The Impact of Information on System Operations

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Abstract. The operating system is a complex system that includes supply and demand. Changes in external information have an impact on the operation of the system, especially on both supply and demand. This paper analyzes the supply and demand and establishes the nonlinear programming problem of system operation under the social optimal goal. With the increase of external information intervention, there will be more suitable travel fares for the demand side. However, the supply side's related operating indicators (for example, frequency, bus fleet, and vehicle capacity, etc.) have shown a trend of first increasing and then decreasing due to existing resource constraints. It can be seen that under the same information interference, there are differences in the law of change between the supply and demand sides. Besides, an example is used to verify the effectiveness of the model. Through the model and calculation examples, we can know that the supplier and the demander can meet their own needs under the social optimal goal. This provides certain theoretical support for future research information on system operation.

1. Introduction

With the rapid economic development and the strengthening of urbanization, the development of urban traffic is also changing with each passing day, which has brought about the problem of urban traffic congestion. Especially with the development of "urban agglomerations", taking China's "Beijing-Tianjin-Hebei" as an example, the development of transportation has promoted an increase in transportation demand and also brought increasingly prominent contradictions between supply and demand. Public transportation has become an inevitable way to alleviate urban congestion because it has the advantages of intensive efficiency and low energy consumption. Likewise, it also brings huge challenges to the development of urban public transportation, especially for sustainable development.

Many countries and regions in the world to promote public transportation, and to encourage public transportation priority, a subsidy policy is implemented for public transportation. For example, some European countries (Germany, France, Finland, etc.) allow commuters to deduct commuting costs for buses from income taxes. There are also included examples of increasing bus travel by subsidizing bus fares (Tscharaktschiew, S. and G. Hirte, 2012). At present, research-based on subsidy policies is generally concerned with increasing the demand for travelers to choose a bus to achieve the priority of bus travel. The bus company, as the main operator of urban bus travel, is responsible for all services of users who choose bus travel. The bus company must maintain the normal operation of the company...
while meeting the needs of users, which brings huge challenges to the bus company. Therefore, the subsidy policy has become an important means to improve the operating system of bus companies.

As the basic department of public transportation operation, the bus company has a strong public welfare nature. Due to its economic attributes (profitability), the bus company is difficult to achieve a balance of revenue and expenditure. Without subsidies, bus companies will continue to lose money, making it difficult for bus companies to operate. The main purpose of the subsidy mechanism is to achieve the purpose of incentivizing the operation of enterprises through subsidies, improve the operating efficiency of bus companies, and at the same time reduce the cost of bus companies so that the resources can be used to the maximum extent.

At present, the existing research only focuses on the profitability of the system, but public transportation is a public product, and its basic attribute is public welfare. The need for both profitability and public welfare has increased the financial pressure on public transportation. To ease the financial burden, the government grants financial subsidies to increase revenue. It can be seen that considering financial information is particularly important for system operations. Table 1 summarizes the differences among the related studies together with this paper's contributions.

### Table 1. Contributions in this paper

| Citation                        | Public welfare | Demand Elasticity | Financial constraints | Solutions          |
|---------------------------------|----------------|-------------------|-----------------------|--------------------|
| Vickrey (1955), Mohring (1972, 1976) | ×              | Fixed             | ×                     | Numerical          |
| Jansson (1980, 1984)            | ×              | Fixed             | ×                     | Analytical         |
| Van de Velde (1999)             | ×              | Fixed             | ×                     | Analytical         |
| Jara-Díaz and Gschwender (2003a, 2003b) | ×              | Fixed             | ×                     | Analytical         |
| Jara-Díaz and Gschwender (2005, 2009) | ×              | Fixed             | √                     | Analytical         |
| Zhou et al. (2008)              | ×              | Elastic           | √                     | Analytical         |
| Sun et al. (2015, 2016)         | √              | Elastic           | √                     | Analytical and Numerical |
| This paper                      | √              | Elastic           | √                     | Analytical and Numerical |

Note: “√” means that the associated item is considered, whereas “×” means that the associated item is not considered.

The remainder of this paper is structured as follows. In the next section, the research describes the basic model integrating by the impact of financial information subsidy policies on system operation. A numerical example is available to illustrate the proposed model in section 3. Finally, the relevant conclusions are presented in Section 4.

### 2. The Basic Model

This paper mainly analyzes the impact of financial information on system operations. In order to solve this problem, we need to start with two aspects of supply and demand. The demand side provides information on the rules of travel, and the supplier not only needs to meet the demand of the demand side but also reflects public welfare. Therefore, the supplier's goal is to maximize the total social welfare.

#### 2.1 The Demand

Each resident who decides to choose a bus trip is based on the generalized travel cost $g_u$, which is a combination of bus fares ($p$), walking time ($t_w$), waiting time ($t_w(f, \Phi)$), and in-vehicles time
Waiting time is affected by frequency \( f \), and vehicle capacity rate \( \Phi \), which calculated by equation (2).

\[
g_w = p + \theta (t_w(f, \Phi) + t_a + t_m)
\]

\[
t_w(f, \Phi) = \frac{1}{f(1-\Phi)} = \frac{K}{f(K - Q)}
\]

where \( \theta \) represents the value of time and \( \Phi = \frac{Q}{K} \) (Jara-Díaz et al. 2003a). \( Q \) denotes the potential demand.

