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Service Network Design Under Static Competitive Conditions: Optimizing Route Selection and Market Share Allocation Using A Logit Function

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Abstract

Transportation is one of the most important aspects of human activity, supporting a wide range of social and economic transactions. Meanwhile, to remain competitive, freight transportation businesses and logistics providers must deliver high-quality, reliable, and effective services. The effective design of the service network in this industry necessitates strategic and tactical decisions regarding service frequency, optimal route selection, and market share allocation among companies. In this study, we have examined static competition between two transportation companies using a Mixed-Integer Nonlinear Programming (MINLP) model. The competition is studied by calculating entrants' service frequency and each company's market share using a logit function. In this type of competition, the incumbent's route selection and frequency decisions are known in advance, and our goal is to maximize the new market entrant's profits. Additionally, several constraints have been considered, including route capacities, the maximum allowable frequency on each link, and penalty costs for incomplete utilization of route capacities. To evaluate and validate the model, real-world data from the Iranian Road Maintenance and Transportation Organization has been employed. Furthermore, during the sensitivity analysis phase, the effects of varying key parameters on the model's outputs were evaluated. This investigation aims to improve understanding of the system's dynamics and clarify how these factors influence optimal decision-making processes.

Keywords: Service network design, Static competition, Logit function.

1 | Introduction

Today, the transportation industry, as one of the most important foundations of each country's economy, plays a key role in the supply chain. This industry not only makes it easier to produce, distribute, and consume goods and services, but it also has a significant impact on all economic activities. As a result, lowering

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transportation costs and, thus, the costs of supplying manufactured goods to consumer markets significantly improves organizational competitiveness and fosters the expansion of economic activities across sectors, from industry to the national economy. In today's competitive environment, studying the interactions between companies and their decision-making processes under pressure has become increasingly important. One of the most difficult challenges in this respect is studying competition among freight companies, especially since the entry of a new company can significantly affect the market structure and the market share of existing enterprises.

In this regard, the design of transportation service networks is acknowledged as crucial in the area. The service network design problem contains the tactical planning decisions for consolidation-based freight transportation systems [1]. Service network design refers to the process of planning and optimizing the activities and resources of a transportation system to meet customer demand while maintaining profitability and quality standards. It involves determining routes, scheduling, and coordinating vehicles while considering integrated transportation and service requirements. Service network design is used across industries, including logistics, transportation, telecommunications, data sharing, and energy distribution.

In the service network design problem, transportation is treated as a service, and the term 'service network design' derives from this concept. The goal of such formulations is to plan services and operations to meet demand and ensure the firm's profitability [2]. Manufacturers require effective transportation services to convey their raw materials, semi-finished products, and finished goods. Service network design is based on integrating customer demand. If a customer's total demand equals the capacity of a wagon or truck, no integration occurs, and the entire load is allocated to a single customer.

Analysing these interactions and optimizing the design of transportation networks can lead to a better understanding of competition within this industry, as well as to operational solutions that decrease costs and boost productivity on a national scale. In the background of location and network design problems, there are generally three categories of competition: static, foresight-based, and dynamic. The fundamental assumption in static competition, which can be modeled as a conventional optimization problem, is that competitors already exist in the market and that their competitive factors do not change after the entry of a new competitor. Now, a new company aims to enter such a market.

The service design and pricing decisions of Logistics Service Integrators (LSIs) are not only influenced by operational costs but also by competitors' offers in the market [3]. Solving high-quality service network design problems not only enhances service providers' competitiveness but also contributes to reducing energy consumption and carbon emissions from a sustainable development perspective. The goal of formulations in this type of network design is to efficiently and economically use assets (such as vehicles, ships, drivers, etc.) to meet customer demands. Generally, the objective is to minimize the total cost of providing transportation services.

This study examines static competition between two transportation companies. The current research comprises route selection by the entrant firm, demand allocation between the two companies based on existing route travel time using a logit function, and, finally, determining route frequency for the entrant company.

2|Literature Review

The most important published papers on the topic of service network design are briefly reviewed in this section. Readers are directed to the review articles by Crainic [2], Wieberneit [2], and Farahani et al. [4] to become aware of the most recent findings in this field.

