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Railway Heavy-haul Cargo Distribution and Transportation System Incentive Mechanism based on Principal-agent Theory

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Abstract: In the railway heavy-haul cargo distribution and transportation system, the partners are confronted with problems such as information asymmetry or conflicts of profits. An effectively designed incentive system is the key to the profit maximization of the integrated cargo distribution and transportation system. While specifying the incentive mechanism of the railway heavy-haul cargo distribution and transportation system, the study has set the incentive goal for cargo distribution and transportation system and further built an incentive model for the cargo distribution and transportation system that involves one principal and multiple agents. Results indicate that the harder the agents work and the higher the risks are, the more outputs will be shared. When the railway companies are delivering services to multiple enterprises or harbors, a more effective incentive mechanism is required to be designed for more important enterprises or harbors that hold more risks. Finally through case studies, it is proved that the proposed incentive mechanism is proper and efficient.

Key words: Railway heavy-haul transport, gaming, principal-agent, incentive mechanism

INTRODUCTION

Railway heavy-haul freight transport is a major trend of the railway service around the world. Considering the heavy traffic volume of railway freight transport, it is of vital importance to realize the integration of cargo distribution and transportation systems. In the cargo distribution and transportation system, enterprises are confronted with problems such as information asymmetry or conflicts of profits. To ensure the efficiency of the railway heavy-haul freight transport system, the partners in this system need to take proper incentive mechanism. Currently most researches on incentive mechanism are based on the principal-agent theory as a part of the Game Theory, focusing on the incentive mechanism about the partners on the supply chain (Chen *et al*., 2001; Li and Zhu, 2005; Yang *et al*., 2006; Zhuang and Zhao, 2007; Chen, 2011; Bai and Liu, 2011), enterprise investment, performance assessment and incentives (Zhang and Yu, 1999; Li and Hou, 2001; Bai, 2007; Liu, 2007; Msogoya and Maerere, 2006; Zhao and Qian, 2008), in-house incentive and partnership (Yu and Zhou, 2003; Xiao, 2003; Xu, 2004; Li *et al*., 2008; Zhang, 2011), the incentive mechanism for teachers in universities (Zhang and Wu, 2008; Duan *et al*., 2011; Tang and An, 2011) and railway transportation (Alhassan and Ben-Edigbe, 2011; Mohammaditabar and Teimoury, 2008; Xuedong and Yin, 2011; Xuedong *et al.* 2011; Fen-Ling and Dan, 2012; Lin and Liang, 2011; Mohammaditabar and Teimoury, 2008; Mazzarello and Ottaviani, 2007; Zehsaz *et al*., 2009). However, literature on the railway heavy-haul freight transport is not abundant, therefore, the article plans to study, in the context of information asymmetry, how to construct an incentive mechanism for the railway heavy-haul freight transport based on the principal-agent theory. By modeling and case studies, it proposes proper incentive measures for the railway companies to maximize the profits of the cargo distribution and transportation system.

INCENTIVE MECHANISM IN RAILWAY HEAVY-HAUL CARGO DISTRIBUTION AND TRANSPORTATION SYSTEM

Principal-agent theory: The principal-agent theory is based on the Asymmetric Information Game Theory. Because of the asymmetry of information distributed between the principal and agent, the agent may gain an advantageous position against the principal through two ways: The first is that leverage the private information that is hardly observable to the principal to again an advantage in information and to put the agent in a disadvantageous position for strategic selection. The second is that after executing the principal-agent contract,

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the agent may gain an advantage in information collection through private actions that are hardly observable to the principal (such as working harder, or changing the original action rules).

In the railway heavy-haul freight transport system, the partners might hide individual information and the acts of participation for the purpose of maximizing their own profits which results in asymmetry of information in the cargo distribution and transportation system. Therefore, a principal-agent relationship is in fact developed between railway companies and other involved parties or harbors which suggest a relationship between market players that are either in the information advantageous position or the information disadvantageous position.

