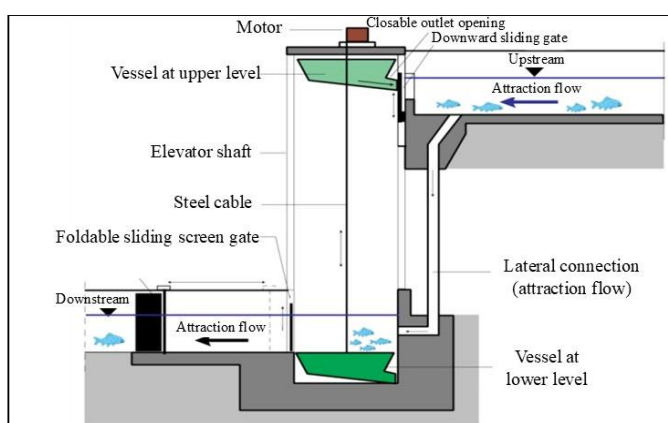


Figure 11. Structure and operation of a fish elevator (Travade and Larinier, 2002:109; Ucuncu and Altindag, 2012:53).

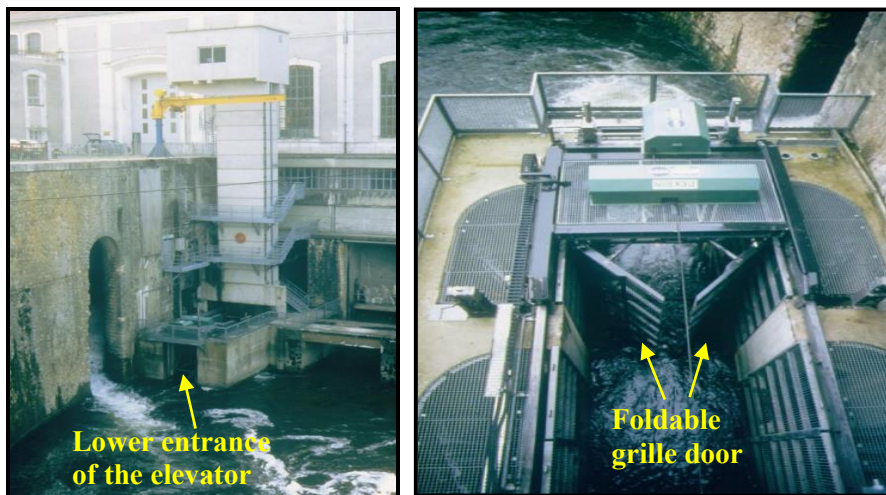


Figure 12. Tuilières fish elevator in the Dordogne River, France (Tufek, 2009:101).

RESULTS AND DISCUSSION

Aquatic organisms inhabiting streams must undertake migrations at specific times to sustain their life cycles. These migrations are critical for essential biological functions such as reproduction, feeding, and seasonal adaptation. However, dams and other hydraulic structures-particularly those constructed for energy production, flood control, and irrigation-disrupt natural stream flow regimes and interrupt migratory routes. This disruption poses serious environmental challenges, threatening not only the viability of target species but also the structural and functional integrity of entire aquatic ecosystems.

As a result, ensuring ecological compatibility between hydraulic structures and riverine ecosystems has become not only a necessity but also an ecological imperative. To support the continuity of fish migrations, engineering solutions must be integrated with ecological considerations. In this context, fish passes emerge as vital structures situated at the intersection of engineering and ecological disciplines, requiring a multidimensional approach to both planning and design. An effective fish pass must be tailored not only to the hydraulic characteristics of the water body but also to the morphological, physiological, and behavioral traits of the target species. In this study, various types of fish passes-including pool passes, vertical slot passes, Denil passes, eel ladders, fish locks, and fish elevators-are evaluated

comparatively in terms of both their structural components and functional performance. Each of these systems offers specific advantages and limitations, depending on factors such as species-specific swimming abilities, stream morphology, and hydraulic conditions.

Moreover, the success of any fish pass design depends on a thorough analysis of key environmental parameters, including water temperature, dissolved oxygen levels, flow velocity, and seasonal flow variations. If these factors are not properly addressed, even the most technically sound engineering solutions may fail from an ecological standpoint. Considering the fragmenting impact of dams on aquatic habitats, it is crucial that fish passes be designed to replicate natural stream conditions as closely as possible.

In conclusion, rather than adopting a standardized, one-size-fits-all approach to fish pass design, site-specific solutions should be developed based on the unique ecological, morphological, and hydraulic context of each project. The findings of this study clearly demonstrate that successful fish passage systems must be informed not only by engineering principles but also by ecological and biological knowledge. Such an integrated and holistic approach will contribute significantly to species conservation efforts and the realization of sustainable water management goals.

