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A Game-Theoretic Approach for Transportation of Oil Products in a Duopolistic Supply Chain

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ABSTRACT: Transportation market is severely impacted by the modes of transportation and the competitiveness between them. Although the fact that the pipeline is considered the most prevalent mode of transporting oil products, policymakers confront several parameters in making a straightforward decision about how to transport such products. Other modes of transportation may be used in many regions due to higher flexibility and affordability. Therefore, competition between pipelines and other modes of transportation exists due to economic concerns. Therefore, a study clarifying this competition is essential. In this study, a game-theoretic framework in a duopolistic supply chain is developed for modeling the competition of two oil products transportation systems, including road and intermodal pipeline-road. These are considered the most prevalent modes of transporting oil and refinery products in many countries. Transportation prices of the two rival systems, in addition to the availability of tanker truck fleet are the main variables considered in this study. Flexible and inflexible schemes are introduced and based on them, the effects of four different policies on the degree of competence in the oil transportation market are analyzed. Moreover, some useful managerial insights are provided including transfer from flexible scheme to inflexible scheme, fuel price increase, employment of modern trucks with low fuel consumption, and decrease of peripheral costs in the intermodal system.

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1- Introduction

Transportation of oil and refinery products including all types of fuels is one of the largest concerns of supply chain managers confronting economic, environmental, and social issues. High benefits related to the transportation of oil products have stimulated transportation systems to achieve higher market shares from the oil industry. Oil and its derivatives can be carried through various modes of transportation, such as pipeline, tanker truck, rail, or ship. It should be noted that the pipeline is generally considered as the most justified mode of carrying oil derivatives because of the higher reliability, affordability, and safety compared to other modes [1, 2]. However, due to various situations of origins and destinations, there may exist a competition between different systems of transportation to increase their share from the transportation market of the oil industry and gain much more profit.

In the oil industry, exploration and production of crude oil are the main upstream activities. Midstream activities consist of all refining and transport procedures of oil and its derivatives to distribution centers. Transportation, marketing, and distribution of petroleum products to the demand nodes are referred to as downstream activities [3, 4]. What makes the competition of different transportation modes much more challenging is the availability of these transportation modes in upstream, midstream, and downstream parts of oil transportation routes [5].

As mentioned earlier, the pipeline is considered the most cost-effective mode of transporting oil and its derivatives [6]. Nevertheless, a comprehensive approach should be followed to achieve a balance between different transportation modes. For instance, short distances between refineries and distribution centers or distribution centers and demand nodes stimulate carriers to use road transportation instead of pipeline or any other modes [7]. High initial construction costs, fixed origins, and destinations, and inflexibilities due to limited capacity are the main disadvantages of pipeline systems [8]. Intermodal transportation of refinery products is a trend thatis accompanied by several profits such as increased flexibility [9]. Intermodalism may reduce the disadvantageous of one single-mode and integrates the cost and service benefits of two or more transportation modes [10].

Several studies have assessed the transportation of oil and its derivatives from various points of view. MirHassani [11] implied that for large consumer markets with high demands, oil companies are eager to utilize pipelines regarding their low operating costs. This research focused on modeling a framework for transportation and scheduling of large-scale problems using mixed-integer linear programming. Kazemi and Szmerekovsky [3] highlighted a petroleum supply chain network problem in which optimal distribution center

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locations and transportation modes have been determined using mixed-integer linear programming. Siddiqui, Verma, and Verter [6] presented a bi-objective MILP with a time-based heuristic solution to solve a problem of one refinery and several distribution centers. The main transportation modes focused on in this study are pipeline and marine. Yue and You [12] determined the optimal design and planning of non-cooperative supply chains from the manufacturer's point of view by proposing a bi-level mixed-integer nonlinear programming (MINLP) model.

Intermodal freight transportation terminals provide an opportunity to integrate loads from at least two modes of transportation before delivering to customers [10]. Although Intermodal competition for different transportation modes has been studied extensively [13-26], few studies have focused on the competition between pipeline, and other transportation modes [9, 27, 28]. Moradinasab, Amin-Naseri, Behbahani and Jafarzadeh [27] proposed a sustainable competitive petroleum supply chain model using a game-theoretical approach. This model features the optimal design of a supply chain network considering economic, social, and environmental aspects. Results illustrated that in Stackelberg Equilibrium, where the government is the leading player and the public sector is the follower, the total revenue of the supply chain is smaller than that of Nash Equilibrium in which the government and private sectors concurrently determine their prices and demands. Oke, Huppmann, Marshall, Poulton, and Siddiqui [9] assessed a dynamic intermodal model for designing multi-fuel energy networks. The model considers the distinct effects of each mode of transportation in the energy network. This research considers four distinct modes: rail, pipeline, river-going barge, and ship (or tanker). Supply chain scheduling is an important issue in both production systems and supply chain management [29, 30].

The main focus of the current research is the application of the game-theoretic approach framework in a duopolistic supply chain to model such a competition problem involving the transport of oil derivatives.

Accordingly, four main contributions are developed in this study to enhance this issue:

Modeling the competition between road and road-pipeline intermodal transportation.

Contemplating both flexible and inflexible schemes for the transportation market.

Solving the static and dynamic models through Nash and Stackelberg games, respectively.

Consideration of different policies and their consequences on the competing systems.

The rest of the paper is structured as follows: Section 2 introduces a description of the problem and the basic assumptions considered. Section 3 is contributed to the problem modeling. In Section 4, the equilibrium solutions are presented. In Section 5, the results and discussion, as well as some managerial insights, are elucidated; and the paper is concluded in the final section

The nomenclature applied for this study is introduced in Appendix.

2- Problem Description

While the pipeline is considered the most efficient means of transporting oil and its derivatives, other modes of transportation may be used in many regions, due to higher flexibility and affordability. In other words, there exists a competition between pipelines and other modes of transportation due to economic concerns. Therefore, a study clarifying this competition is essential.

Considered in this paper are the conditions in which two different competing transportation systems including road and intermodal pipeline-road compete with each other. These systems are the most common means of transporting refinery products in many regions. A constant demand must be carried between origin and destination nodes. The origin node may be either a refinery or distribution center, while the destination node can be either a distribution center or a demand node. Each transportation system carries refinery products from a specific route. A mode shift is performed in an intermodal system. A schematic representation of two competing modes is illustrated in Fig. 1.

