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

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Abstract:

Oil and its derivatives can be distributed through various transportation modes. In spite of the fact that pipeline is considered as the most prevalent mode of transporting oil products, policy makers confront with 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, a competition between pipeline 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 as 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 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 intermodal system.

Keywords:

Transportation, Competitive Market, Game Theory, Oil Products, Intermodality
1. Introduction

Transportation of oil and refinery products including all types of fuels is one of the largest concerns of supply chain managers confronting with economic, environmental, and social issues. High benefits related to the transportation of oil products have stimulated transportation systems to achieve higher market shares from 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 in order to increase their share from 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, pipeline is considered as the most cost-effective mode of transporting oil and its derivatives [6]. Nevertheless, a comprehensive approach should be followed in order 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 which is accompanied by several profits such as increased flexibility [9]. Intermodalism may reduce disadvantageous of one single mode and integrates the cost and service benefits of two or more transportation modes [10].
Several studies have assessed 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 pipeline 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 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 in this study are pipeline and marine. Yue and You [12] determined the optimal design and planning of non-cooperative supply chains from manufacturer 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 have been studies 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 game theoretical approach. This model features optimal design of supply chain network considering economic, social and environmental aspects. Results illustrated that in Stackelberg Equilibrium, where the government is the leader 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 application of the game theoretic approach framework in a duopolistic supply chain to model such a competition problem involving 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 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 pipeline is considered as 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 pipeline 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 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, with the aim of maximizing its own 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).

\[ q_R = \frac{C}{h_R} \]  

(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 game theoretic approach results in equilibrium prices \( p_R \) and \( p_M \), and equilibrium amount of road fleet availability \( q_R \). Two different schemes are 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 word, relevant equilibrium prices as well as equilibrium road fleet availability are determined by simultaneous maximization of road and intermodal...
road-pipeline transportation profits. This approach is formulated through 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 in order 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 parameter 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 in order to carry a specific amount of product from origin to destination. The first route is a 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 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: capacity of each tanker truck and road fleet headways.

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

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

Demand of each mode is more sensitive to its own 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: ($D_R > d D_M$).

### 3. Problem Modeling

The main objective of this section is to formulate demands, costs, and profit functions in order to calculate equilibrium prices of each transportation system besides equilibrium road fleet availability. 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:

\[
Q_R[p_R, q_R, p_M] = \alpha - \beta_p p_R + \gamma_p p_M + \beta_q q_R - \gamma_q q_M
\]

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

The summation of two demand functions is equal to the fixed amount $Q$ defined in volume transported per time unit. It is worth to note that both higher prices and lower facilities have negative effects on amount of equilibrium demands of each transportation system.
The costs imposed to the road transportation system to carry the refinery products include the cost of fuel consumed by tanker trucks which is related to the distance traveled, and the fixed expenses associated to 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]. 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:

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

\[
c_M = \bar{c}_M + f d D_M + c_{op} (1 - d) D_M \quad (5)
\]

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.

\[
\Pi_R[p_R, q_R, p_M] = (p_R - c_R) Q_R[p_R, q_R, p_M] - \lambda_R q_R^2
\]

\[
\Pi_M[p_R, q_R, p_M] = (p_M - c_M) Q_M[p_R, q_R, p_M]
\]

The term \( \lambda_R q_R^2 \) represents 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).

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

\[
\Pi_M[p_R, q_R, p_M] = (p_M - \bar{c}_M - (df \theta + c_{op} - dc_{op}) D_M) \left( Q - (\alpha - p_R \beta_p + p_M \gamma_p + q_R \beta_q - q_M \gamma_q) \right)
\]
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 road transportation system, while the second objective maximizes the total profit of intermodal pipeline-road transportation system. The objectives are formulated as follows:

\[
\begin{align*}
\text{max } \pi_R(p_R, q_R, p_M) \\
\text{max } \pi_M(p_R, q_R, p_M)
\end{align*}
\]  

For solving 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. With respect to Nash equilibrium, both prices and road fleet availability is specified by maximizing both systems profits and are determined concurrently.