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Minimizing System Costs in Branched Urban Bus Transit Networks: A Heuristic Approach

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ABSTRACT

Urban transportation systems face mounting challenges as increasing private vehicle ownership overwhelms inadequate infrastructure, necessitating improved public transportation solutions. This study develops a comprehensive mathematical optimization model for urban bus transit network design that combines express and conventional service modes within tree-structured networks to minimize total system costs while maintaining service quality standards.

The research addresses the simultaneous routing and assignment problem by formulating a multi-objective optimization framework that balances vehicle operation costs with user travel and waiting costs. A heuristic algorithm handles the combinatorial complexity, utilizing iterative route elimination and demand reassignment strategies based on cost-benefit analysis. Key decision variables include route configurations, service types, headways, and fleet allocations. Optimization points out that user costs typically constitute 70-80% of total system costs, making passenger time savings the primary optimization target.

Computational studies using a 14-stop tree network demonstrate the methodology's effectiveness across different demand patterns. For many-to-many demand scenarios, the algorithm achieved 12% reduction in total system costs and 25% reduction in operator costs by consolidating 30 initial routes into 8 optimized routes. For concentrated one-to-one demand patterns, 4% total cost reduction and 14% operator cost reduction were achieved while maintaining 46% of passengers on express services. Thus, systematic route optimization can simultaneously improve operational efficiency and user service quality. Demand consolidation effects enable significant headway reductions that decrease passenger waiting times more than the elimination of some express services increases in-vehicle travel times. Two case studies demonstrate the practicality of the optimization framework for the design and operation of efficient bus transportation systems, particularly on peak period service optimization where concentrated demand patterns create clear improvement opportunities.

Keywords –Urban transportation, Bus transit optimization, Network design, Mathematical modelling, Heuristic algorithms

INTRODUCTION

Urban transportation problems are intensifying as cities grow, with increasing private vehicle ownership overwhelming inadequate infrastructure and management systems. While private vehicle owners spend hours in traffic and face parking difficulties, those without private vehicles or choosing not to use them turn to public transportation systems operating in the same chaotic environment. This situation necessitates careful attention to urban public transportation, as making public transit more attractive could open pathways to solving these problems.

Transportation problems, by their nature, require a systems approach (Alpöge, 1974) due to their multi-modal, multi-sectoral, multi-problem, and multi-disciplinary structure (Yardim, 1994). A system is defined as "a set of components organized such that their actions can be directed by inputs toward specific goals and objectives" (Hutchinson, 1974). Systems interact with their external environment through inputs and outputs, creating a continuous cycle where the environment provides inputs to the system, the system processes these inputs to generate outputs, and these outputs affect the environment, which in turn influences the system.

For transportation systems, Manheim (1979) identifies three main input groups: demand, resources and constraints, and transportation policies and objectives. System outputs comprise "supply" (transportation network capabilities, service levels, costs) and "effects" (accessibility changes, land use modifications, environmental impacts, quality of life changes).

Urban transportation systems serve people's needs to move between social and economic activity centres within cities. These systems consist of transportation networks, vehicles, and operations. Urban transportation has three fundamental functions: mobility (rapid, safe, and economical movement of large passenger volumes), accessibility (ease of reaching activity centres), and livability (supporting activities beyond mere access, such as pedestrian areas and commercial streets).

People use both private transportation and public transportation to meet their urban travel demands. Private transportation offers flexibility with door-to-door service but is expensive and environmentally harmful. Public transportation serves those without private vehicles and those choosing public transit, providing economic benefits, efficient road capacity utilization, energy savings, and reduced environmental impacts compared to private vehicles.

Public transportation systems can be categorized into road-based systems (buses, minibuses, taxis), rail systems (metro, light rail, tramway), waterway systems (ferries, water buses), and cable systems (cable cars). Bus transportation is the most flexible and widely used public transportation mode, capable of serving capacity ranges from 500-12,000 passengers per track-hour.

Public transportation systems operate through various inputs including policies and objectives, demand characteristics, network information, available resources and constraints, information about other operators, and effects from other activity systems. System outputs include supply elements (routes, schedules, fleet composition, service levels) and effects (accessibility changes, land use impacts, environmental consequences).

The decision-making process in public transportation involves hierarchical planning levels: strategic level (long-term policy and investment decisions), tactical level (medium-term resource allocation), and operational level (short-term scheduling and control) (Lardinois, 1989). Key decisions include network determination, service level and fare setting, scheduling, vehicle routing, and personnel assignment.

Various operating strategies address temporal and spatial demand variations:

Classical/Conventional Operation: All-stop service with regular departures, providing many-to-many connectivity with high accessibility but potentially slower speeds.

Skip-Stop Operation: Vehicles and stops are divided into groups (e.g., odd-even), with each vehicle stopping only at designated stops, reducing travel time while maintaining coverage.

Express Operation: Limited-stop service focusing on major stations, providing faster connections between key destinations with few-to-few or many-to-one demand patterns.