Each transportation system has its cost, demand, and profit functions and provides transportation services, tomaximize its profit. Consequently, both systems tend towards an equilibrium situation in which their profits are concurrently maximized. In this way, the game-theoretic approach can be applied to determine the equilibrium solutions of the problem. Each transportation system has a specific price for the service provided. The road system provides the services according to its final price, as well as the available tanker truck fleet; while, the intermodal pipeline-road system provides the services based on its final price and the amount of pipeline flow rate. The main variables considered in this study are the prices of the two competing systems for transporting the products, as well as the variable representing fleet availability of the road system. These variables have been applied in some previous studies[31-34]. Road fleet availability is calculated using Eq. (1).

$$q_R = \frac{C}{h_R} \tag{1}$$

Where q_R is the volume transported in any time unit. The transportation demand functions are assumed as linear functions of the equilibrium prices p_R and p_M and facilities of both systems including road fleet availability q_R and pipeline flow rate q_M. The pipeline flow rate is assumed a predefined parameter. Applying the game-theoretic approach results in equilibrium prices p_R and p_M, and equilibrium amount of road fleet availability q_R. Two different schemesare considered in this study. In the first scheme, the system is regarded as flexible. Therefore, in this scheme, both road and intermodal pipeline-road transportation systems act at the same level. In other words, relevant equilibrium prices, as well as equilibrium road fleet availability, are determined by simultaneous maximization of road and intermodal road-

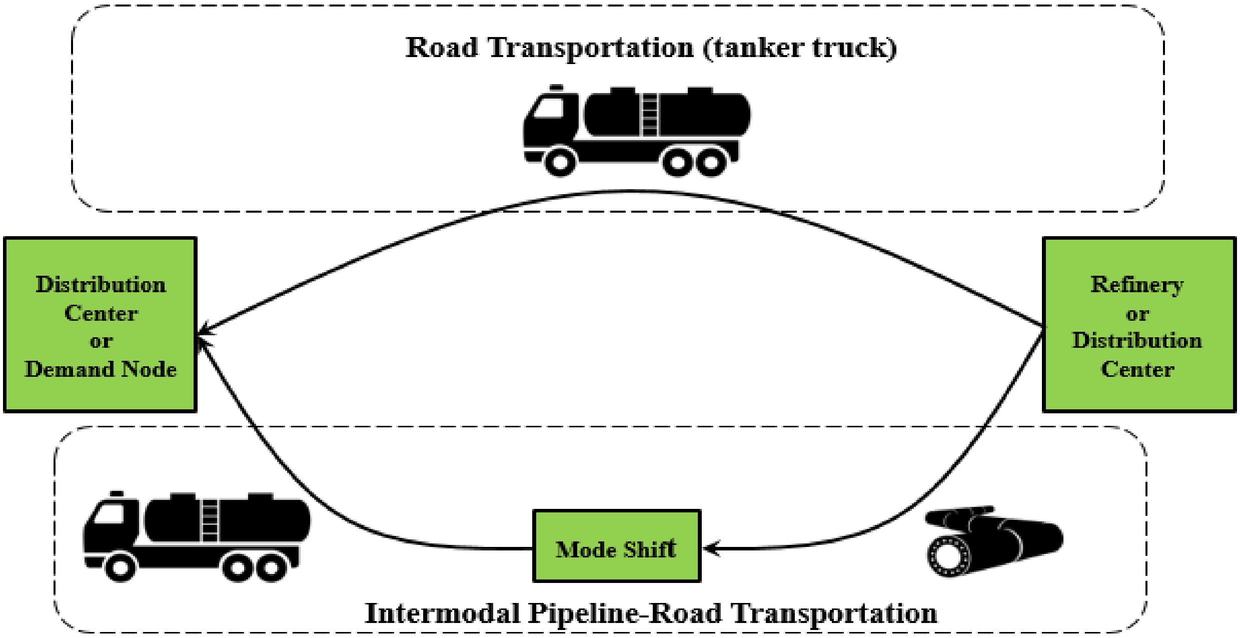


Fig. 1. Two competing systems considered in the study

pipeline transportation profits. This approach is formulated through the Nash equilibrium model. The second scheme is regarded as inflexible. In this scheme, the problem is solved in two levels in which a leader chooses his best strategy freely and a follower acts correspondingly to gain his best response. In this case, road fleet availability which varies depending on the facilities available can be chosen as the leader and both system prices act as followers. In the first stage, road fleet availability is determined based on assumed parameters and by maximization of road transportation profit. In the second stage, transportation prices are calculated based on determined road fleet availability and by profit maximization of both systems. This approach is formulated through Stackelberg equilibrium models. The solutions and further analysis elucidate the effect of different policies on demand and profits gained by each transportation system. Fig. 2 illustrates the structure of both Nash and Stackelberg schemes.

There exists a separate route for each transportation system to carry a specific amount of product from origin to destination. The first route is road haulage with a length of D_R and the second route is a combination of pipeline and road transportation with a length of D_M, for which $d.D_M$ is considered as road part of the intermodal system. It should be noted that transportation of refinery products through a pipeline is restricted to a maximum allowable flow rate which is related to transported material and pumping facilities. Each transportation mode is managed by a distinct logistic stakeholder. Each system plays its role in attracting much more transportation demand.

Here are some assumptions used for this study:

All parameters are non-negative.

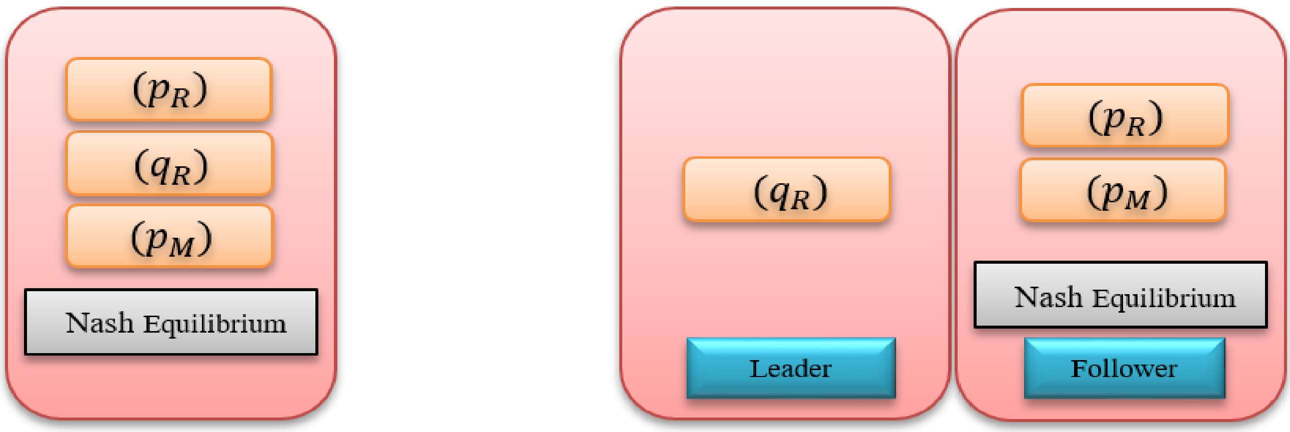
Road fleet availability is a function of two main parameters including the capacity of each tanker truck and road fleet headways.