The principal-agent relationship is deemed as a contract: The principal designs an optimal contract which offers proper rewards to attract and encourage the agents and to supervise and restrain the actions made by the agents. All this is for the purpose of unification of the agents' profits and the principal's profits under the contract. In the railway heavy-haul freight transport system, the railway companies are, as a principal, in an information disadvantageous position, while the other parties or harbors, as the agents, are in an information advantageous position, as their efforts are observable to the railway companies. Therefore, for the maximization of profits of varied partners in the cargo distribution and transportation system, a proper and effective incentive mechanism is to be designed based on the principal-agent theory. The railway companies offer proper rewards to attract and encourage other involved enterprises and harbors and thus improve the partner's efforts and minimize the actions of risk aversion.

Goal of incentive mechanism: Enterprises or harbors can decide their actions by the private information they have controlled. Although the railway companies also need the information, chances are high that they may not get the truth by direction questioning. Therefore, the railway companies need to design an effective incentive mechanism. In the railway heavy-haul cargo distribution and transportation system, the partner's interests and responsibilities are different and the individuals' best interests vary from the overall cargo distribution and transportation system's best interests. Also in view of the characteristics of the railway heavy-haul cargo distribution and transportation system, the goal of designed incentive mechanism is:

- Considering the fact that agents (other enterprises or harbors) might conceal the information that makes it disadvantageous for the principal, the goal of incentive policy is to encourage the agents to present their private information or true preference on their own initiative (encourage true words)
- Considering the fact that agents (other enterprises or harbors) might conceal the information that makes it all the more risky, the goal of incentive policy is to push the agents to work as best as they can on their own initiative and encourage them not to take morally risky actions (encourage diligence)

With the two goals set, it is intended for the improvement of the operation efficiency of railway heavy-haul cargo distribution and transportation system and for the maximization of the cargo distribution and transportation system's interests. To sum up, it is designed to ensure the steady development of railway heavy-haul collecting and distributing integration process.

MODEL CONSTRUCTION AND SOLUTION ANALYSIS

Most of the current researches simply deal with the relation between one principal and one agent. However, in fact, railway companies provide services to multiple enterprises or harbors. Therefore, it is presumed that railway companies are delivering services to $n(n\geq 1)$ enterprises at the same time. The commissioning model is adopted to analyze the incentive decisions. The leading modeling method is "space state model" as initiated by Wilson, Spence and Zeckhauser and Ross, in combination with the "parameterized distribution formulation" as proposed by Mirrlees and Holmstrom. Meanwhile, the model hypothesis is widened to meet the actualities.

Basic hypothesis

Hypothesis 1: A railway company delivers services to n enterprises or harbors and the level of hardship the enterprises or harbors work is e_i, i = 1, 2, ..., n. Due to the information asymmetry, the agents are presenting different levels of hard-working spirits and the railway company has no way to identify the level of efforts. Therefore, the only observable result is W_i:

$$W_i = A_i e_i + B_i + C_i \theta_i \tag{1}$$

B_i is a fixed constant, θ_i is the normal random variable whose mean value is 0 and variance is σ^2_i. For the sake of analysis, suppose $B_1 = B_2 = ... = B_n = B$, $C_1 = C_2 = ... = C_n = C$, $\theta_1 = \theta_2 = ... = \theta_n = \theta$ (mean value is 0, variance is $\sigma^2{}_i$), A_i and C_i being the level of efforts made and the factor of influences of random issues on enterprises' outputs.

Hypothesis 2: Costs of enterprises or harbors' efforts are $c(e_i)$, $c'>0$, $c''>0$. For the sake of analysis, suppose:

$$c(e_i) = be_i^2/2 \quad (2)$$

$b>0$ which means the factor of influences of efforts on costs.

Hypothesis 3: The railway company develops a liner incentive contract to reward the enterprises or harbors. Therefore, the rewards to enterprises or harbors are:

$$W(W_i) = D_i + E_i W_i \quad (3)$$

D_i and E_i represents the enterprises or harbors' fixed incomes and share coefficient on outputs.