Zonal Operation: Combines express service on trunk corridors with local service in zones, optimizing both connectivity and accessibility functions. This strategy has shown particular effectiveness in peak periods and tree-branch network configurations.

The field of bus transit network design has undergone significant methodological evolution, transitioning from early analytical models to sophisticated optimization frameworks that address real-world complexities. Guihaire and Hao (2008) provided a comprehensive survey of transit network design problems, establishing a classification of problem variants and solution approaches that continues to influence contemporary research.

Extensive research has been conducted on analytical optimization of public bus systems. Most early studies assumed fixed demand and focused on two primary decision variables: vehicle headways and line spacing (Salzborn, 1972; Hurdle, 1973; Byrne, 1976; Newell, 1979; Kocur and Hendrickson, 1982; Chang and Schonfeld, 1991).

Byrne and Vuchic developed an iterative algorithm for parallel feeder lines, finding that optimal vehicle headways occur where waiting costs equal operating costs, with vehicle allocation proportional to the square root of passenger demand on each route (Byrne and Vuchic, 1971). Byrne extended this work to radial networks, showing that optimal line numbers depend on the ratio of access costs to total waiting and operating costs (Byrne, 1976).

Recent developments have shifted toward sophisticated multi-objective frameworks that simultaneously consider passenger convenience, operator costs, and system performance. Cevallos and Zhao pioneered the application of genetic algorithms to minimize transfer times, establishing a foundation for metaheuristic approaches in transit network design (Cevallos and Zhao, 2006).

Cipriani et al. advanced the field by developing integrated optimization models that consider both service quality and operational efficiency, demonstrating practical application to large urban areas (Cipriani et al., 2012). Their work highlighted the importance of balancing multiple conflicting objectives in real-world transit planning scenarios.

The incorporation of uncertainty and robust optimization has become increasingly important in contemporary research. Yan et al. introduced robust optimization models for bus transit network design under stochastic travel times, addressing the inherent variability in urban transportation systems (Yan et al., 2013).

Jha et al. developed a multi-objective meta-heuristic approach using Modified Multi-Objective Particle Swarm Optimization for simultaneous network design and frequency setting (Jha et al., 2019). Their two-stage optimization framework demonstrated superior performance on benchmark problems while maintaining computational efficiency.

Recent research has emphasized the integration of bus networks with existing rail infrastructure. Liang et al. developed a two-step model framework for bus transit network design with uncertainties, building upon existing metro networks (Liang et al., 2019). Their approach addresses the growing need for coordinated multi-modal transportation planning.

Wang et al. advanced this concept through hierarchical bus transit network design in coordination with existing metro systems, proposing sophisticated mathematical models that optimize the complementary relationship between different transportation modes (Wang et al., 2025).

Owais and Osman developed a complete hierarchical multi-objective genetic algorithm for transit network design, incorporating multiple stakeholder perspectives and practical constraints (Owais and Osman, 2018). Their approach demonstrates the evolution toward comprehensive optimization frameworks that address real-world implementation challenges.

Huang et al. contributed to multimodal transit network design through hub-and-spoke network frameworks, providing insights into the integration of different transportation modes within unified optimization models (Huang et al., 2018).

Recent literature increasingly addresses emerging technologies and sustainability considerations. Mahmoudi et al. provided a critical review of analytical approaches in public bus transit network design, with particular focus on emerging technologies and sustainability metrics (Mahmoudi et al., 2024). Their comprehensive analysis highlights the growing importance of environmental considerations and technological integration in contemporary transit planning.

Shimamoto et al. demonstrated practical application through evaluation of existing bus networks using optimization models, providing valuable insights into the relationship between theoretical optimization approaches and real-world network performance (Shimamoto et al., 2010).

The concept of zonal public transportation emerged from research in the 1960s-1980s, with significant contributions from Black (1962), Eisele (1968), and later analytical developments by Tsao and Schonfeld (Tsao and Schonfeld, 1983; Tsao and Schonfeld, 1984). Zonal operation combines express service on trunk corridors with local service in designated zones, offering advantages including reduced vehicle-kilometers, higher average speeds, improved passenger travel times, and better service reliability.

Chang and Schonfeld developed comprehensive analytical models incorporating multiple decision variables including zone boundaries, headways, route lengths, line spacing, and fares (Chang and Schonfeld, 1991; Chang and Schonfeld, 1993). Their work addressed both fixed and elastic demand scenarios with various objective functions (cost minimization, profit maximization, social welfare maximization).