According to Sun. et al. (2015, 2016), the linear demand function can be expressed as (3).

\[
q = Q\left(1 - e_s g_u(p, f, K)\right)
\]

where \( e_s \) represents the coefficient of generalized cost in demand function. Therefore, the consumer surplus is \( \frac{1}{e_s} - p \).

According to this demand function, it is easy to find that when the generalized travel cost is large, the demand will decrease, which is in line with the characteristics of the price-demand function.

2.2 The Supply

2.2.1 The cost

The bus company operates an isolated corridor served by one bus line of \( L \) kilometers long, operating at a frequency \( f \) with a fleet of \( B \) vehicles (Jansson 1980, 1984; Jara-Díaz, Sergio R. et al. 2003, 2009). This paper uses \( T \) to represent the average time of the vehicle within a cycle, and \( t \) is the average boarding and alighting time per passenger, the cycle time can be expressed as

\[
t_c = T + \frac{q}{f}
\]

According to the model of Morhing (1972, 1976), and Jansson (1980, 1984), it can be known that the frequency is a ratio of the fleet size and cycle time \( \frac{B}{t_c} \), combined with the equation (4). Therefore, the fleet size of a bus company can be expressed as a relationship between frequency and demand function.

\[
B = fT + tq
\]

The operating cost per unit of time can be written as a linear relationship about the vehicle capacity \( K \).

\[
c = c_0 + c_1 K
\]

where \( c_0 \) and \( c_1 \) are constant. \( c_0 \) is the fixed cost in the unit time and is the marginal cost in the unit time.

Besides, the cost of the bus company also includes the delay cost \( c_d \), which is a linear function related to the scheduled delay.

\[
c_d = \frac{\alpha}{f} + \beta \psi(f)
\]
where $\beta$ and $\alpha$ are coefficient in delay cost and are positive. $\psi(f)$ calculates by $\frac{1}{2}\left(\frac{Q}{fL}\right)^2$. $l$ is the travel distance.

Therefore, the total cost of resource consumption per unit time of the bus company can be expressed as

$$ TC = B(c + c_d) \quad (8) $$

Substituting equations (4)-(7) into (8), the total cost can be obtained

$$ TC = (fT + t_q)\left(c_0 + c_iK + \left(\frac{\alpha}{f} + \beta\psi(f)\right)\right) \quad (9) $$

### 2.2.2 The revenue

The bus company's main business revenue is fare income, which is multiplied by the bus fare and the actual demand of the cycle.

$$ TR = pq \quad (10) $$

### 2.2.3 The profits

The profit of the bus company can be expressed as

$$ \pi = TR - TC = pq - (fT + t_q)\left(c_0 + c_iK + \left(\frac{\alpha}{f} + \beta\psi(f)\right)\right) \quad (11) $$

### 2.3 The Total Social Welfare

The bus company needs to meet its profit maximization under the constraints of vehicle capacity and financial capital ($A$). However, public transport companies, as public transport service companies, have a strong public interest. Therefore, the bus company as an operating company needs to have both business and public welfare, so the bus company needs to maximize social welfare ($SW$) as the goal, and the model is transformed into the following form:

$$ \max_{f,k} SW = \int_{s,(f,K)} Q(1 - e_g s_a) dp + pq - (fT + t_q)\left(c_0 + c_iK + \left(\frac{\alpha}{f} + \beta\psi(f)\right)\right) \quad (12) $$

s.t.

$$ k(f) \leq K $$

$$ B(c + c_d) \leq A $$

where $k(f)$ denotes that vehicle capacity should be able to accommodate passengers in each vehicle, ie $k(f) = \frac{Q}{fL}$.

### 2.4 The Impact of Information on System Operations

#### 2.4.1 The solutions

By solving the problem in (12), it is a classic KKT condition problem with constraints. The impact of financial information on system operations mainly includes the bus fleet, frequency, vehicle capacity, and bus fare. By solving, we can obtain the optimal result of the main influencing factors under the goal of public welfare.

$$ p_w^* = \frac{1}{2e_g} \left( t_a + t_i + \frac{K^*}{f^* (K^* - Q)} \right) + \frac{(1 - \mu_d)}{2} \left( c\left(K^* + c_d(f)\right) + \frac{1}{e_g} - p \right) \quad (13) $$
The impact of information on system operations

The government provides cost subsidies to public transport companies to alleviate their operating pressure and ensure that they provide existing public services. This paper assumes that the government pays the cost subsidy of $W$ at a time, and the total cost of the producer can be covered by the cost subsidy. Finance without subsidies can be expressed as $C_s$. If the total costs are covered by financial $T\le A+W$, $C_s = A+W$; otherwise, $C_s = A$. Then the goal of public transport companies considering public welfare is to solve the following problems in (17).

