

High Performance in a Wired-and-Wireless Integrated IC Card Ticket System

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Abstract. Automatic Fare Collection Systems (AFCSs) require high performance and high reliability. The automatic fare collection gates (AFCGs) must let the passengers pass as quickly as possible because the congested passengers rush to them during rush hours. High performance on wireless communications lowers reliability, which had been a problem when a company was developing a wireless IC card ticket system. "Autonomous Decentralized Processing Technology" and "Decentralized Algorithm on the Fare Calculations with an IC Card and AFCGs" were designed as the solutions. This paper introduces the two models – the decentralized processes for the fare calculations and the workstation-centralized one – to simulate the performances and shows the satisfactory results on the decentralized one. These technologies are implemented to the practical system and have proven the effectiveness.

1 Introduction

Declining birthrates, aging, and globalization – The society is changing in Japan and the railway companies are not the exception; they are required to provide more safety, more comfort, and more convenience in addition to the conventional duties such as safety and accuracy. So is the Automatic Fare Collection System (AFCS), one of the most important systems to support the transportation. The conventional AFCS was difficult to coexist with different systems, impossible to satisfy various needs, and hard to be upgraded. The conventional Automatic Fare Collection Gates (AFCGs), for example, forced the passengers to insert their magnetic tickets into the slots and then, to take them away. In addition, the system was expensive to maintain and poor to expand because it was too simple and centralized within the stations. The new AFCS had been expected to solve these problems, to improve the passengers' convenience, and to reduce the maintenance costs.

A wireless IC card ticket system had been taken into consideration in such a mood. In this system, the passengers would simply touch their IC cards to the AFCGs and then go through. The less mechanical parts could decrease the maintenance costs, too. The benefits persuaded the board and the new system was scheduled on the renewal of the conventional magnetic AFCS.

The development of the wireless IC card ticket system is concretely aimed at the gain in the processing speed because it is very important to let the passengers pass through

the AFCGs as smoothly as possible, especially during the rush hours. The walking speed of the passengers is reduced to 1.0m/s along the AFCGs [1] while the random walk in a station shows 1.4m/s [2]. The AFCGs must work as quickly as the people move at this velocity [3][4].

On the other hand, reliability is indispensable to the AFCS because the tickets are worth notes; that is, the AFCS must be equipped with both high performance and high reliability. However, it is difficult for the wireless IC card ticket system because the wireless communications between an IC card and an AFCG are unstable in the manual operations by the passengers.

The unstableness in the manual operations is fixed by introducing the "Touch & Go" method, the way of the operation. The compatibility of high performance and reliability is entrusted to the Autonomous Decentralized Architecture where "IC cards," "AFCGs," and a "center server" are designed as the autonomous units.

This paper focuses on the high performance in the wireless IC card ticket system based on the Autonomous Decentralized Processing Technology. "Autonomous Decentralized Algorithm on the Fare Calculation with an IC Card and AFCGs" is also proposed to achieve the high performance. Two models, with and without this algorithm, are compared in the efficiency.

On the application to the real environment, other technologies for high reliability and assurance [5] are also equipped, which are to be mentioned in the later papers.

2 Autonomous Decentralized IC Card Ticket System

The system consists of "IC cards," "terminals" (e.g. AFCGs), "stations servers," and a "center server" and between the nodes exist three different data fields (DFs).

The terminals use wireless communications with the IC cards. The IC cards broadcast the data with an ID code (contents code) to the DF1 and the AFCGs, for example, select the data to collect and to process. The terminals and the station servers are linked to the station LAN and work on the Autonomous Decentralized Processes through the DF2. At the stations the station servers broadcast the data to the DF2 and the terminals such as AFCGs and Ticket Vending Machines (TVMs) select the data to receive. Then the terminals check the "negative" (invalid) cards, calculate the fare, and process any necessary tasks. Each terminal operates autonomously and the failures at some terminals do not influence on the others. When a station server fails, some functions are suspended because the data from the center server do not flow. However, the operations at the station can be kept normal with the stored data in each terminal. The station servers are connected to the center server through the DF3 and thus, the passengers can use all the functions, derived from the DF3 among stations, when they move to another station with a normal station server.