THE MATHEMATICAL MODEL

Nomenclature

Indices and Sets

- i, j : Stop indices for forward direction (for return direction: j, i)
- k : Boarding stop index for forward direction
- l : Boarding stop index for return direction
- r : Route number or identifier
- m : Number of stops on a r line
- M : Set of all stops in the network
- H_M : Total number of possible line configurations in a transportation network with M stops
- R : Set of all routes in the transit network
- x : Number of possible lines in a configuration
- X : Maximum possible set of lines in a configuration
- τ : Set of terminal points
- τ_o : Set of potential terminal points
- p : Number of express routes in the route set

Demand and Flow Variables

- q_{ij} : Hourly passenger flow from stop i to stop j (pax/h)
- q_{ji} : Hourly passenger flow from stop j to stop i (pax/h)
- Q_r : Total hourly boarding passengers on route r in both directions (pax/h)
- $A_{\max}$: Maximum passenger flow between consecutive stops (pax/h)

Service and Operating Parameters

- n : Number of stop intervals on route r
- L_r : Length of route r (km)
- l_d : Distance between consecutive stops (km)
- c : Vehicle capacity (pax/vehicle)
- V_{av}^e : Average operating speed for express service (km/h)
- V_{av}^k : Average operating speed for conventional service (km/h)
- h_r : Headway for route r (min)
- $h_{r,\max}$: Maximum allowable headway for route r (min)
- f_r : Required hourly frequency for route r (trips/h)
- F_r : Required hourly fleet size for route r (vehicles)

Time Components

- t_{rt} : Round-trip time for route r (min)
- t_{rt}^e : Round-trip time for express route r (min)
- t_{rt}^k : Round-trip time for conventional route r (min)
- t_s : Driver rest and maneuvering time between trips (min)
- t_d : Dwell time at intermediate stops (min)
- t_k : Total passenger travel time (min/pax)
- t_{tk} : Passenger in-vehicle time (min/pax)
- t_{bk} : Passenger waiting time at stops (min/pax)
- t_{tk}^e : Passenger in-vehicle time for express route (min/pax)
- t_{tk}^k : Passenger in-vehicle time for conventional route (min/pax)
- σ : Ratio of waiting time to headway

Cost Components

- B_{rt} : Unit vehicle operating cost (TL/vehicle-h)
- b_{tk} : Value of time (TL/pax-h)
- b : Average fare (TL/pax) (it can be express or conventional type)
- C_{ri} : Operator cost for route r (TL/h)
- C_{rk} : User cost for route r (TL/h)
- C_r^e : Total system cost for the express route r within 1 hour (TL/h)
- C_r^k : Total system cost for the conventional route r within 1 hour (TL/h)
- C_r : Total system cost a route configuration within 1 hour (TL/h)
- G_r : Revenue for route r (TL/h)
- P_r : Net profit for route r (TL/h)
- Z_r : Net loss for route r (TL/h)
- Z : Total system cost
- $Z(n)$: Total system cost for the solution obtained by the heuristic in step n
- Z_{best} : Total system cost for the best solution obtained by the heuristic

Time Aggregates

- T_{rk}^e : Total user time for express route r within one hour (pax-min/h)
- T_{tk}^e : Total in-vehicle time for express route within one hour (pax-min/h)

- T_{bk}^e : Total waiting time for express route within one hour (pax-min/h)
- T_{rk}^k : Total user time for conventional route r within one hour (pax-min/h)
- T_{tk}^k : Total in-vehicle time for conventional route within one hour (pax-min/h)
- T_{bk}^k : Total waiting time for conventional route within one hour (pax-min/h)

Problem Formulation and Model Structure

Urban bus transit systems frequently suffer from inefficiencies arising from excessively long routes that traverse entire corridors with extended travel times. The fundamental challenge lies in balancing the conflicting objectives of transit operators, who seek to minimize operating costs, and passengers, who desire reduced travel times and improved service levels. This research develops a comprehensive mathematical model to determine optimal bus transit operating configurations by combining express and conventional service modes within branched type transit networks (Figure 1). The branching can be either single-sided or double-sided.

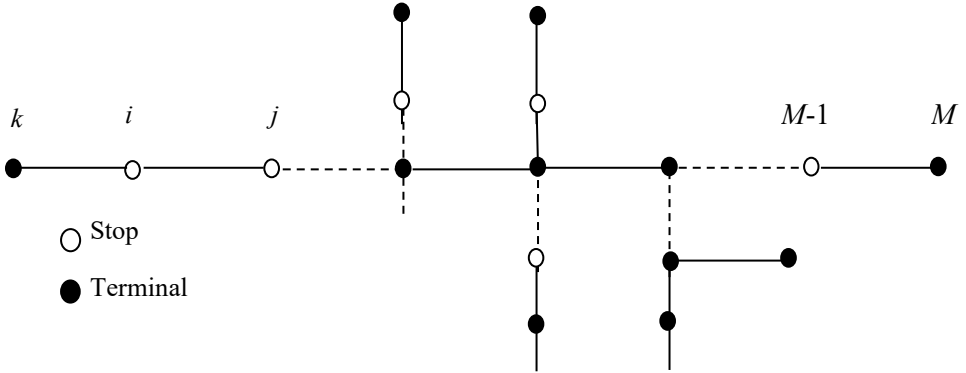


Figure 1: A branched (trunk line) transportation network scheme

The model addresses the simultaneous routing and assignment problem, seeking to minimize total system cost while maintaining acceptable service standards. The approach recognizes that total system cost comprises operator costs associated with vehicle operations and user costs reflecting passenger time expenditures within the transit system. The mathematical framework treats this optimization challenge as a combinatorial problem