In the study by Lüer-Villagra and Marianov [5], this paper addresses the hub location and pricing problem in a competitive environment, where multiple transportation service providers aim to optimize hub locations and determine pricing strategies to maximize customer attraction and increase their profits. Competition among companies is modeled using customer choice models, such as the logit function. The study by

Nagurney et al. [6] develops static and dynamic models of supply chain networks in which multiple manufacturers and transportation service providers compete on price and quality. The competitive attributes of manufacturers are the price and quality of their products. Transportation service providers, on the other hand, compete in the price and quality of their transportation services under various conditions. Both decision-making groups aim to maximize profits while considering competitors' prices and quality levels. The models in this paper are formulated using game theory and variational inequalities, thereby aiding the analysis of competitive behavior in complex supply chains. In the study by Wang and Qi [1], integrated transportation systems that offer various services are examined, attracting increasing attention given the diversity of demand.

In this paper, the authors present two optimization models for the service network design problem, considering different types of services: 1) a deterministic model, and 2) a two-stage robust optimization model. Computational results demonstrate that the proposed robust optimization model can provide high-quality solutions that are resilient to demand uncertainties.

In the study by Tawfik and Limbourg [7], which served as the foundational work for the previous study, a bi-level model for network design and pricing based on Level-of-Service evaluation is presented. This model enables the simultaneous optimization of network design decisions and pricing strategies. The proposed model, by considering factors such as service quality, route capacities, and user behavior, aims to achieve a balance between the service provider's profit and maximizing customer attraction. The study by Li et al. [8] addresses the service network design problem with single paths and resource constraints, where each shipment must be delivered through a single path without flow splitting, and the number of available resources at each terminal is limited. The authors proposed two types of mathematical formulations for this problem: 1) node-arc formulation and 2) arc-cycle formulation. To address the models' high complexity, a two-stage heuristic based on integer programming and column generation was developed. Experimental results demonstrate that this approach is more efficient compared to commercial solvers such as CPLEX.

The study by Martin et al. [9] explores the design of fast transportation service networks that account for customer choices and delivery time constraints. The authors developed an optimization model that simultaneously determines proposed delivery times, pricing, and loading schedules to maximize profit. The proposed model demonstrates that considering both time constraints and customer choices concurrently yields better performance compared to sequential approaches. This research provides an effective solution for logistics companies seeking to optimize their service networks based on customer preferences and operational constraints. In the study by Tawfik et al. [10], a two-stage iterative heuristic algorithm is proposed to solve a bi-level network design and pricing model. By combining iterative and metaheuristic algorithms, the approach aims to find efficient and optimal solutions. The competition in this study is static, in which the upper-level decision-maker (such as a transportation company or logistics service provider) designs the service network and sets prices, while the lower-level decision-makers (users or competitors) select routes and service providers based on these decisions. Numerical results indicate that the proposed algorithm can improve solution quality.

The study by Wang et al. [3] created a bi-level programming model that simultaneously handles service network design and transportation service pricing under static competitive conditions. At the upper level, the model maximizes the profit of transportation companies by designing the service network and implementing cargo-based pricing for routes that align with heterogeneous demand for transportation services. At the lower level, the total cost for shippers in the network, who select services based on their preferences, is minimized. The results indicate that cargo-based pricing strategies are profitable for transportation companies, particularly when heterogeneous shipper preferences for time and reliability are taken into account. The study by Hewitt and Lehuédé [11] introduces a novel approach to formulating the Scheduled Service Network Design Problem (SSNDP), which models cargo consolidation in the physical network. Based on the innovations of this study, it can be presented as a consolidation-based formulation and a hybrid formulation that combines ideas from the consolidation-based and time-space network approaches. The results demonstrate that this hybrid formulation is easier to solve than both pure consolidation-based and time-space network-based formulations.