Hypothesis 4: For the sake of calculation, the influences of enterprises or harbors' outputs on railway company's revenues are ignored. First-order linear function is applied and the railway company's revenues are:

$$\begin{aligned} Y_{VC} &= \sum_{i=1}^{n} W_i - \sum_{i=1}^{n} W(W_i) = \sum_{i=1}^{n} (A_i e_i + B_i + C_i\theta_i) \\ &- \sum_{i=1}^{n} [D_i + E_i(A_i e_i + B_i + C_i\theta_i)] \end{aligned} \quad (4)$$

Hypothesis 5: Railway company's risks are neutral and enterprises or harbor's risks are avoided.

Hypothesis 6: Enterprises or harbors' revenues:

$$Y_{ei} = W(W_i) - c(e_i) \quad (5)$$

In accord with the nature of risk aversion, suppose the utility function has absolute risk aversion features:

$$u(Y) = e^{-\alpha_i Y} \quad (6)$$

Y is the enterprises or harbors' actual revenues, $\alpha_i>0$ means the degree of absolute risk aversion.

Model construction

Railway company's expected revenues: As the railway company's risks are neutral, the expected utility equals expected revenues, namely:

$$\begin{aligned} E(U) &= E(Y_{VC}) = E(\sum_{i=1}^{n} (A_i e_i + B_i + C_i\theta_i) \\ &- \sum_{i=1}^{n} [D_i + E_i(A_i e_i + B_i + C_i\theta_i)]) \\ &= \sum_{i=1}^{n} (A_i e_i + B) - \sum_{i=1}^{n} D_i - \sum_{i=1}^{n} E_i(A_i e_i + B) = \sum_{i=1}^{n} (1-E_i)(A_i e_i + B) - \sum_{i=1}^{n} D_i \end{aligned} \quad (7)$$

Enterprises or harbors' certainly equivalent yields: As the enterprises or harbors' revenues Y_{ei} are random, if Y'_{ei} meets the requirement $u(Y'_{ei}) = Eu(Y_{ei})$, Y'_{ei} is the certainly equivalent yields of random yield Y_{ei} and:

$$\begin{aligned} Eu(Y_{e_i}) &= \int_{-\infty}^{+\infty} u(Y_{e_i}) f(Y_{e_i}) dY_{e_i} \\ &= \frac{1}{\sqrt{2\pi}\sigma} \int_{-\infty}^{+\infty} e^{-\alpha_i Y_{e_i}} \exp[-\frac{(Y_{e_i} - E(Y_{e_i}))^2}{2\sigma^2}] dY_{e_i} \\ &= \exp[-\alpha_i (E(Y_{ei}) - \frac{1}{2}\alpha_i E_i^2 C^2 \sigma^2)] \end{aligned} \quad (8)$$

Therefore, the enterprises or harbors' certainly equivalent revenues:

$$\begin{aligned} Y'_{e_i} &= E(Y_{ei}) - \frac{1}{2}\alpha_i E_i^2 C^2 \sigma^2 = \\ &D_i + E_i(A_i e_i + B) - \frac{b}{2} e_i^2 - \frac{1}{2}\alpha_i E_i^2 C^2 \sigma^2 \end{aligned} \quad (9)$$

$$\frac{1}{2}\alpha_i E_i^2 C^2 \sigma^2$$

is defined as the enterprises or harbors' risk costs.

Railway company and other enterprises and harbors' principal-agent model: Goal of the railway company is the maximization of Expected Utility (EU) and the goal of enterprise or harbors is the maximization of certainly equivalent yield Y'_{ei}.

Suppose the enterprises or harbors' reserved yields are $\bar{Y}_{e_i}, \bar{Y}_{e_1} = \bar{Y}_{e_2} = \ldots = \bar{Y}_{e_n} = \bar{Y}_e$ enterprises or harbors' involvement restraint (IR) is:

$$Y'_{e_i} = D_i + E_i(A_i e_i + B) - \frac{b}{2} e_i^2 - \frac{1}{2}\alpha_i E_i^2 C^2 \sigma^2 \geq \bar{Y}_e \quad (10)$$

Enterprises or harbors' incentive compatibility constraint (IC) is:

$$\begin{aligned} &D_i + E_i(A_i e_i + B) - \frac{b}{2} e_i^2 - \frac{1}{2}\alpha_i E_i^2 C^2 \sigma^2 \\ &\geq D_i + E_i(A_i e_i' + B) - \frac{b}{2} e_i'^2 - \frac{1}{2}\alpha_i E_i^2 C^2 \sigma^2 \end{aligned} \quad (11)$$

$\forall e'_i \in \Lambda$, Λ is the action space allowable for enterprises or harbors.