Lemma 1. In order to maximize \( \pi_R \) and \( \pi_M \), these functions must be concave on the defined variables. Based on the proof provided in Appendix, \( \pi_R \) is concave on \( p_R \) and \( q_R \) and \( \pi_M \) is concave on \( p_M \).

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

\[
p_R = \frac{(\bar{c}_R + f \theta D_R)\beta_q^2 - 2(Q + \alpha + 2(\bar{c}_R + f \theta D_R)\beta_p + \bar{c}_M\gamma_p + (df \theta + (1 - d)c_{op})D_M\gamma_p - q_M\gamma_q)\lambda_R}{\beta_q^2 - 6\beta_p\lambda_R}
\]

\[
q_R = \frac{\beta_p(Q + \alpha - (\bar{c}_R + f \theta D_R)\beta_p + \bar{c}_M\gamma_p + (df \theta + (1 - d)c_{op})D_M\gamma_p - q_M\gamma_q)}{\beta_q^2 - 6\beta_p\lambda_R}
\]
\[
\begin{align*}
p_M &= \frac{2\beta_p(2Q - \alpha + \bar{c}_p \beta_p + f\theta D\bar{p}_p + \bar{c}_M \gamma_p + \beta \gamma_q)\lambda_R}{\gamma_p(\beta_q^2 - 6\beta_p \lambda_R)} \\
Q_R[p_R, q_R, p_M] &= 2\beta_p(Q + \alpha - (\bar{c}_R + f\theta D\bar{R})\beta_p + \bar{c}_M \gamma_p + (df\theta + (1 - d)\bar{c}_op)D\gamma_M - q_M \gamma_q)\lambda_R \\
\Pi_R[p_R, q_R, p_M] &= \frac{(Q + \alpha - (\bar{c}_R + f\theta D\bar{R})\beta_p + \bar{c}_M \gamma_p + (df\theta + (1 - d)\bar{c}_op)D\gamma_M - q_M \gamma_q)^2}{(\beta_q^2 - 6\beta_p \lambda_R)^2} \\
Q_M[p_R, q_R, p_M] &= \frac{Q\beta_q^2 + 2\beta_p \lambda_R(\bar{c}_M \gamma_p + (df\theta + (1 - d)\bar{c}_op)D\gamma_M - q_M \gamma_q)}{\gamma_p(\beta_q^2 - 6\beta_p \lambda_R)^2} \\
\Pi_M[p_R, q_R, p_M] &= \frac{(Q\beta_q^2 + 2\beta_p (\bar{c}_M \gamma_p + (df\theta + (1 - d)\bar{c}_op)D\gamma_M - q_M \gamma_q)\lambda_R)^2}{\gamma_p(\beta_q^2 - 6\beta_p \lambda_R)^2}
\end{align*}
\]

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 simultaneous maximization of both systems profits.
Lemma 2. In order to maximize $\pi_R$ and $\pi_M$, these functions must be concave on the defined variables. Based on the proof provided in Appendix, $\pi_R$ is concave on $p_R$ and $q_R$ and $\pi_M$ is concave on $p_M$.

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

\[
p_R = Q + \alpha + 2(\tilde{c}_R + f \theta D_R)\beta_p + q_R\beta_q + \bar{c}_M\gamma_p + (d \theta + (1 - d) c_{op})D_M\gamma_p - q_M\gamma_q \quad \frac{3\beta_p}{3\beta_p}
\]

\[
p_M = 2Q - \alpha + \tilde{c}_M\beta_p + f \theta D_M\beta_p - q_M\gamma_q + 2(\bar{c}_M + (d \theta + (1 - d) c_{op})D_M)\gamma_p + q_M\gamma_q \quad \frac{3\gamma_p}{3\gamma_p}
\]

\[
q_R = \beta_q(Q + \alpha - (\tilde{c}_R + f \theta D_R)\beta_p + \bar{c}_M\gamma_p + (d \theta + (1 - d) c_{op})D_M\gamma_p - q_M\gamma_q) \quad \frac{\beta_q}{-\beta_q^2 + 9\beta_p\lambda_R}
\]