where the number of possible route configurations grows exponentially with network size according to:

$$H_M = \sum_{x=1}^X \binom{W}{x} \cdot 2^x \quad (1)$$

Where

$$W = \frac{M^2 - M}{2} \cdot 2 \quad (2)$$

represents the total number of possible route combinations, and the factor of 2 accounts for the availability of both express and conventional operating modes.

Mathematical Model Formulation

Operator Cost Structure

The operator cost for any route r is fundamentally determined by the fleet requirements and unit operating costs:

$$C_{ri} = F_r \times B_{ri} \quad (3)$$

where the required fleet size depends on round-trip time and desired service frequency:

$$F_r = \frac{t_{rt}}{h_r} \quad (4)$$

In addition, the symbols C_{ri}^e , C_{ri}^k will be used in the following sections to represent the operator costs of express and conventional routes, respectively.

Round-trip time calculations differ between service types. For express operations:

$$t_{rt}^e = 2 \cdot \frac{n \cdot l_d \cdot 60}{V_{av}^e} + t_s \quad (5)$$

For conventional service with intermediate stops:

$$t_{rt}^k = 2 \cdot \frac{n \cdot l_d \cdot 60}{V_{av}^k} + (n-1) \cdot t_d + t_s \quad (6)$$

The headway constraint relates service capacity to demand through:

$$h_r = \frac{c \cdot 60}{A_{\max}} \quad (7)$$

where $A_{\max}$ represents the maximum passenger load on any route segment. By using the equation 6, the required number of trips per hour for a route is calculated for lines as follows:

$$f_r = \frac{1}{h_r} \cdot 60 \quad (8)$$

Operator Income

In the decision-making process, it is essential to identify the profit or loss generated from the provided service. For this purpose, in addition to the costs, the operating revenue for each route should be calculated as follows. General form of route operation revenue:

$$G_r = Q_r \cdot b \quad (9)$$

for express routes:

$$G_r^e = Q_r \cdot b^e \quad (10)$$

for conventional routes:

$$G_r^k = Q_r \cdot b^k \quad (11)$$

From the operator's perspective, the revenue–expenditure balance of operating route r results in either profit or loss. Profit is defined as follows in general form. If the outcome is negative, it is termed a loss ($Z_r = -G_r$)

$$P_r = G_r - C_{ri} \quad (12)$$

User Cost Analysis

User costs encompass both in-vehicle time and waiting time at stops:

$$t_k = t_{tk} + t_{bk} \quad (13)$$

For express services, in-vehicle time is:

$$t_{ik}^e = \frac{n \cdot l_d \cdot 60}{V_{av}^e} \quad (14)$$

For conventional services with intermediate stops:

$$t_{ik}^k = \frac{n \cdot l_d \cdot 60}{V_{av}^k} + (n-1) \cdot t_d \quad (15)$$

Waiting time relates to service frequency:

$$t_{bk} = h_r \cdot \sigma \quad (16)$$

where σ typically ranges from 0.25 to 0.5 depending on passenger arrival patterns. Accordingly, the waiting times for express and conventional services can be formulated as follows.

$$t_{bk}^e = h_r^e \cdot \sigma \quad (17)$$

$$t_{bk}^k = h_r^k \cdot \sigma \quad (18)$$

The travel time of passengers using a route within a given time period is obtained as the sum of the travel times of all passengers using that route. Thus, the total user cost for the corresponding route (express or conventional) can be obtained. Total user time expressions are given below for express and conventional routes. For express routes:

$$T_{rk}^e = T_{ik}^e + T_{bk}^e = Q_r(t_{ik}^e + t_{bk}^e) \quad (19)$$

for conventional routes:

$$T_{rk}^k = T_{ik}^k + T_{bk}^k \quad (20)$$

Given that the demand between different O-D pairs along a route is non-uniform, the in-vehicle time in conventional operation is formulated as the aggregate of both directional flows.

$$T_{rk}^k = \left(\sum_{\substack{i=1, \dots, m-1 \\ j=2, \dots, m}} t_{ik,ij}^k \cdot q_{ij} + \sum_{\substack{j=2, \dots, m \\ i=1, \dots, m-1}} t_{ik,ji}^k \cdot q_{ji} \right) \quad (21)$$

For the conventional route, the waiting time is determined as follows.

$$T_{bk}^k = Q_r \cdot t_{bk}^k \quad (22)$$

To calculate the monetary value of user cost for a route C_{rk} , the total user time within a unit period (1 hour) is multiplied by the value of time.