For the railway company, the optimization problems to be solved:

$$\max_{E_i} E(U) = \max_{E_i} \sum_{i=1}^{n} (1-E_i)(A_i e_i + B) - \sum_{i=1}^{n} D_i \quad (12)$$

$$\text{s.t.}\begin{cases} Y'_{ei} = D_i + E_i(A_i e_i + B) - \frac{b}{2}e_i^2 - \frac{1}{2}\alpha_i E_i^2 C^2\sigma^2 \geq \bar{Y}_e, \\ D_i + E_i(A_i e_i + B) - \frac{b}{2}e_i^2 - \frac{1}{2}\alpha_i E_i^2 C^2\sigma^2 \geq D_i + E_i(A_i e'_i + B) - \frac{b}{2}e'^2_i \\ -\frac{1}{2}\alpha_i E_i^2 C^2\sigma_o^2, \forall e'_i \in \Lambda \end{cases}$$

Λ is the action space allowable for enterprises or harbors.

Model solution: Incentive compatibility constraint (IC) equals

$$\max_{e_i} D_i + E_i(A_i e_i + B) - \frac{b}{2}e_i^2 - \frac{1}{2}\alpha_i E_i^2 C^2\sigma^2$$

Based on the first-order conditions for maximization, it is easily concluded:

$$e_i^* = E_i A_i / b \tag{13}$$

The railway company, for the sake of utility maximization, is not going to provide more services to enterprises or harbors. Therefore, enterprises or harbors' IR will get an equal, that is:

$$D_i + E_i(A_i e_i + B) - \frac{b}{2}e_i^2 - \frac{1}{2}\alpha_i E_i^2 C^2\sigma^2 = \bar{Y}_e$$

So:

$$D_i = \bar{Y}_e + \frac{1}{2}\alpha_i E_i^2 C^2\sigma^2 + \frac{b}{2}e_i^2 - E_i(A_i e_i + B) \tag{14}$$

Input E(U) to get:

$$E(U) = \sum_{i=1}^{n}\frac{E_i A_i^2}{b} + B\cdot n - 2\bar{Y}_e\cdot n - \frac{1}{2}C^2\sigma^2\sum_{i=1}^{n}\alpha_i E_i^2 - \frac{1}{2b}\sum_{i=1}^{n}E_i^2 A_i^2 \tag{15}$$

Analysis of single agent:
When n = 1:

$$E(U) = \frac{E_1 A_1^2}{b} + B - 2\bar{Y}_e - \frac{1}{2}C^2\sigma^2\alpha_1 E_1^2 - \frac{1}{2b}E_1^2 A_1^2$$

Based on the first-order maximization condition, we get:

$$\frac{\partial E(U)}{\partial E_1} = \frac{A_1^2}{b} - E_1 C^2\sigma^2\alpha_1 - \frac{E_1^2 A_1^2}{b} = 0$$

And conclude:

$$E_1 = \frac{A_1^2}{A_1^2 + C^2\sigma^2\alpha_1} \tag{16}$$

When n = 1 (one principal corresponds to one agent):

$$E_1 = \frac{A_1^2}{A_1^2 + C^2\sigma^2\alpha_1} > 0$$

means the agent (enterprise or harbor) has to take some risks. Apparently, E_1 is the decline function of A_1, σ^2, α_1 which means the more risks the agent avoids, the bigger the variance of the output W_1 is and if the agent fears to work harder, the less risks he will take. It is easily concluded that $\partial E/\partial\alpha_1<0$ and $\partial E/\partial\sigma^2<0$. Optimization incentive contract is intended for the balance between incentive and insurance. The bigger the given E_1, α_1 is (or the higher σ^2 is),the higher risk costs are. Therefore, for optimization of risk sharing, E_1 is required to be smaller.