The study by Rahiminia et al. [12] examines a freight transportation network involving both rail and road modes using a bi-level model, in which shipper choices significantly influence decision-making. The rail operator is considered the leader, and the shipper is the follower. The rail operator determines transportation prices, after which the shipper decides which transport mode to use. For modelling, a bi-level multi-objective mixed-integer programming model has been developed that incorporates financial, social, and environmental aspects. In the domain of service network design, competition is a key factor influencing system performance and efficiency. However, the examination of competition in the design of these networks has rarely been addressed. Previous studies, which have primarily focused on static competition in service network design, have addressed this issue by presenting bi-level models.

In these models, at the upper level, transportation companies seek to maximize their profits and revenues by providing transportation services. In contrast, at the lower level, customers aim to minimize the costs associated with meeting their demand. Due to the inherent complexity of these models, solving them is NP-hard. Prior research has predominantly concentrated on aspects such as competition in pricing and service quality across various markets, including the transportation industry. Some of these studies have merely proposed strategies to enhance a transportation company's competitiveness without considering competition over travel time on its routes. This argument is noteworthy, as travel time is a critical factor in attracting and retaining customers; the shorter the travel time, the higher the likelihood of attracting and retaining them.

A review of the literature has identified a scientific gap: static competition in service network design has not yet been examined simultaneously within a single-level model. These models, due to their simpler structure, exhibit lower complexity and shorter solution times than bi-level models. Consequently, the development of a single-level model for analysing competition in service network design, particularly by considering the role of travel time, could represent a significant step forward in advancing research in this field.

3 | Problem Definition

In this study, a model for service network design under static competition conditions is presented. In this model, the first company (the incumbent, the market leader) determines the frequency of its flows on existing routes based on customer demand. Upon the second company (entrant) entering the market, this company, aware of the first company's flow frequencies, selects optimal routes for its shipments and specifies its own flow frequencies. To determine each company's share of demand for each shipment, a logit function is used.

This function effectively models the impact of route attractiveness and competition, determining each company's share based on the travel time of the selected routes. This approach enables a more precise analysis of competitive interactions and the impact of each company's decisions on market share. For the entrant company, higher profits are achieved when transporting passengers over longer routes, as transportation costs increase. However, the profit percentage for transporting shipments, determined by the market regulatory organization, is fixed. Therefore, the longer the route, the higher the profit. On the other hand, longer routes impose greater travel time on customers, creating competition between the incumbent and the entrant companies.

In this study, the following assumptions have been considered:

I. The problem is defined on a network. No specific assumptions are made about the network's structure beyond its connectivity.

II. The type of competition in this research is static.

III. The problem is examined in a single-period framework.

IV. All parameters are known and deterministic; uncertainty is not addressed in this study.

V. Demand between origin and destination pairs is specified.

VI. Services or vehicles have a defined capacity.

VII. The proposed model is route-based.

VIII. The road transport mode is considered in this problem.

IX. The problem is of a multi-commodity type.

3.1 | Mathematical Modelling

In this section, we introduce the symbols used in the model, including sets, parameters, and decision variables.

Table 1. Definition of sets.

Set	Definition
N	Index for the set of nodes
A	Index for the set of edges
r^E	Index for the set of routes of the entrant
r^I	Index for the set of routes of the incumbent

Table 2. Definition of parameters.

Parameter	Definition
q_k	Demand volume for commodity k
c_{road}	Variable transportation cost on edge (i, j)
u_{road}	Maximum capacity of transportation service on edge (i, j)
f_{road}	Fixed cost of a single transportation operation on edge (i, j)
t_{ij}	Travel time of the transportation service on edge (i, j)
t^k_{max}	Maximum delivery time for commodity k
ψ	Unit penalty cost if the maximum capacity of an edge/vehicle is not fully utilized
l_{ij}	Length of edge (i, j)
δ^r_{ij}	Binary parameter – equals one if edge (i, j) is part of route r
y^I_{ij}	Service frequency of the incumbent on edge (i, j)
θ_k	Sensitivity parameter of commodity k to travel time and delivery time
Δ	Profit rate of the service network on network routes (determined by the Market Regulator).
$W^I_{k,r}$	Binary parameter – equals one if commodity k is transported via route r belonging to the incumbent
maxF	Maximum frequency per period on each edge
T_{max}	Maximum travel time for edges established by both companies

Table 3. Definition of decision variables.