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

\[
Q_M[p_R, q_R, p_M] = \frac{Q\beta_q^2 + 3\beta_p(-2Q + \alpha - (\tilde{c}_R + f \theta D_R)\beta_p + \bar{c}_M\gamma_p + (d \theta + (1 - d) c_{op})D_M\gamma_p - q_M\gamma_q)\lambda_R}{-\beta_q^2 + 9\beta_p\lambda_R}
\]

\[
\pi_R[p_R, q_R, p_M] = \frac{(Q + \alpha - (\tilde{c}_R + f \theta D_R)\beta_p + \bar{c}_M\gamma_p + (d \theta + (1 - d) c_{op})D_M\gamma_p - q_M\gamma_q)^2}{-\beta_q^2 + 9\beta_p\lambda_R}
\]

\[
\pi_M[p_R, q_R, p_M] = \frac{(Q\beta_q^2 + 3\beta_p(-2Q + \alpha - (\tilde{c}_R + f \theta D_R)\beta_p + \bar{c}_M\gamma_p + (d \theta + (1 - d) c_{op})D_M\gamma_p - q_M\gamma_q)\lambda_R)^2}{9\beta_p\lambda_R\gamma_p(-\beta_q^2 + 9\beta_p\lambda_R)^2}
\]
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 intermodal system

5-1- Analysis of Variation in road segment ratio of intermodal system (d)

Parametric analysis of road segment ratio of intermodal transportation system (d), with respect to \( p_R, q_R, p_M, Q_R, Q_M, \pi_R \) and \( \pi_M \) are analyzed using Mathematica software. As a result, if fuel cost exceeds pipeline operational cost for one unit of demand transported \( (f > \frac{\text{cap}}{\theta}) \), by any increase in road segment ratio, \( p_R, q_R, p_M, Q_R, \) and \( \pi_R \) increase. This trend is reversed in \( Q_M \), and \( \pi_M \) cases, which means that if \( f > \frac{\text{cap}}{\theta} \) then by any increase of \( d \), 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 possibility of changing the road fleet availability. According to the parametric analysis, the following relations are obtained:
Based on the abovementioned results, the following conclusions can be drawn:

- Inflexible scheme results in a higher price for intermodal transportation system \(p_M\), 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 number of tanker truck fleet.

- For flexible scheme, the demand of road system is higher than that of intermodal system, which is in contrast with inflexible scheme.

- In spite of the customer dissatisfaction, both systems tend to use inflexible scheme 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 road transportation system declines. Therefore, fewer number of road fleet should be available due to less equilibrium demands (This feature holds for both schemes).

- The higher the fuel price, the more profitability of intermodal transportation system. This trend is reversed for road transportation system in which fuel price increase would make the system less profitable (The trends hold for both schemes).

In order to realize 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 field of intermodal pipeline-road transportation [27, 35, 37, 38]

\[
\begin{align*}
\beta_p &= 10.7 & \gamma_p &= 6 & \beta_q &= 2.6 & \gamma_q &= 1 & f &= 1\left(\frac{S}{lit}\right) & \lambda_R &= 0.5 & d &= 0.4 & \theta = 0.0445\left(\frac{lit}{ton.Km}\right) \\
q_M &= 300\left(\frac{m^3}{hr}\right) & Q &= 1000\left(\frac{m^3}{hr}\right) & \alpha &= 1300\left(\frac{m^3}{hr}\right)
\end{align*}
\]
\[ \bar{c}_M = 2.5 \ \text{(\$/m$^3$)} \quad c_{op} = 0.02 \ \text{(\$/Km.m$^3$)} \quad \bar{c}_R = 3.4 \ \text{(\$/m$^3$)} \quad D_M = 1100 \text{ Km} \]

\[ D_R = 1100 \text{ Km} \]

Some main results obtained from 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 road system in the flexible scheme is higher than that in inflexible scheme. This trend is reversed in intermodal transportation system.

- The equilibrium road fleet availability is shown in Fig. 4. Higher values of road fleet availability are determined in flexible 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 of intermodal transportation system exceeds that of road transportation system.