Analysis of multiple agents:
When n = 2:

$$E(U) = \frac{E_1 A_1^2}{b} + \frac{E_2 A_2^2}{b} + 2B - 4\bar{Y}_e - \frac{1}{2}C^2\sigma^2\alpha_1 E_1^2 - \frac{1}{2}C^2\sigma^2\alpha_2 E_2^2 - \frac{1}{2b}E_1^2 A_1^2 - \frac{1}{2b}E_2^2 A_2^2$$

Based on the first-order maximization condition, we get:

$$\frac{\partial E(U)}{\partial E_1} = \frac{A_1^2}{b} - E_1 C^2\sigma^2\alpha_1 - \frac{E_1^2 A_1^2}{b} = 0$$
$$\frac{\partial E(U)}{\partial E_2} = \frac{A_2^2}{b} - E_2 C^2\sigma^2\alpha_2 - \frac{E_2^2 A_2^2}{b} = 0$$

And conclude:

$$E_1 = \frac{A_1^2}{A_1^2 + C^2\sigma^2\alpha_1}$$
$$E_2 = \frac{A_2^2}{A_2^2 + C^2\sigma^2\alpha_2}$$
$$\frac{E_1}{E_2} = \left(\frac{A_1}{A_2}\right)^2\cdot\frac{bC^2\sigma^2\alpha_2 + A_2^2}{bC^2\sigma^2\alpha_1 + A_1^2}$$

When n = 3,

Based on the first-order maximization condition, we get:

$$E(U) = \frac{E_1 A_1^2}{b} + \frac{E_2 A_2^2}{b} + \frac{E_3 A_3^2}{b} + 2B - 4\bar{Y}_e - \frac{1}{2}C^2\sigma^2\alpha_1 E_1^2 - \frac{1}{2}C^2\sigma^2\alpha_2 E_2^2 - \frac{1}{2}C^2\sigma^2\alpha_3 E_3^2 - \frac{1}{2b}E_1^2 A_1^2 - \frac{1}{2b}E_2^2 A_2^2 - \frac{1}{2b}E_3^2 A_3^2$$

And conclude:

$$\frac{\partial E(U)}{\partial E_1}=\frac{A_1^2}{b}-E_1C^2\sigma^2\alpha_1-\frac{E_1^2A_1^2}{b}=0$$
$$\frac{\partial E(U)}{\partial E_2}=\frac{A_2^2}{b}-E_2C^2\sigma^2\alpha_2-\frac{E_2^2A_2^2}{b}=0$$
$$\frac{\partial E(U)}{\partial E_3}=\frac{A_3^2}{b}-E_3C^2\sigma^2\alpha_3-\frac{E_3^2A_3^2}{b}=0$$

And the like, when n = m:

$$E_m=\frac{A_m^2}{A_m^2+C^2\sigma^2\alpha_m} \tag{17}$$

When n = m (one principal corresponds to m agents), make $E_{m-1}/E_m = t$ is the relative incentive power. The higher t is, the incentive power set on No. m-1 enterprise or harbor will be when the railway company does not change in the incentives to No. m enterprise or harbor.
Influence of α on t:

$$\frac{\partial k}{\partial \rho_{m-1}}=-(\frac{A_{m-1}}{A_{m-2}})^2\cdot\frac{2A_{m-1}}{(bC^2\sigma^2\alpha_{m-1}+A_{m-1}^2)^2}<0$$

it can be seen that as more risks are avoided by No. m enterprise or harbor, the lower relative incentive power t will be. It suggests that when other conditions do not change, the railway company is more willing to provide more incentives to those enterprises or harbors that are willing to take more risks.

CASE STUDIES

In a heavy-haul cargo distribution and transportation system, there are one railway company, six other enterprises involved (n = 6) and all 6 hypotheses are satisfied. Table 1 is the statistic sum-up of the cargos as operated by the 6 agents in the cargo distribution and transportation system, the overall outputs are RMB 132.47006 million Yuan. Table 2 is the statistic data of the 6 agents, respectively.