This system is unique with the three different DFs with various time ranges. In the DF1, wireless communications are done within a second while the data flow hourly in the DF2. The data transmission in the DF3 has two cycles: daily and hourly (Fig. 1). These time ranges are varied for the needs and aim at both high performance and high reliability [6][7][8][9].

The minimum operation must be guaranteed in case of failures, which can lead to terrible confusion at stations. This is why the Autonomous Decentralized Architecture

is used. The basic functions of the IC card ticket system are checking the "negative" cards and calculating the fares.

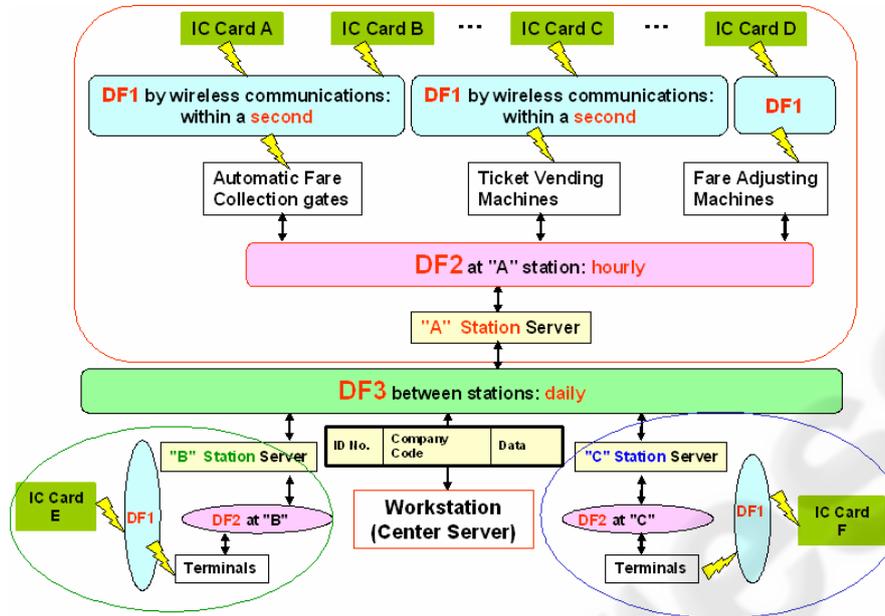


Fig. 1. Autonomous decentralized IC card system. Terminals broadcast the fare data every hour and station servers select the necessary data to collect. Station servers broadcast fare data every day and the center server select the necessary data to collect. The center server broadcast "negative" data once a day (every 5 minutes in emergency) and station servers and terminals select the necessary data to collect.

3 Autonomous Decentralized Algorithm on Fare Calculations

Fig. 2 shows the fare calculations at the AFCGs. A passenger is supposed to have a commuter pass which allows free rides between the stations X and Y. When he/she got on a train at the station A, out of the free-ride area, he/she had to purchase a conjunction ticket to the closest station J between X and Y. When he/she got off at the station B, out of the area, he/she had to adjust the fare from the closest station K between X and Y. In the IC card ticket system, he/she simply touches the IC card to the AFCGs at the stations A and B. The AFCG at the station A automatically judges that the pass is not valid there, deducting the minimum fare (F_0) from the IC card. Then it selects the station J and writes the data such as the station name "J" and the fare from A to J (FAJ) in the IC card. The AFCG at the station B also judges that the pass is not valid there. Then, it selects the station K and calculates the fare from K to B (FKB). Finally it compares (1) the direct fare from A to B (FAB) minus F_0 and (2)

the sum of FAJ and FKB minus F0. The less expensive fare is selected and the IC card is processed so.