Road fleet availability and pipeline flow rate have the same unit (volume per time unit).

The demand of each mode is more sensitive to its price than the price of the competing model. Therefore, self-elasticity is higher than cross-elasticity $(\beta_p > \gamma_p)$.

The demand of each mode is more sensitive to its amount of facility compared to its competing mode $(\beta_n > \gamma_q)$.

The following relationship exists which means that road haulage in intermodal transportation is smaller than road haulage in road-only transportation mode: $(D_R > d\ D_M)$.



Flexible Scheme **Inflexible Scheme**

Fig. 2. Structure of both flexible and inflexible schemes

3- Problem Modeling

The main objective of this section is to formulate demands, costs, and profit functions to calculate equilibrium prices of each transportation system besides equilibrium road fleet availability. The serviceability of tanker trucks depends on-road facilities available which should be considered variable. Nevertheless, it should be noticed that pipeline flow rate is dependent on materials being carried and therefore is predefined and considered as a parameter. As a consequence, $p_R, p_M,$ *and* q_R are assumed to be variables. The demand functions for road and road-pipeline modes are represented as follows:

$$Q_R\left[p_R, q_R, p_M\right] = \alpha - \beta_p p_R + \gamma_p p_M + \beta_q q_R - \gamma_q q_M \quad (2)$$

$$Q_M\left[p_R, q_R, p_M\right] = Q - \left(\alpha - \beta_p p_R + \gamma_p p_M + \beta_q q_R - \gamma_q q_M\right) \quad (3)$$

The summation of two demand functions is equal to the fixed amount defined in volume transported per time unit. It is worth noting that both higher prices and lower facilities have negative effects on the number of equilibrium demands of each transportation system.

The costs imposed on the road transportation system to carry the refinery products include the cost of fuel consumed by tanker trucks which are related to the distance traveled and the fixed expenses associated with wages and toll payments. On the other hand, the intermodal transportation costs include intermodal fixed costs including wages, toll payments, and other costs imposed due to mode shift, storage, extra loading, and variable costs of pipeline transportation [35, 36]. The operational cost of pipeline transportation c_{op} is determined per volume transferred per distance unit. It is assumed that there exist no infrastructure costs related to road and pipeline constructions.

The cost functions for carrying one unit of demand from origin to destination are introduced in Eq. (4) and Eq. (5) as follows:

$$c_R = \bar{c}_R + f\,\theta D_R \quad (4)$$

$$c_M = \bar{c}_M + f\,\theta d D_M + c_{op}\left(1-d\right)D_M \quad (5)$$

As mentioned in Eq. (4) and Eq. (5), the fuel cost is assumed a function of distance traveled, fuel consumption rate and price of fuel consumed by tanker trucks.

Eq. (6) and Eq. (7) illustrate profit functions that should be maximized.

$$\Pi_R\left[p_R, q_R, p_M\right] = \left(p_R - c_R\right)Q_R\left[p_R, q_R, p_M\right] - \lambda_R q_R^{\,2} \quad (6)$$

$$\Pi_M\left[p_R, q_R, p_M\right] = \left(p_M - c_M\right)Q_M\left[p_R, q_R, p_M\right] \quad (7)$$

The term $\lambda_R {q_R}^2$ represents the investment cost required for increasing road facilities.

Eq. (8) and Eq. (9) are resulted by substituting Eq. (2) to Eq. (5) in Eq. (6) and Eq. (7).

$$\Pi_R[p_R,q_R,p_M]=(p_R-\bar{c}_R-f\,\theta D_R)\begin{pmatrix}\alpha-p_R\beta_p+p_M\gamma_p+q_R\beta_q-\\ q_M\gamma_q\end{pmatrix}-\lambda_R {q_R}^2 \quad (8)$$

$$\Pi_M[p_R,q_R,p_M]=\begin{pmatrix}p_M-\bar{c}_M-\\ (df\,\theta+c_{op}-dc_{op})D_M\end{pmatrix}\left(Q-(\alpha-p_R\beta_p+p_M\gamma_p+q_R\beta_q-q_M\gamma_q)\right) \quad \textbf{(9)}$$

4- The Equilibrium Solution for the Two Competitive Systems

In this section, it is assumed that both transportation systems have the same power in attracting customer demands. It should be noted that what makes them more preferable for customers is their final transportation prices and available facilities. The model is formulated with two main objectives. The first objective of the model aims to maximize the total profit of the road transportation system, while the second objective maximizes the total profit of the intermodal pipeline-road transportation system. The objectives are formulated as follows:

$$\begin{cases}\max\limits_{p_R,q_R}\pi_R(p_R,q_R,p_M)\\ \max\limits_{p_M}\pi_M(p_R,q_R,p_M)\end{cases} \quad (10)$$

For solving the abovementioned problem, two different schemes can be followed. All the steps are followed using Mathematica software

4.1. Flexible Scheme

In this scheme, road fleet availability and prices are calculated concurrently. The main reason behind this scheme is consideration of any resulted fleet size which should be affordable. To Nash equilibrium, both prices and road fleet availability are specified by maximizing both system's profits and are determined concurrently.

Lemma 1. To maximize π_R and π_M, these functions must be concave on the defined variables. Based on the proof provided in Appendix, π_R is concave on p_R and q_R and π_M is concave on p_M.