$$\max_{f,K} SW = \int_{s(f,K)} Q \left(1-e^{-g_s} dp + pq - (fT + tq) \left(c_0 + c_i K + \left(\frac{\alpha}{f} + \beta \psi(f)\right)\right)\right)$$

$$s.t. \quad k(f) \le K$$

$$B(c+c_d) \le C_s$$

(17)

### 3. Numerical Study

In this section, a numerical example is provided to illustrate the properties of the proposed model and its applications. It can be seen from this that financial information is beneficial to the operation of the system, but increasing financial subsidies is not necessarily beneficial. The baseline parameter values are specified in Table 2.

| Notation | $t_u$ | $t_m$ | $e_s$ | $\theta$ | $T$ | $t$ | $c_0$ | $c_i$ | $Q$ |
|----------|-------|-------|-------|---------|-----|-----|------|------|-----|
| Baseline value | 0.25h | 0.45h | 0.2   | 0.5     | 2.72h| 0.03h| 10.65/h| 0.203/h| 3000/h|

### 3.1 The Impact of Information on the Frequency

The frequency is the most intuitive indicator for suppliers to attract demand, and it will directly affect the demand side's selection behavior. In one-time subsidy, if the financing is covered by the total costs, the subsidy is equal to zero, otherwise, the subsidy is equal to $A+W$. It can be seen from Figure 1 that the financial constraints under the one-time subsidy make the bus frequency also increase. However, the frequency decreases as subsidies continue to increase. In other words, under the existing resources, increasing the input of financial information will not improve the operational performance of the system.
The share of an enterprise in the economic system is a measure of its strength. In order to make the enterprise competitive, managers only need to control the scale and quantity of operations. As a public transportation company, it mainly explains from two aspects: bus fleet and vehicle capacity. Through the above derivation, we can know that the relationship between bus fleet and vehicle capacity is inversely proportional. Under the existing demand, if an enterprise expands the scale of the bus fleet, the vehicle capacity of each vehicle will become smaller. However, with the increase of financial subsidies, the relationship between the two also shows different laws. It can be seen from Figure 2 that with the gradual increase of financial subsidies, the bus fleet first decreased and then increased, but the vehicle capacity first increased and then decreased. This is consistent with the relationship derived in the previous paper. However, when the financial subsidy reaches a certain amount, the trend gap between bus fleet and vehicle capacity gradually increases. The reason for this phenomenon is limited demand. As long as the scale is large enough, the reasonable use of resources can be achieved by expanding the bus fleet.

3.3 The Impact of Information on Bus Fare
Bus fare is the most intuitive factor for the supply side to attract the demand side. Reasonable prices have higher attractiveness, and vice versa, lower attractiveness. Public transportation is the main body of profitability and public welfare, and the price has become the most important evaluation criterion.
Figure 3 compares the price law under profitability and public welfare conditions. We can see that with the increase of financial subsidies, the profitability price trend is relatively flat but the value is higher. However, the price of public welfare decreased with the gradual increase of financial subsidies, showing cyclical changes. Therefore, we can easily know that public welfare can achieve the goal of profitability under appropriate financial subsidies.

![Figure 3. The impact of information on bus fare](image)

### 3.4 The Impact of Information on Profits

The level of profit is a measure of the profitability of an enterprise. Profit is determined by two factors, price, and quantity. It can be seen from Figure 3 that as the amount of subsidies increases, prices under different targets will show regular changes. Therefore, Figure 4 shows the changing trend of profits under different goals as the amount of subsidies increases. Under the existing demand, profits are affected by the changing trend of prices, but because of limited resources, companies have been in a state of loss. It further illustrates that financial information plays an important role in the profitability of the system.

![Figure 4. The impact of transit subsidy on total social welfare](image)

### 4. Conclusion

This paper studies the impact of financial information on the operation of public transportation companies from two aspects of supply and demand. Through mathematical modeling, the influence factors of financial information on operations are found. Therefore, this paper can draw the following
conclusions.

(1) Public transportation companies are profitable and public. To ensure the normal operation of the system, financial subsidies play an important role in weighing the relationship between two basic attributes. The government uses one-time subsidies to improve the operation of the system. But with the increase of financial subsidies, the operating conditions of the system are also different.

(2) This paper studies the impact of subsidy information on system operation from the perspective of supply and demand. For the demand side, the fare under the goal of maximizing corporate profitability is higher than the fare under the goal of maximizing corporate social utility. Therefore, the demand side is more inclined to travel in the context of lower fares. For the supplier, frequency, bus fleet, and vehicle capacity show regular changes as the subsidy amount increases. Provide a theoretical basis for suppliers to formulate frequency, bus fleet, and vehicle capacity.

(3) The operating system is a complex system that includes supply and demand. The interference of external information will affect both supply and demand. However, the larger the subsidy amount is not, the better the operation effect is. In other words, under current conditions, more subsidy funds will not necessarily reduce the frequency and ticket prices of enterprises.

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