Decision Variable	Definition
$x^I_{k,r}$	Continuous variable – the percentage of demand for commodity k transported by the incumbent via route r
$x^E_{k,r}$	Continuous variable – the percentage of demand for commodity k transported by the entrant via route r
y^E_{ij}	Integer variable – the service frequency of the entrant on edge (i, j)
$W^E_{k,r}$	Binary variable – equals one if commodity k reaches its destination via route r

Nodes in such models represent locations in time and space, while arcs or links represent physical movements between locations or temporal movements at a single location [2]. To formulate the mathematical model for the research problem, the network is represented as the graph G = (N, A). In this graph, N denotes the set of nodes, and A represents the set of edges. The set of edges A includes road edges. Below, we present the mathematical model for a set of Origin-Destination (O/D) pairs.

$$\text{Max } Z = \Delta\left[\sum_{r\in r_k^E}\sum_{k\in K}\sum_{(i,j)\in N} q_k\, c_{road}\, l_{ij}\, \delta_{ij}^r\, x_{k,r}^E\right] - \sum_{(i,j)\in N} f_{road}\; y_{ij}^E - \sum_{r\in r_k^E}\sum_{k\in K}\sum_{(i,j)\in N} \psi\left(u_{road}\, y_{ij}^E - q_k\, \delta_{ij}^r\, x_{k,r}^E\right). \quad (1)$$

$$\sum_{(i,j)\in N} t_{ij}\; \delta_{ij}^r\, W_{k,r}^E \le\; t_{max}^k, \text{For all } k \in K, \text{For all } r \in r_k^E. \quad (2)$$

$$\sum_{r\in r_k^E}\sum_{k\in K} q_k\, \delta_{ij}^r\, x_{k,r}^E \le u_{road}\, y_{ij}^E, \text{For all } (i,j) \in N. \quad (3)$$

$$\sum_{r\in r_k^I}\sum_{k\in K} q_k\, \delta_{ij}^r\, x_{k,r}^I \le u_{road}\, y_{ij}^I, \qquad \text{For all } (i,j) \in N. \quad (4)$$

$$\sum_{r\in r_k^I} x_{k,r}^I + \sum_{r\in r_k^E} x_{k,r}^E = 1, \text{for all } k \in K. \quad (5)$$

$$x_{k,r}^E = \frac{W_{k,r}^E \exp\left(-\theta_k \sum_{(i,j)\in N}(t_{ij}/T_{max})\delta_{ij}^r\right)}{\sum_{r\in r_k^E} W_{k,r}^E \exp\left(-\theta_k \sum_{(i,j)\in N}(t_{ij}/T_{max})\delta_{ij}^r\right) + \sum_{r\in r_k^I} W_{k,r}^I \exp\left(-\theta_k \sum_{(i,j)\in N}(t_{ij}/T_{max})\delta_{ij}^r\right)}, \quad (6)$$

For all $r \in r_k^E$, For all $k \in K$.

$$x_{k,r}^I = \frac{W_{k,r}^I \exp\left(-\theta_k \sum_{(i,j)\in N}(t_{ij}/T_{max})\delta_{ij}^r\right)}{\sum_{r\in r_k^E} W_{k,r}^E \exp\left(-\theta_k \sum_{(i,j)\in N}(t_{ij}/T_{max})\delta_{ij}^r\right) + \sum_{r\in r_k^I} W_{k,r}^I \exp\left(-\theta_k \sum_{(i,j)\in N}(t_{ij}/T_{max})\delta_{ij}^r\right)}, \quad (7)$$

For all $r \in r_k^I$, For all $k \in K$.