The results of the Nash equilibrium approach Karush-Kuhn-Tucker method are introduced in Eq. (11) to Eq. (17).

$$p_R=\frac{(\bar{c}_R+f\,\theta D_R)\beta_q^2-2\begin{pmatrix}Q+\alpha+2(\bar{c}_R+f\,\theta D_R)\beta_p+\bar{c}_M\gamma_p\\ +(df\,\theta+(1-d)c_{op})D_M\gamma_p-q_M\gamma_q\end{pmatrix}\lambda_R}{\beta_q^2-6\beta_p\lambda_R} \quad (11)$$

$$q_R=-\frac{\beta_p\begin{pmatrix}Q+\alpha-(\bar{c}_R+f\,\theta D_R)\beta_p+\bar{c}_M\gamma_p\\ +(df\,\theta+(1-d)c_{op})D_M\gamma_p-q_M\gamma_q\end{pmatrix}}{\beta_q^2-6\beta_p\lambda_R} \quad (12)$$

$$p_M=\frac{\beta_q^2\left(Q+(\bar{c}_M+(df\,\theta+(1-d)c_{op})D_M)\gamma_p\right)-2\beta_p\begin{pmatrix}2Q-\alpha+\bar{c}_R\beta_p+\\ f\,\theta D_R\beta_p\\ +2(\bar{c}_M+(df\,\theta+(1-d)c_{op})D_M)\gamma_p\\ +q_M\gamma_q\end{pmatrix}\lambda_R}{\gamma_p(\beta_q^2-6\beta_p\lambda_R)} \quad (13)$$

$$Q_R[p_R,q_R,p_M]=\frac{2\beta_p\begin{pmatrix}Q+\alpha-(\bar{c}_R+f\,\theta D_R)\beta_p+\bar{c}_M\gamma_p\\ +(df\,\theta+(1-d)c_{op})D_M\gamma_p-q_M\gamma_q\end{pmatrix}\lambda_R}{-\beta_q^2+6\beta_p\lambda_R} \quad (14)$$

$$Q_M[p_R,q_R,p_M]=\frac{Q\beta_q^2+2\beta_p\lambda_R\begin{pmatrix}-2Q+\alpha-(\bar{c}_R+f\,\theta D_R)\beta_p+\\ \bar{c}_M\gamma_p+(df\,\theta+(1-d)c_{op})D_M\gamma_p-q_M\gamma_q\end{pmatrix}}{\beta_q^2-6\beta_p\lambda_R} \quad (15)$$

$$\Pi_R\left[p_R,q_R,p_M\right]=\frac{\begin{pmatrix}Q+\alpha-\left(\bar{c}_R+f\,\theta D_R\right)\beta_p+\bar{c}_M\gamma_p+\\ \left(df\,\theta+(1-d)c_{\text{op}}\right)D_M\gamma_p-q_M\gamma_q\end{pmatrix}^2\lambda_R\left(-\beta_q^2+4\beta_p\lambda_R\right)}{\left(\beta_q^2-6\beta_p\lambda_R\right)^2} \quad (16)$$

$$\Pi_M\left[p_R,q_R,p_M\right]=\frac{\begin{pmatrix}Q\beta_q^2+2\beta_p\\ \begin{pmatrix}-2Q+\alpha-\left(\bar{c}_R+f\,\theta D_R\right)\beta_p\\ +\bar{c}_M\gamma_p+\left(df\,\theta+(1-d)c_{\text{op}}\right)D_M\gamma_p-q_M\gamma_q\end{pmatrix}\lambda_R\end{pmatrix}^2}{\gamma_p\left(\beta_q^2-6\beta_p\lambda_R\right)^2} \quad (17)$$

4.2. Inflexible Scheme

In this scheme, a two-level problem solution is considered. Therefore, road fleet availability is chosen as the leader and both systems prices act as followers. This approach is formulated and solved through Stackelberg equilibrium models. As a consequence, road fleet availability is regarded as the leader, and prices are considered as the followers. Road fleet availability is calculated by maximization of road transportation profit. Equilibrium prices are determined based on the simultaneous maximization of both system's profits.

Lemma 2. To maximize and , these functions must be concave on the defined variables. Based on the proof provided in Appendix, is concave on and and is concave on .

Theorem 2. The results of the Stackelberg equilibrium approach using the Karush-Kuhn-Tucker method are introduced in Eq. (18) to Eq. (24).

$$p_R=\frac{Q+\alpha+2\left(\bar{c}_R+f\,\theta D_R\right)\beta_p+q_R\beta_q+\bar{c}_M\gamma_p+\left(df\,\theta+(1-d)c_{\text{op}}\right)D_M\gamma_p-q_M\gamma_q}{3\beta_p} \quad (18)$$

$$p_M=\frac{2Q-\alpha+\bar{c}_R\beta_p+f\,\theta D_R\beta_p-q_R\beta_q+2\left(\bar{c}_M+\left(df\,\theta+(1-d)c_{\text{op}}\right)D_M\right)\gamma_p+q_M\gamma_q}{3\gamma_p} \quad (19)$$

$$q_R=-\frac{\beta_q\begin{pmatrix}Q+\alpha-\left(\bar{c}_R+f\,\theta D_R\right)\beta_p+\bar{c}_M\gamma_p\\ +\left(df\,\theta+(1-d)c_{\text{op}}\right)D_M\gamma_p-q_M\gamma_q\end{pmatrix}}{\beta_q^2-9\beta_p\lambda_R} \quad (20)$$

$$Q_R\left[p_R,q_R,p_M\right]=\frac{3\beta_p\begin{pmatrix}Q+\alpha-\left(\bar{c}_R+f\,\theta D_R\right)\beta_p+\bar{c}_M\gamma_p\\ +\left(df\,\theta+(1-d)c_{\text{op}}\right)D_M\gamma_p-q_M\gamma_q\end{pmatrix}\lambda_R}{-\beta_q^2+9\beta_p\lambda_R} \quad (21)$$

$$Q_M\left[p_R,q_R,p_M\right]=\frac{Q\beta_q^2+3\beta_p\begin{pmatrix}-2Q+\alpha-\left(\bar{c}_R+f\,\theta D_R\right)\beta_p+\bar{c}_M\gamma_p\\ +\left(df\,\theta+(1-d)c_{\text{op}}\right)D_M\gamma_p-q_M\gamma_q\end{pmatrix}\lambda_R}{\beta_q^2-9\beta_p\lambda_R} \quad (22)$$