This can be written separately for express and conventional routes as follows. Thus, in subsequent analyses and comparisons, all quantities are expressed in the same unit.

$$C_{rk}^e = \frac{T_{rk}^e}{60} \cdot b_{tk} \quad (23)$$

$$C_{rk}^k = \frac{T_{rk}^k}{60} \cdot b_{tk} \quad (24)$$

The total cost of a route is determined by combining the operator and user costs. For express and conventional routes, it can be formulated as follows:

$$C_r^e = C_{ri}^e + C_{rk}^e \quad (25)$$

$$C_r^k = C_{ri}^k + C_{rk}^k \quad (26)$$

System Cost Optimization

The complete optimization objective minimizes total system cost:

$$Z = \min C_r = \min \left(\sum_{r=1}^p C_r^e + \sum_{r=p+1}^R C_r^k \right) \quad (27)$$

subject to operational constraints:

$$h_r \leq h_{r,\max} \quad (28)$$

$$f_r, F_r \geq 1 \quad (29)$$

$$R \leq \frac{M^2 - M}{2} \quad (30)$$

$$R, M > 0 \quad (31)$$

and integer constraints on decision variables.

Method: The Heuristic Solution Algorithm

Given the combinatorial complexity, a heuristic approach provides near-optimal solutions efficiently. The algorithm design centres on the observation that user costs typically constitute 70-80% of total system costs, making them the primary optimization target. The algorithm framework is as follows:

Step 1: Initial Configuration

In this step, user-optimal configuration is obtained as an initialization of the solution. Here, the objective is to minimize the user costs. This involves:

- Assigning express services to all high-demand terminal pairs
- Assigning remaining demand to conventional routes by zone coverage:
 - Group 1: Single-zone routes (local service)
 - Group 2: Two-zone routes (medium distance)
 - Group 3: Multi-zone routes (long distance)
- Iteration counter is initialized, $n = 1$.

Step 2: Route Removal

This iterative step aims to reduce operator costs by removing the highest-loss route, i.e., the route where the highest system cost is incurred:

- Identify the route $\bar{r}$ with maximum loss (highest operating deficit, $Z_{\bar{r}} \geq Z_r$ for all other operating routes r) from the current configuration and remove it.

Step 3: Demand Reassignment

The demand of the removed route is transferred to an alternative route. While maintaining service coverage, the efficiency of the route selected is assured by the hierarchy of rules presented in Table 1.

Table 1. Demand reassignment routes.

Removed Route Type	Reassignment Target	Criterion
Express	Conventional (same corridor)	Minimum travel time increase
Group 1 Conventional	Group 2 Conventional	Minimum headway
Group 2 Conventional	Group 3 Conventional	Minimum headway
Group k Conventional	Group k+1 Conventional	Minimum headway

After the reassignment based on the rules in Table 1, headways are recalculated for all routes affected by the shifting demand.

Step 4: System Cost Evaluation

After each route removal and demand reassignment, the total system cost $Z(n)$ is recalculated by equation (11). This evaluation quantifies change

in operator costs (reduced routes), change in user costs (increased travel times/waiting), and thus the overall net system benefit/deterioration.

Step 5: Termination Decision

If the system cost of the new configuration is lower than the best system cost obtained through iterations, the best is updated and the algorithm continues with Step 2. Otherwise, the algorithm terminates.

- If $Z(n) < Z_{best}$,
 - $Z_{best} = Z(n)$,
 - $n = n + 1$,
 - GO TO Step 2.
- Otherwise, STOP.

Terminal selection dramatically reduces computational burden. For a network with M stops, restricting analysis to τ strategically selected terminals reduces candidate routes from $\frac{M(M-1)}{2}$ to $\frac{\tau(\tau-1)}{2}$, achieving up to 95% complexity reduction while retaining optimal solutions.

COMPUTATIONAL RESULTS

Network Configuration and Parameters

The computational analysis employs a carefully designed 14-stop tree network representing a typical urban transit corridor with branching characteristics. The network structure includes a main trunk line with two branch extensions, reflecting common urban development patterns where transit corridors serve both linear and distributed activity centres.

Key network parameters were established based on realistic urban transit conditions. Inter-stop distances were set at 1.65 kilometres, representing typical urban arterial spacing. Vehicle capacity was fixed at 75 passengers, corresponding to standard bus configurations. Operating speeds were set at 35 km/h for both express and conventional services, reflecting urban traffic conditions (Yardim, 2002).

The cost structure employed realistic values derived from Istanbul's transit system financial data (The average exchange rate of the US dollar in 2000 was considered as 625,000 TL per USD for the calculations). Unit vehicle operating costs were set at 15.7 million TL per vehicle-hour, incorporating fuel, maintenance, labour, and overhead expenses. The value

of passenger time was established at 1.336 million TL per passenger-hour, reflecting economic valuations used in transit planning studies (Yardı, 2002).