$$x_{k,r}^E \le\; W_{k,r}^E, \text{For all } r \in r_k^E \text{ , For all } k \in K. \quad (8)$$

$$x_{k,r}^E \ge \varepsilon\, W_{k,r}^E, \text{For all } r \in r_k^E \text{ , For all } k \in K. \quad (9)$$

$$\sum_{r\in r_k^E} W_{k,r}^E = 1, \text{for all } k \in K. \quad (10)$$

$$y_{ij}^E \le \text{maxF}, \text{For all } (i,j) \in N. \quad (11)$$

$$x_{k,r}^E \ge 0, \text{For all } r \in r_k^E \text{ , For all } k \in K. \quad (12)$$

$$x_{k,r}^I \ge 0, \text{For all } r \in r_k^E \text{ , For all } k \in K. \quad (13)$$

$$y_{ij}^E \in Z^+, , \text{For all } (i,j) \in N. \quad (14)$$

$$W^{E}_{k,r} \in \{0,1\}, \text{For all } r \in r^{E}_{k}, \text{For all } k \in K. \quad (15)$$

This model is a Mixed-Integer Nonlinear Programming (MINLP) model. In this model, the objective *Function (1)* seeks to maximize the profit of the entrant, defined as the difference between the revenue generated from transporting shipments and the sum of two different types of costs. The first term represents the profit from transporting shipments, which is directly proportional to the route length. The second term is the fixed operational cost, determined based on the service frequency. The third term in the objective function is a penalty cost for vehicles if the full capacity is not utilized. In international freight transportation over long distances, insufficient demand or inefficient planning can lead to underutilized capacity, resulting in wasted resources.

Constraints (2) ensure that shipments transported by the entrant arrive at their destination within the maximum delivery time. *Constraints (3)* and *(4)* represent capacity constraints on transportation edges. It means that the flow values on an edge cannot exceed the capacity provided by a specific service, which is determined by the service's operational frequency.

Constraints (5) ensure that the total demand for each shipment is allocated between the entrant and the incumbent, and no portion of the demand is lost. *Constraints (6)* determine the percentage of the flow of commodity k directed by the entrant on the route r^{E}_{k} using a logit function. To prevent excessive dispersion of route travel times, travel times have been normalized. The numerator of the fraction represents the utility the customer derives from the entrant. *Constraints (7)*, similar to the previous constraint, determine the percentage of the flow of commodity k directed by the incumbent on the route r^{I}_{k}.

Constraints (8) ensure that a route is selected only if a portion of the demand is directed through that route. *Constraints (9)* indicate that a portion of the flow of commodity k is allocated to the entrant's route only if the entrant has selected that route. *Constraint (10)* ensures that at most one route from the entrant can be selected for each commodity. *Constraints (11)* enforce the maximum allowable frequency per period on each edge. Finally, the last four constraints describe the domain of the decision variables.

4 | Computational Experiments

All the required data for the research problem parameters were extracted from the Iran Road Transportation Yearbook. Based on the information available in this yearbook, data on the research model's parameters were collected and organized. In the first step, to define the network nodes, a set of key logistics cities in Iran was examined, leading to the selection of 29 cities as the network nodes. In this model, each company proposes two routes for each demand, and the final selection is one route from each company. In this study, 15 types of commodities were considered, for which the incumbent company investigated one route, and the entrant company investigated two routes.

Eventually, one route must be selected from the two proposed by the entrant, and the demand for each commodity should be allocated between the two routes based on their travel times. To acquire information about the incumbent firm, we initially addressed a service network design problem with capacity constraints, maximum frequency limits, and time-bound delivery constraints, to maximize profit. We derived the incumbent's selected routes and the corresponding frequency decisions for each route. Subsequently, the obtained data was utilized to solve the problem related to the entrant. The model was executed on a computer with 8 GB of RAM using GAMS version 25.1. The problem was solved using the BARON solver in GAMS. The solution was obtained within one minute.

Table 4. Market share of each company by commodity type.

Commodity	Entrant's Market Share	Incumbent's Market Share
k1	0/38	0/62
k2	0/437	0/563
k3	0/13	0/87
k4	0/688	0/312
k5	0/475	0/525
k6	0/976	0/024
k7	0/443	0/557
k8	0/941	0/059
k9	0/429	0/571
k10	0/766	0/234
k11	0/435	0/565
k12	0/665	0/335
k13	0/007	0/993
k14	0/296	0/704
k15	0/548	0/452