$$\Pi_R\left[p_R,q_R,p_M\right]=\frac{\begin{pmatrix}Q+\alpha-\left(\bar{c}_R+f\,\theta D_R\right)\beta_p+\bar{c}_M\gamma_p\\ +\left(df\,\theta+(1-d)c_{\text{op}}\right)D_M\gamma_p-q_M\gamma_q\end{pmatrix}^2\lambda_R}{-\beta_q^2+9\beta_p\lambda_R} \quad (23)$$

$$\Pi_M\left[p_R,q_R,p_M\right]=\frac{\begin{pmatrix}Q\beta_q^2+3\beta_p\\ \begin{pmatrix}-2Q+\alpha-\left(\bar{c}_R+f\,\theta D_R\right)\beta_p\\ +\bar{c}_M\gamma_p+\left(df\,\theta+(1-d)c_{\text{op}}\right)D_M\gamma_p-q_M\gamma_q\end{pmatrix}\lambda_R\end{pmatrix}^2}{\gamma_p\left(\beta_q^2-9\beta_p\lambda_R\right)^2} \quad (24)$$

5- Results and Discussion

In the preceding section, equilibrium prices and road fleet availability besides corresponding transportation demands and profits are determined using two main approaches including Nash and Stackelberg. The following section represents parametric analysis related to change in road segment ratio. Additionally, a numerical example is represented and the effects of four critical policies on equilibrium prices, road fleet availability, demands, and profits are assessed both parametrically and numerically. These policies include:

- Transfer from flexible scheme to inflexible scheme
- Fuel price increase
- Employment of modern trucks with low fuel consumption
- Decrease of peripheral costs in the intermodal system

5.1. Analysis of Variation in road segment ratio of the intermodal system(d)

Parametric analysis of road segment ratio of the intermodal transportation system , with respect to p_R , q_R, p_M , Q_R , Q_M , π_R and π_M are analyzed using Mathematica software. As a result, if fuel cost exceeds pipeline operational cost for one unit of demand transported $(f > \frac{c_{op}}{\theta})$, by any increase in road segment ratio, p_R , q_R , p_M, Q_R , and π_R increase. This trend is reversed in Q_M , and π_M cases, which means that if $f > \frac{c_{op}}{\theta}$ then by any increase of , demand and profit of intermodal system will be decreased.

5-2- Assessment of Different Policies

5.2.1. Policy 1: Transfer from inflexible to flexible Scheme

As mentioned earlier, the difference between flexible and inflexible schemes is in the possibility of changing the road fleet availability. According to the parametric analysis, the following relations are obtained:

$$\begin{cases} p_R^{Sc.1} > p_R^{Sc.2} \\ q_R^{Sc.1} > q_R^{Sc.2} \\ p_M^{Sc.1} < p_M^{Sc.2} \end{cases} \begin{cases} Q_R^{Sc.1} > Q_R^{Sc.2} \\ Q_M^{Sc.1} < Q_M^{Sc.2} \end{cases} \begin{cases} \pi_R^{Sc.1} < \pi_R^{Sc.2} \\ \pi_M^{Sc.1} < \pi_M^{Sc.2} \end{cases} \quad (25)$$

Based on the abovementioned results, the following conclusions can be drawn:- Inflexible scheme results in a higher price for the intermodal transportation system , compared to the flexible scheme. It implies that tending towards the flexible scheme can decrease the equilibrium intermodal price, and consequently make this system more affordable for the customers. Also, the increase of flexibility obliges the road system to augment its tanker truck fleet.

- For a flexible scheme, the demand for a road system is higher than that of the intermodal system, which is in contrast with an inflexible scheme.
- In spite of the customer dissatisfaction, both systems tend to use inflexible schemes due to higher profits gained.

5.2.2. Policy 2: Increase in fuel price

The relations between fuel price and equilibrium transportation prices, road fleet availability, equilibrium demands, and profits are analyzed. Accordingly, the following results are derived:

- As the fuel price increases, demands for the road transportation system decline. Therefore, fewer road fleets should be available due to fewer equilibrium demands (This feature holds for both schemes).
- The higher the fuel price, the more profitability of the intermodal transportation system. This trend is reversed for the road transportation system in which fuel price increase would make the system less profitable (The trends hold for both schemes).

In order to realize the possible impacts of each parameter, a numerical example has been examined. All of these parameters are selected based on sensible ranges of problem solutions. The values are based on relevant studies performed in the field of intermodal pipeline-road transportation [27, 35, 37, 38]

$$\beta_p = 10.7 \qquad \gamma_p = 6 \qquad \beta_q = 2.6 \qquad \gamma_q = 1$$

$$f = 1\left(\frac{\$}{lit}\right) \qquad \lambda_R = 0.5 \qquad d = 0.4$$

$$\theta = 0.0445\left(\frac{lit}{ton.Km}\right) \qquad q_M = 300\left(\frac{m^3}{hr}\right)$$

$$Q = 1000\left(\frac{m^3}{hr}\right) \qquad \alpha = 1300\left(\frac{m^3}{hr}\right)$$

$$\bar{c}_M = 2.5\left(\frac{\$}{m^3}\right) \qquad c_{op} = 0.02\left(\frac{\$}{Km.m^3}\right)$$

$$\bar{c}_R = 3.4\left(\frac{\$}{m^3}\right) \qquad D_M = 1100\ Km$$

$$D_R = 1100\ Km$$

Some main results obtained from the analysis of equilibrium solutions with respect to fuel price are as follows:

- Variations in equilibrium transportation prices for both road and intermodal systems with respect to changes in fuel price are displayed in Fig. 3. The equilibrium price of the road system in the flexible scheme is higher than that in the inflexible scheme. This trend is reversed in the intermodal transportation system.
- The equilibrium road fleet availability is shown in Fig. 4. Higher values of road fleet availability are determined inflexible scheme, in comparison with inflexible one.
- Fig. 5 illustrates road and intermodal demands in both schemes based on fuel price variations. It can be deduced that in higher fuel prices, the demand for intermodal transportation systems exceeds that of the road transportation system.
- Fig. 6 depicts the total profit of each transportation system based on fuel price variations. Fig. 7 and Fig. 8 represent three-dimensional relations between fuel price, road segment ratio, and profits of each system for both schemes.