- Fig. 6 depicts 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.

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

Based on the parametric analysis, further conclusions are derived:

- Any increase in peripheral cost of the intermodal system would increase the equilibrium price of the road system.
- Any increase in 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 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 which 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 a lower equilibrium transportation prices of both systems, which yields to the 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 which mandates a 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 the both systems, along with the size of 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 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 scheme due to higher profits gained. For both schemes, any increase of fuel price decreases demand for road transportation system. Therefore, fewer number of tanker truck fleet is employed. Any increase in loading/unloading cost associated to the intermodal system yields to 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 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 $\pi_M$ with respect to $p_M$ is maintained since $\partial^2 p_M \pi_M = -2 \gamma_p < 0$. The Hessian of $\pi_M$ 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, $\pi_M$ is a concave function with respect to $p_M$.

The proof of Lemma 2.

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

Nomenclature

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
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<tbody>
<tr>
<td>$q_R$</td>
<td>Road fleet availability</td>
</tr>
<tr>
<td>$q_M$</td>
<td>Pipeline flow rate</td>
</tr>
<tr>
<td>$Q_R$</td>
<td>Transportation demand of road transportation system</td>
</tr>
<tr>
<td>$Q_M$</td>
<td>Transportation demand of intermodal transportation system</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>The market baseline for demand of road transportation system</td>
</tr>
<tr>
<td>$\beta_p$</td>
<td>Elasticity of demand with respect to transportation price for road haulage</td>
</tr>
<tr>
<td>$\beta_q$</td>
<td>Elasticity of demand with respect to road fleet availability</td>
</tr>
<tr>
<td>$\gamma_p$</td>
<td>Cross-elasticity of demand with respect to transportation price for intermodal haulage</td>
</tr>
<tr>
<td>$\gamma_q$</td>
<td>Cross-elasticity of demand with respect to pipeline flow rate</td>
</tr>
<tr>
<td>$\pi_R$</td>
<td>Profit function in road transportation system</td>
</tr>
<tr>
<td>$\pi_M$</td>
<td>Profit function in intermodal transportation system</td>
</tr>
<tr>
<td>$D_R$</td>
<td>Distance between origin and destination for road transportation system</td>
</tr>
<tr>
<td>$D_M$</td>
<td>Distance between origin and destination for intermodal transportation system</td>
</tr>
<tr>
<td>$d$</td>
<td>Road segment ratio of intermodal transportation system ($0 \leq d &lt; 1$)</td>
</tr>
<tr>
<td>$\lambda_R$</td>
<td>Cost coefficient to add one unit of road fleet availability</td>
</tr>
<tr>
<td>$f$</td>
<td>Base price of one unit of fuel</td>
</tr>
<tr>
<td>$c_R$</td>
<td>Fixed cost related to wages and toll payments for road transportation system</td>
</tr>
<tr>
<td>$c_M$</td>
<td>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</td>
</tr>
<tr>
<td>$c_{op}$</td>
<td>Operational cost of pipeline transportation for each unit of demand per distance unit</td>
</tr>
<tr>
<td>$c_R$</td>
<td>Total cost for carrying one unit of demand from origin to destination in road transportation system</td>
</tr>
<tr>
<td>$c_M$</td>
<td>Total cost for carrying one unit of demand from origin to destination in intermodal transportation system</td>
</tr>
<tr>
<td>$p_R$</td>
<td>Transportation price of road carriage for one unit of demand</td>
</tr>
<tr>
<td>$p_M$</td>
<td>Transportation price of intermodal pipeline-road carriage for one unit of demand</td>
</tr>
<tr>
<td>$\theta$</td>
<td>Fuel consumption rate of a tanker truck for carrying one unit of demand within one unit of distance</td>
</tr>
<tr>
<td>$h_R$</td>
<td>Headway between tanker trucks</td>
</tr>
<tr>
<td>$C$</td>
<td>Tanker truck capacity</td>
</tr>
</tbody>
</table>
References:

[38] A.P.L. Morrison, Demand Model for Crude Oil Rail and Pipeline Shipments in Canada, University of Waterloo, 2018.