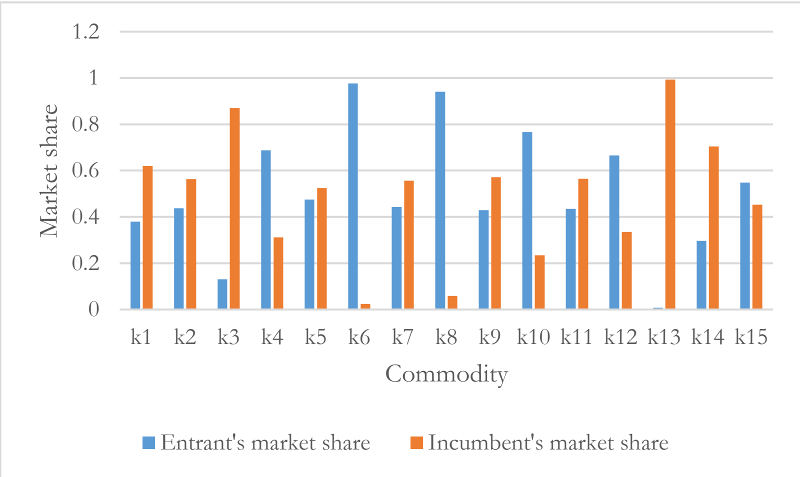

Fig. 1. Market share of each company by commodity type.

After solving the model, the optimal solutions for demand allocation to routes and route selection were obtained. According to *Table 4* and *Fig. 1*, the results indicate that approximately 51% of the market share belongs to the entrant company, while the incumbent company holds the remaining 49%. The profit generated by the entrant company from providing transportation services equals 6,132,732.276. To prevent excessive dispersion of route travel times, travel times have been normalized.

In this section, the impact of three key model parameters on the research results is analyzed through six graphs. These three parameters include:

I. Profit rate (Δ)

II. Customer sensitivity to travel time between origin and destination (θ).

III. Travel times

In the sensitivity analysis for each parameter, the other parameters are held constant to examine the independent impact of each accurately.

Fig. 2. Entrant's profit variations relative to profit rate changes.

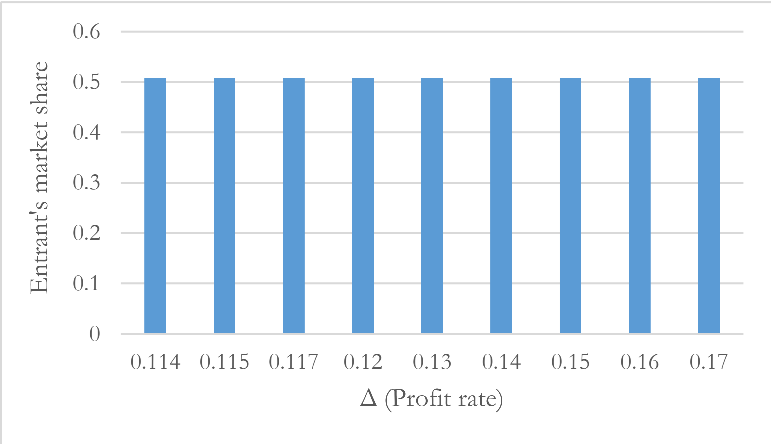

Fig. 3. Entrant's market share variations relative to profit rate changes.

According to *Fig. 1*, as Δ (the profit rate) increases, the profit of the entrant company also increases. Since Δ represents the network's profit rate on the routes associated with that company, a higher profit rate directly increases the entrant's profit. As shown in *Fig. 2*, since the solution does not change with variations in Δ, the market share remains constant.