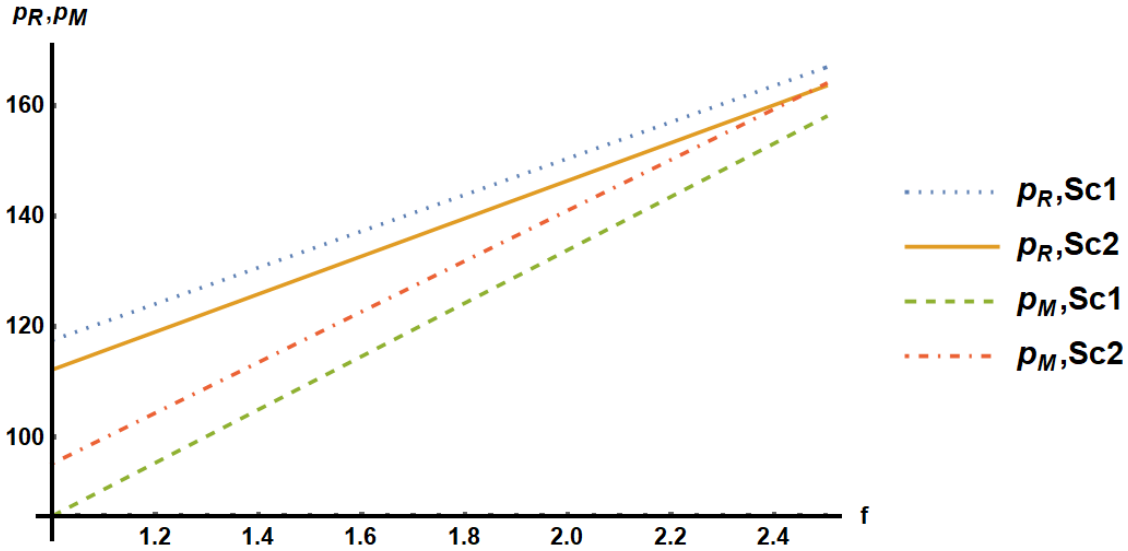


Fig. 3. Equilibrium price variations with respect to fuel price

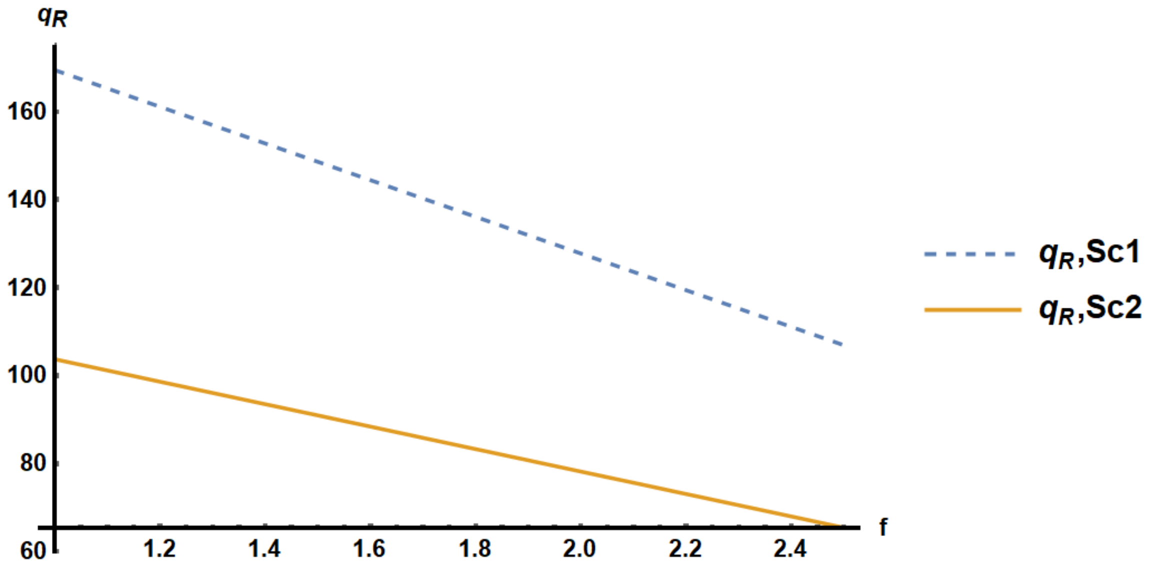


Fig. 4. Equilibrium road fleet availability variations with respect to fuel price