In the incentive mechanism model, some variables and parameters are to be determined by the data in cases (Table 3). For instance, A_i (factor of influences of the efforts made on the outputs) is the ratio of the cargo transportation revenues achieved by the enterprises involved in the cargo distribution and transportation system and the enterprises' overall cargo carrying incomes and suppose each enterprise's cargo carrying incomes are the same (RMB 500 million Yuan):

$$A_i=\frac{\text{Cargo carrying incomes achieved by the enterprise involved in the cargo distribution and transportation system}}{\text{enterprise's overall cargo carrying incomes}} \tag{18}$$

Table 1: Statistics of the agents in railway heavy-haul cargo distribution and transportation system

	Data
Cargo carrying incomes (RMB 10,000)	132470.06
Cargo delivery	18609.60
Cargo pick-up (arrived or passed)	104475.70
Other cargo carrying incomes	9384.76
Cargo carrying capacity (10,000 tons)	7014.11
Cargo delivery	1684.66
Cargo pick-up (arrived or passed)	5329.45

Table 2: Distribution and transportation statistics of the each agent

	m = 1	m = 2	m = 3	m = 4	m = 5	m = 6
Cargo carrying incomes (RMB 10,000)	28193.04	39739.20	36540.97	7637.2	4628.94	6342.90
Cargo carrying capacity (10,000 tons)	1438.2	2027.2	1864.05	691.4	419.06	574.2

Input the data into Eq. 18 and 19, to get the values of A_i and α_i

Table 3: Modulus value of the incentive mechanism model

M	1	2	3	4	5	6
A_I	0.56	0.79	0.73	0.15	0.09	0.13
α_1	0.71	0.59	0.63	0.86	0.92	0.89

α_i is (absolute risk aversion) is the result of 1 min the ratio of the cargo carrying capacity of the enterprise involved in the cargo distribution and transportation system/enterprise's overall cargo carrying capacity; Suppose each enterprise's cargo carrying capacity is the same (50 million tons):

$$\alpha_i=1-\frac{\text{cargo carrying capacity of the enterprise involved in the cargo distribution and transportation system}}{\text{enterprise's overall cargo carrying capacity}} \tag{19}$$

C is the factor of influences of random factors on enterprises' outputs, a value is generated randomly; σ^2 is 1.

It is concluded that:

Suppose C = 0.2, E_1 = 0.92, E_2 = 0.96, E_3 = 0.95, E_4 = 0.40, E_5 = 0.18, E_6 = 0.32, $t_1 = E_1/E_2$ = 0.96, $t_2 = E_3/E_2$ = 0.99 is the relative incentive power, $t_1<t_2$ which means when the dedicated railway cargo carrying line does not change its incentives to No.1 enterprise, the incentives to No. 3 enterprise can be higher and the rewards to it will also be raised.

CONCLUSIONS

The article adopts the principal-agent theory and on the condition of information asymmetry, it constructs an incentive mechanism model for the railway heavy-haul cargo distribution and transportation system. In the model, it involves one principal and multiple agents. By calculations, it tries to get solutions to the model and make analyses of the incentive mechanism in railway heavy-haul cargo distribution and transportation system. It is demonstrated that the model can effectively solve the problems discussed. The conclusions are given as below:

As E_i is the decline function of α_i, A_i, σ^2, it means the more an enterprise or harbor tries to avert the risks, the less rewards will be provided. The more an enterprise or harbor tries to make efforts, the less risk they will take. The more unstable the market it, the less shares the enterprise will get.

Information asymmetry means the railway company is not in a position to conduct effective checks of the enterprises or harbors and the enterprises or harbors will choose not to work harder. Therefore, it is necessary to connect the enterprises or harbors' incomes with the yields of their efforts. However, it will increase the railway company's costs and the conflict of "insurance and incentive" will be seen. The model designs an incentive contract by adding the profits shared to the fixed rewards to prevent moral risks as a result of information asymmetry.

When a railway company provides multiple enterprises or harbors with services, a more effective incentive mechanism is required to be designed for more important enterprises or harbors that hold more risks, to better achieve the goal of profit maximization of the overall cargo distribution and transportation system.

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