Case Study 1: Many-to-Many Demand Pattern

The first computational experiment examined a demand pattern characterized by distributed passenger movements between multiple origin-destination pairs throughout the network. This pattern represents typical urban travel during peak periods when passengers move between various residential, employment, and activity centres.

The initial configuration included 30 potential routes serving a total demand of 5,267 passengers per hour. Express services were initially assigned to serve 26% of total passenger demand, with the remaining 74% assigned to conventional routes. This configuration required 69 vehicles and generated a total system cost of 4,225 million TL per hour (Yardı, 2002).

The optimization algorithm converged after 17 iterations (Figure 2), producing a dramatically simplified configuration.

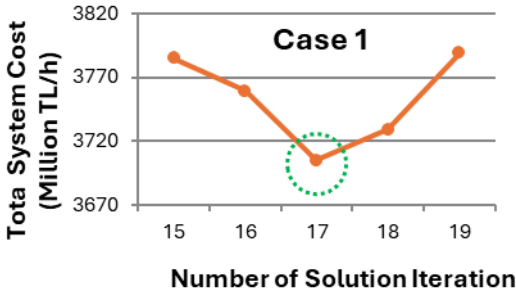


Figure 2: Optimal Solution Iteration-Case 1

The optimal solution eliminated 22 routes, retaining only 8 routes that more efficiently serve the passenger demand. The express service component was reduced to a single route serving just 5% of passengers, while conventional routes handled 95% of demand. This restructuring reduced the required fleet to 52 vehicles, representing a 25% reduction in vehicle requirements.

The cost implications were substantial across all categories. Operator costs decreased by 25% from 1,083 to 816 million TL per hour, reflecting the reduced fleet size and improved vehicle utilization (Table 2). User costs decreased by 8% from 3,142 to 2,889 million TL per hour, despite the reduction in express services (Table 3).

Table 2. Initial and optimal solution costs.

Costs (Mil. TL/h)	Case 1		Case 2	
	Initial solution	Optimal solution	Initial solution	Optimal solution
C_{ri}	1.083	816	1.099	942
C_{tk}	1.883	2.086	2.140	2.212
C_{bk}	1.259	803	1.047	956
C_{rk}	3.142	2.889	3.187	3.168
C_r	4.225	3.705	4.286	4.110

This seemingly counterintuitive result occurred because demand consolidation onto fewer routes enabled significant headway reductions, decreasing passenger waiting times more than the elimination of express services increased in-vehicle travel times.

The algorithm's progression revealed interesting dynamics in cost component behaviour. Operator costs decreased steadily throughout the optimization process as unprofitable routes were eliminated. User costs initially remained stable but began decreasing in later iterations as demand consolidation effects became pronounced. The waiting time component of user costs decreased by 36%, while in-vehicle time costs increased by only 9%, resulting in net user cost savings (Table 3).

Table 3. Cost changes: initial vs. optimal

Cost Components	Differences: Initial vs. Optimal	
	Case 1	Case 2
C_{ri}	-25%	-14%
C_{tk}	11%	3%
C_{bk}	-36%	-9%
C_{rk}	-8%	-1%
C_r	-12%	-4%

Case Study 2: One-to-One Demand Pattern

The second experiment examined a more concentrated demand pattern where passenger movements were focused between specific origin-destination pairs, representing scenarios such as commuter flows between residential areas and major employment centres or connections to high-capacity transit terminals.

This demand structure included 5,979 passengers per hour, with express services initially capturing 49% of demand due to the concentrated nature of passenger flows. The initial configuration again included 30 routes requiring 70 vehicles with a system cost of 4,286 million TL per hour (Yardim, 2002).

The optimization process converged more rapidly in this case, reaching optimality after only 11 iterations (Figure 3).

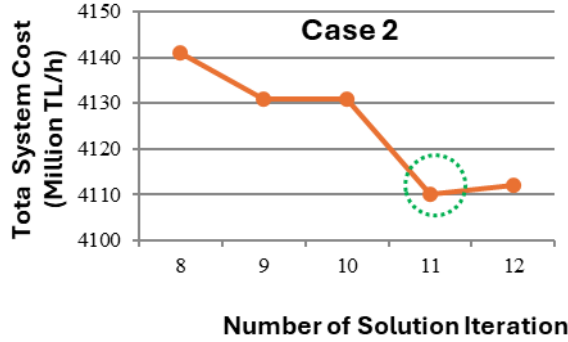


Figure 3: Optimal Solution Iteration-Case 2

The concentrated demand pattern proved more amenable to express service provision, with the optimal configuration retaining 6 express routes serving 46% of passengers. The fleet requirement was reduced to 60 vehicles, representing a 14% decrease from the initial configuration.