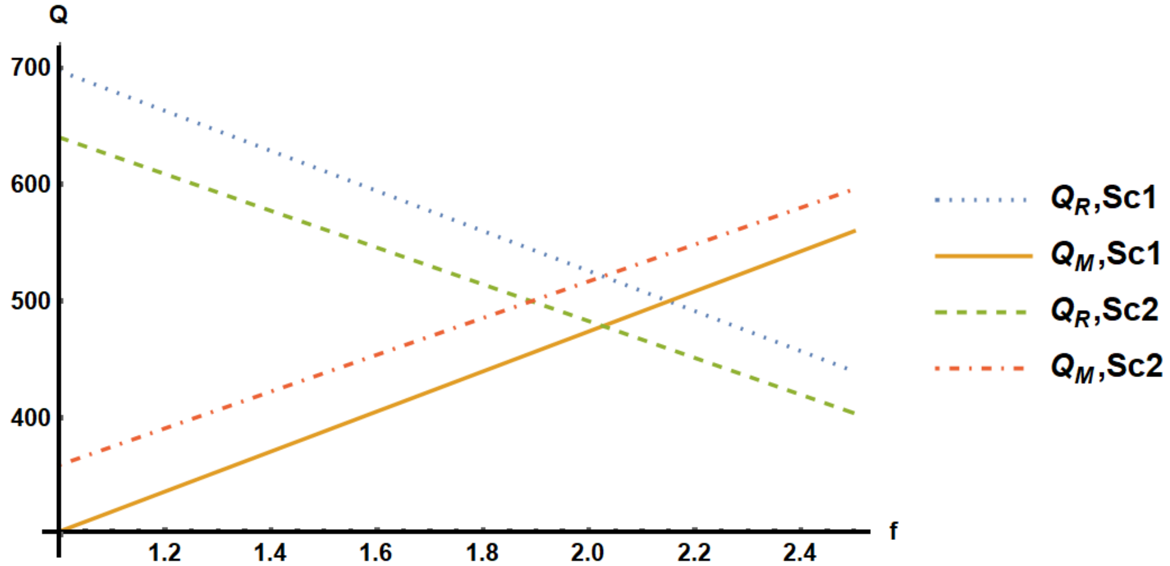


Fig. 5. Equilibrium demands variations with respect to fuel price

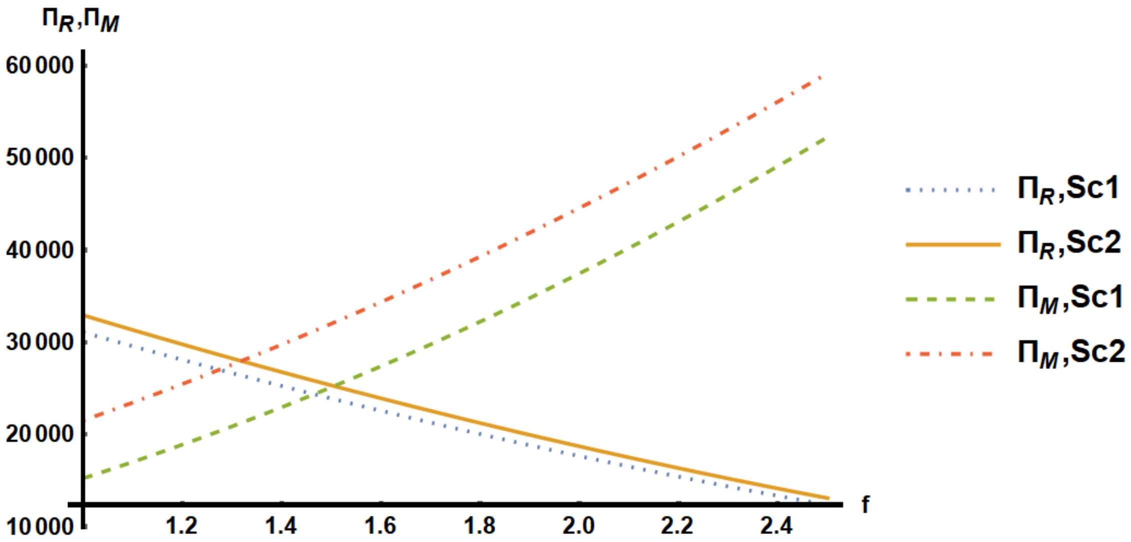


Fig. 6. Equilibrium profits variations with respect to fuel price

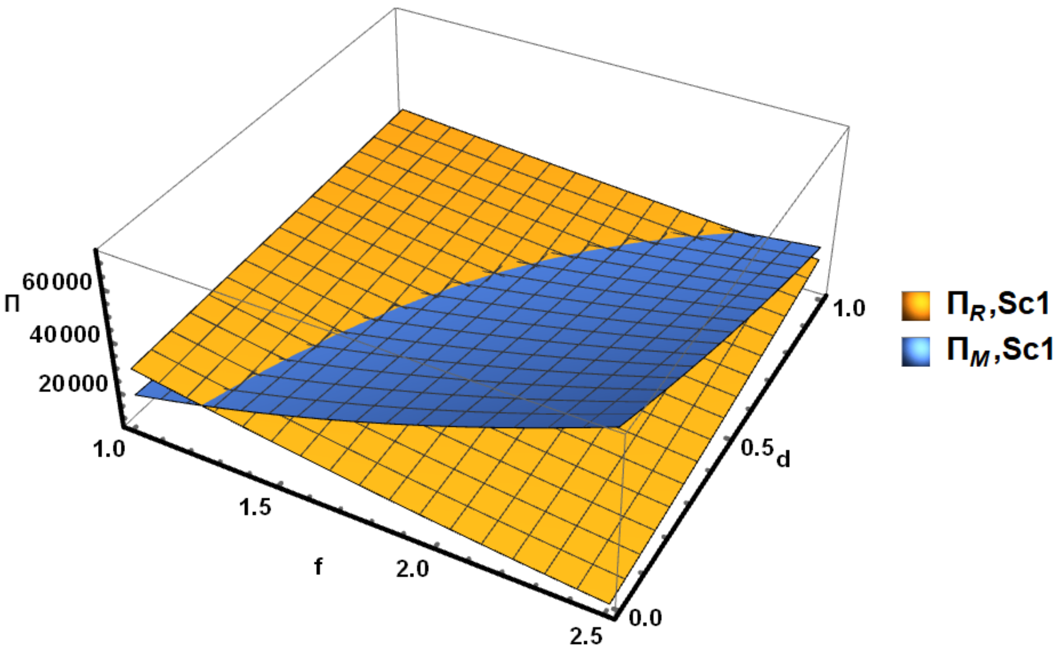


Fig. 7. Three-dimensional figure representing profits of each system based on the first scenario

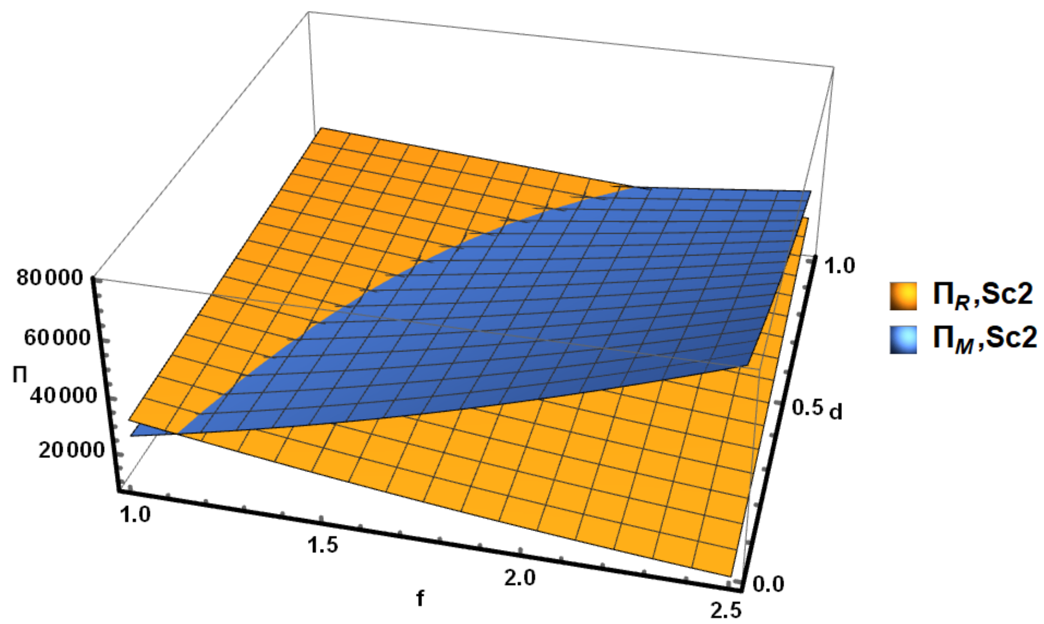


Fig. 8. Three-dimensional figure representing profits of each system based on the second scenario