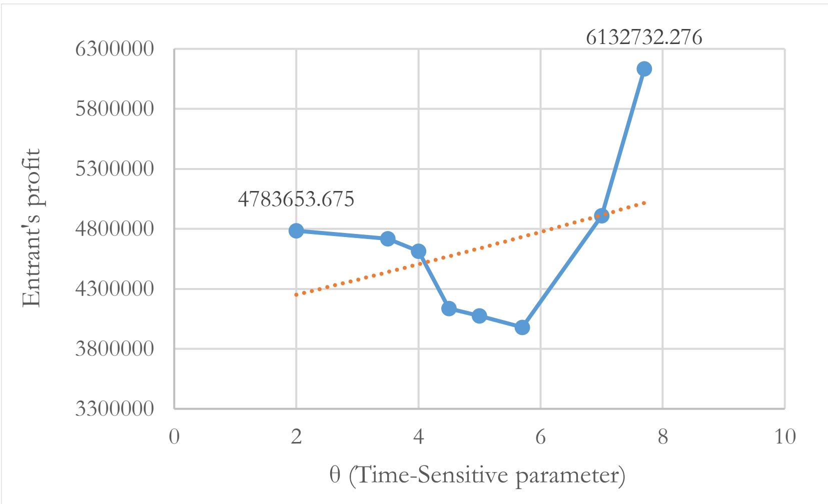

Fig. 4. Entrant's profit variations relative to time-sensitive parameter changes.

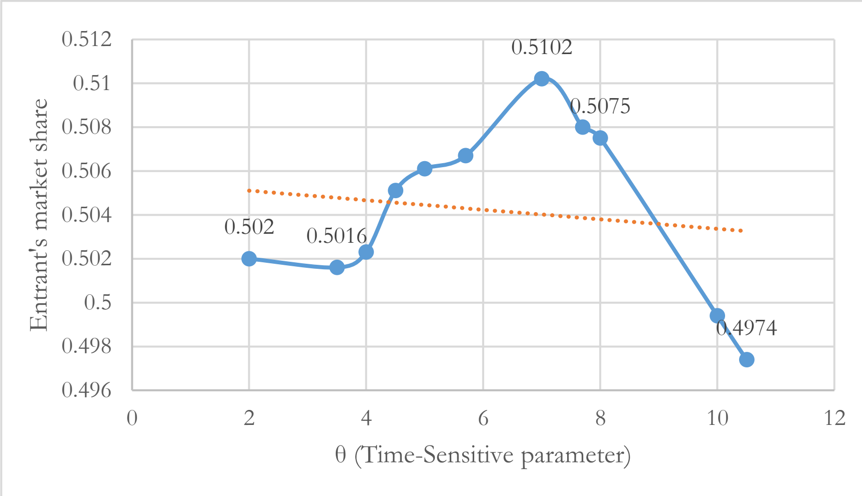

Fig. 5. Entrant's market share variations relative to time-sensitive parameter changes.

According to *Fig. 3*, an increase in θ (the parameter representing the customer's sensitivity to travel time between the origin and destination) initially leads to a decrease in the entrant company's profit, followed by an increase. The logit model includes a parameter that is sensitive to θ. The higher this parameter's value, the more sensitive customers are to travel time, preferring routes with shorter travel times. A lower value of θ indicates that customers are less sensitive to time (or time differences), resulting in a more dispersed distribution of shipments across the routes offered by the two companies. Therefore, the logit function, which also introduces nonlinearity into the model, causes such variations in profit.

Since the solutions change completely with an increase in θ, as shown in *Fig. 4*, this initially leads to an increase in the entrant's market share, followed by a decrease. The graph indicates that the entrant achieves its maximum market share when θ equals 7. One of the key parameters in this study is travel time. In this section, incremental and decremental changes to the travel times of the entrant's edges, while keeping the competitor's edges' travel times constant, are applied to examine their impact on the entrant's market share and profit. As shown in *Fig. 5*, a decrease in travel time increases customers' preference for choosing the second company, thereby increasing its market share. Conversely, an increase in travel time negatively affects the attractiveness of the entrant company, leading to a reduction in its market share.