Cost reductions were more modest but still significant. Operator costs decreased by 14% to 942 million TL per hour, while user costs decreased by 1% to 3,168 million TL per hour (Table 2, Table 3). The smaller user cost reduction reflected the already efficient nature of express services for the concentrated demand pattern.

The financial performance improvement was notable in both cases. Net operator profit increased from 157 to 313 million TL per hour, demonstrating that route optimization can simultaneously improve both efficiency and financial viability.

Algorithm Performance and Convergence Characteristics

The heuristic algorithm demonstrated robust convergence characteristics across both test cases. The solution process exhibited three distinct phases: rapid initial improvement, gradual refinement, and clear convergence identification. The algorithm successfully identified optimal stopping points by monitoring system cost trends and detecting when further route eliminations would increase rather than decrease total costs.

Computational efficiency was excellent, with both cases converging within 11-17 iterations. The algorithm required approximately 2-3 minutes of computation time on standard desktop hardware, demonstrating practical applicability for real-world transit planning applications.

The robustness of solutions was verified through sensitivity analysis on key parameters. Variations in the value of time parameter, operating speeds, and headway constraints produced stable results with only minor adjustments to optimal configurations, indicating that the solutions are not overly sensitive to parameter uncertainties.

Service Type Utilization Analysis

The computational results revealed strong relationships between demand patterns and optimal service type utilization. Many-to-many demand patterns favour conventional services that can efficiently serve diverse passenger movements with reasonable transfer requirements. The optimal configuration in Case 1 utilized conventional services for 95% of passengers, with express services retained only for the highest-demand corridor.

Conversely, one-to-one demand patterns are well-suited to express service provision. Case 2 maintained 46% of passengers on express services, reflecting the efficiency of direct service for concentrated demand flows. This finding suggests that express service planning should focus on corridors with strong directional flows and concentrated activity centres.

The analysis also revealed important insights about route length and demand density relationships. Short routes with high demand consistently generated profits, while long routes required substantial demand volumes to achieve financial viability. Routes serving low-demand, long-distance markets were typically unprofitable and candidates for elimination or service reduction.

User Cost Component Analysis

A detailed examination of user cost components provided valuable insights into the optimization dynamics. The unexpected result that both operator and user costs decreased simultaneously was explained through careful analysis of user cost components.

Waiting time costs, which typically represent 30-40% of total user costs, decreased substantially as demand consolidation reduced headways on retained routes. In-vehicle time costs increased modestly due to the reduction in express services, but this increase was more than offset by waiting time reductions.

The waiting time parameter σ proved particularly influential in determining optimal configurations. Lower values of σ , representing more

schedule-oriented passenger behaviour typical during peak periods, favoured configurations with fewer, higher-frequency routes. Higher values representing random passenger arrivals favoured more diverse route offerings with potentially longer headways. Interested reader can access a more detailed account of computational results from the doctoral dissertation by Yardim (2002).

CONCLUSIONS

The computational studies demonstrate that systematic route optimization can achieve significant improvements in both operational efficiency and user service quality. The 4-12% reductions in total system costs, combined with 14-25% reductions in operator costs, suggest substantial potential for improving urban transit system performance through analytical optimization approaches.

The methodology is promising, particularly for the peak period service optimization, where concentrated demand patterns and capacity constraints create clear optimization opportunities. The approach could be extended to address off-peak periods through modifications to account for different demand patterns and service level requirements.

Future research directions include integration with multi-modal transportation networks, consideration of transfer-based travel patterns, and extension to more complex network topologies including grid and radial configurations. The incorporation of dynamic demand patterns and real-time optimization capabilities represents another promising avenue for practical application.

Bus transportation remains a critical component of urban mobility systems due to its flexibility, relatively low infrastructure requirements, and ability to serve diverse demand patterns. While significant progress has been made in developing analytical optimization models for bus systems, there remains substantial opportunity for creating more realistic and applicable models that can guide the design and operation of effective urban bus transportation systems. The continued evolution of urban form, travel patterns, and transportation technologies necessitates ongoing research to ensure bus systems can effectively contribute to sustainable urban mobility. Current analytical models, while providing valuable insights, remain largely limited to simplified and idealized geographical conditions. Most studies assume fixed demand patterns and focus on peak-period conditions, limiting their applicability to real-world scenarios with temporal demand variations.

Oversimplified spatial demand distributions; limited consideration of temporal demand variations; idealized network geometries such as grid, radial and trees; insufficient integration of multiple transportation modes; not accounting for service reliability and disruptions can be considered as some limitations.

Future research should address limitations by developing more realistic models that can handle complex urban geometries, variable demand patterns, and multi-modal integration. Additionally, there is a need for models that better incorporate the trade-offs between different service strategies and their impacts on various stakeholder groups.

The integration of new technologies, real-time information systems, and dynamic routing capabilities also presents opportunities for developing more responsive and efficient bus transportation systems that can better serve diverse urban mobility needs.

ACKNOWLEDGMENT

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