5.2.3. Policy 3: Decrease of Peripheral Cost in Intermodal Transportation System

In this paper, the peripheral cost is considered as a portion of the fixed cost of the intermodal transportation system $\overline{c}_M$, associated with mode shift operations like loading-unloading the products. This cost can be decreased by the application of more efficient equipment for the operations.

Based on the parametric analysis, further conclusions are derived:

- Any increase in the peripheral cost of the intermodal system would increase the equilibrium price of the road system.
- Any increase in the peripheral cost of the intermodal system would lead to an increase in the equilibrium demand and profit of the road system, but a decrease in the equilibrium demand and profit of the intermodal system.

5.2.4. Policy 4: Employment of Modern Trucks with Low Fuel Consumption

Fuel consumption of the tanker trucks has a direct impact on the transportation cost and consequently, on the equilibrium prices and equilibrium road fleet availability. The employment of modern tanker trucks with low fuel consumption is a policy that can influence the equilibrium state of the competitive transportation market. The results of parametric analysis maintain that:

The policy of employing tanker trucks with lower fuel consumption leads to a bigger equilibrium fleet size in both flexible and inflexible schemes.

Employment of low-consuming tanker trucks results in lower equilibrium transportation prices of both systems, which yields customer satisfaction.

The policy leads to a decline in intermodal transportation demand and profit, but a rise in road transportation demand and profit.

6- Conclusions

Distributing the oil products and energy carriers in a competitive transportation market is a critical problem that mandates careful consideration. There exists a competition between different transportation modes in order to convey oil products in an affordable manner. The current research makes a comprehensive assessment to analyze the competition between road and intermodal pipeline-road systems as the most prevalent modes of transporting oil products in many regions. The demand and profit functions for both competing systems are developed. The transportation prices of both systems, along with the size of the tanker truck fleet (named as road fleet availability) are considered as the main decision variables of the problem, achieved through the proposed game-theoretic approach. Two main schemes including flexible and inflexible are analyzed. In the flexible scheme, the variables are determined concurrently, while in the inflexible scheme, the equilibrium road fleet availability is determined first, and subsequently, the equilibrium transportation prices are specified. In order to understand the effects of different approaches and parameters, four policies are assessed in both parametric and numerical manners. The results demonstrate that in spite of the customer dissatisfaction, both systems tend to use inflexible schemesdue to higher profits gained. For both schemes, any increase in fuel price decreases the demand for the road transportation system. Therefore, a fewer number tanker truck fleet is employed. Any increase in loading/unloading cost associated with the intermodal system yields an increase in equilibrium price, demand, and profit of the road system, but a decrease in the equilibrium demand and profit of the intermodal system. The policy of employing lower-consuming tanker trucks yields to a decline in intermodal transportation demand and profit, but a rise in road transportation demand and profit. The insights introduced in this study can contribute to the managers to optimally make policies for transporting oil products and energy carriers through various transportation systems.

Appendix

A. Proofs

The proof of Lemma 1.

Concavity of π_M with respect to p_M is maintained since $\partial^2_{{p_M}^2}\pi_M = -2\gamma_p < 0$, . The Hessian matrix of is $\begin{pmatrix} -2\beta_p & \beta_q \\ \beta_q & -2\lambda_R \end{pmatrix}$. Considering the assumption $\beta_q^2 < 4\beta_p\lambda_R$. , this matrix is negative definite. Hence, . is a concave function with respect to and .

The proof of Lemma 2.

Concavity of with respect to is maintained since $\partial^2_{{p_R}^2}\pi_R = -2\beta_p < 0$,.Similarly, since $\partial^2_{{q_R}^2}\pi_R = \left(\frac{2\beta_q^2}{9\beta_p} - 2\lambda_R\right)$, therefore equation $\left(\frac{2\beta_q^2}{9\beta_p} - 2\lambda_R\right)$ must be negative. Moreover, since $\partial^2_{{p_M}^2}\pi_M = -2\gamma_p < 0$, π_M is concave with respect to p_M .

Nomenclature

q_R	Road fleet availability
q_M	Pipeline flow rate
Q_R	Transportation demand of road transportation system
Q_M	Transportation demand of intermodal transportation system
α	The market baseline for demand of road transportation system

β_p Elasticity of demand with respect to transportation price for road haulage

β_q Elasticity of demand with respect to road fleet availability

γ_p Cross-elasticity of demand with respect to transportation price for intermodal haulage

γ_q Cross-elasticity of demand with respect to pipeline flow rate

π_R Profit function in road transportation system

π_M Profit function in intermodal transportation system

D_R Distance between origin and destination for road transportation system

D_M Distance between origin and destination for intermodal transportation system

d Road segment ratio of intermodal transportation system ($0 \le d < 1$)

λ_R Cost coefficient to add one unit of road fleet availability

f Base price of one unit of fuel

$\bar{c}_R$ Fixed cost related to wages and toll payments for road transportation system

$\bar{c}_M$ Fixed cost related to wages, toll payments, mode shift, storage, extra loading and unloading, as well as fixed cost of pipeline in intermodal transportation system

c_{op} Operational cost of pipeline transportation for each unit of demand per distance unit

c_R Total cost for carrying one unit of demand from origin to destination in road transportation system

c_M Total cost for carrying one unit of demand from origin to destination in intermodal transportation system

p_R Transportation price of road carriage for one unit of demand

p_M Transportation price of intermodal pipeline-road carriage for one unit of demand

θ Fuel consumption rate of a tanker truck for carrying one unit of demand within one unit of distance

h_R Headway between tanker trucks

C Tanker truck capacity

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