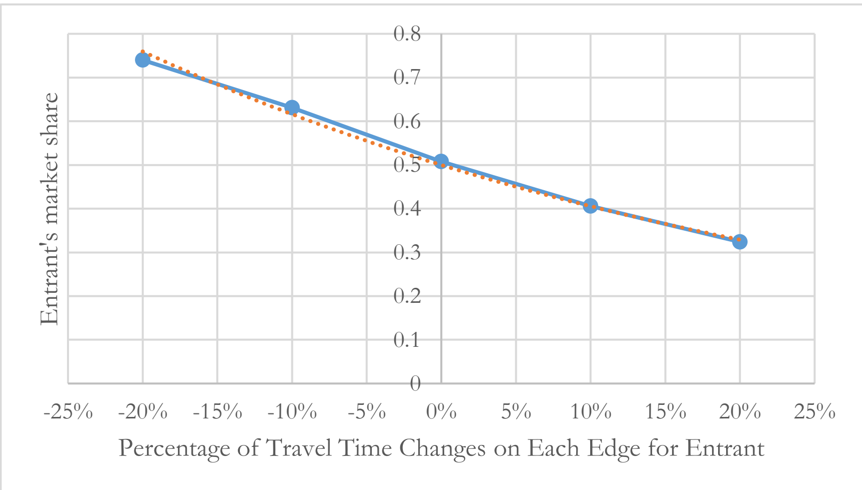

Fig. 6. Entrant's market share variations relative to edge's travel time changes.

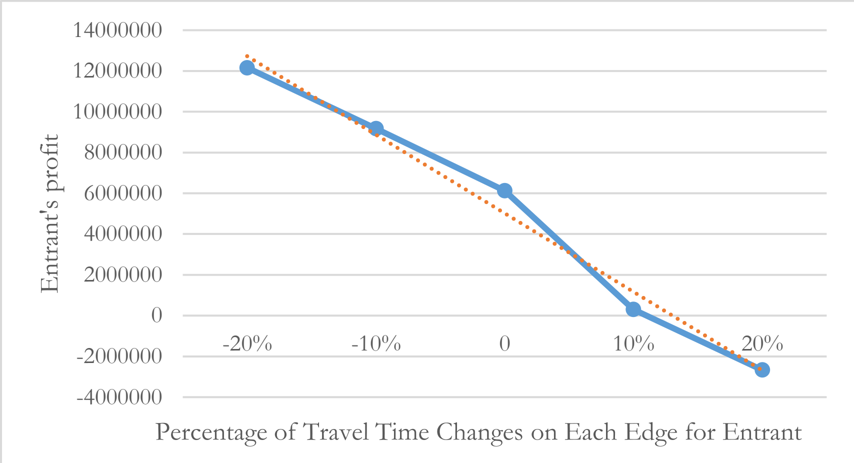

Fig. 7. Entrant's profit variations relative to edge's travel time changes.

Therefore, changes in profit align with changes in market share (*Fig. 6*). Given that several parameters influence the model's design, the role of each in achieving the optimal solution is particularly important. Additionally, changes in parameters do not always result in a uniform or linear change in the entrant's profit. The results indicate that altering a parameter can increase or decrease the entrant's profit under different conditions, and these changes do not always follow a strictly increasing or decreasing trend.

5 | Conclusion

This study investigated the design of service networks under static competitive conditions, where competition between companies was defined by route travel times. The shorter the travel time of a route, the more attractive it becomes to customers. To model this problem, a MINLP model was proposed, incorporating a logit function to determine each company's market share. Additionally, time constraints for shipments, limited edge capacities, and maximum frequencies per edge were also considered in the model. To evaluate the model and validate the results, a numerical analysis was conducted. The findings indicate that an increase in the profit rate (set by the market regulatory organization) leads to higher overall company profits.

Furthermore, the optimal value of the parameter θ (customer sensitivity to travel time) was determined for the research problem. The results show that if θ deviates from its optimal value, either higher or lower, the entrant's market share decreases. The key contributions of this study are the following:

I. Developing a mathematical model for service network design under static competitive conditions, incorporating the logit function.

II. Analysing the impact of competition on the configuration of service networks and examining the effects of changes in key parameters.

III. Utilization of customer-imposed travel time as the basis for competition, which represents the primary innovation of this research.

Finally, there are several suggestions for future research as follows:

I. Developing efficient solution methods for solving the problem at both small and large scales.

II. Investigating other transportation modes alongside road transportation to achieve a more comprehensive model.

The findings of this study can serve as a foundation for future research in the optimization of competitive service networks and the analysis of regulatory policy impacts on supply chains.

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Data Availability

All data are included in the text.

Conflicts of Interest

The authors declare no competing interests.

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