It shall take a long time if this complicated calculation is thoroughly processed at the station B. The solution is the "Autonomous Decentralized Algorithm on the Fare Calculations." In this algorithm, the fares are autonomously calculated twice: the "Pre-boarding Process" upon entrance and the "Post-boarding Process" upon exit, followed by the autonomous cooperative process. This algorithm has succeeded in shortening each processing time [10].

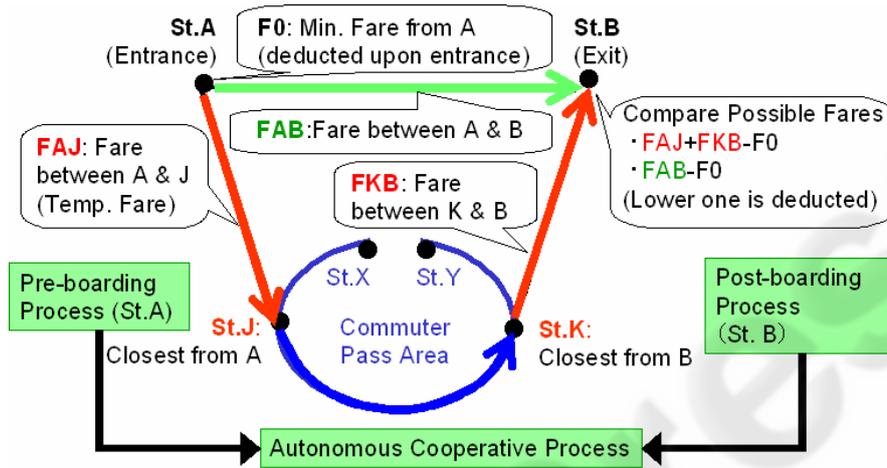


Fig. 2. Temporary memory method for fast fare adjustment. When enter at St.A, "F0" and "FAJ" is written in the card. When exit from St.B, "FAJ" + "FKB" - "F0" and "FAB" - "F0" is compared and the less expensive one is selected.

4 System Modeling

This chapter introduces the two models of the IC card ticket system to evaluate the performances; One is based on the "decentralized processes on cards and terminals" and the other is on the "centralized processes on a center server." These two models are to compete in the basic functions of the IC card ticket system: checking the "negative" cards and calculating the fares. The negative cards are checked every time the AFCs process the IC cards. The ways of the fare calculations are different by the models. Either in the decentralized model or in the centralized one, the total processing time T is defined as in Equation 1: the sum of T_1 for "checking and processing the negative cards", T_2 for "calculating the fares," and T_3 for "communicating and the other processes." This formula is the base when the processing times of the two models are discussed.

$$T = T_1 + T_2 + T_3 \quad (1)$$

4.1 Decentralized Model

In the decentralized processes on cards and terminals, the processes are separated in two: the pre-boarding process at the station A and the post-boarding process at the station B. Therefore, the total processing time T_{AB} can be divided into T_A for the pre-boarding process at the station A and T_B for the post-boarding process (Equation 2).

$$T_{AB} = T_A + T_B \quad (2)$$

T_A and T_B are broken down like T in the Equation 1 (Equations 3 and 4).

$$T_A = T_{1A} + T_{2A} + T_{0A} \quad (3)$$

$$T_B = T_{1B} + T_{2B} + T_{0B} \quad (4)$$

In Equation 3, T_{1A} is the time for checking and processing the negative cards at the station A while T_{2A} for calculating the fares and T_{0A} for communicating and the others there. The same indexing rule applies to Equation 4.

Fig. 3 shows the pre-boarding process at the station A. First, the AFCG checks the "negative" bit in the IC card. Second, it checks whether the ID number of the IC card is on the "negative" list or not. Third, it seeks the fare data. Finally, it calculates the fare. T_{0A} simply reflects the amount of data to be read and to be written. Hence, T_{1A} , T_{2A} , and T_{0A} are written as

$$T_A = T_{1A} + T_{2A} + T_{0A} = (t_0 + t_n) + (t_s + t_c) + \{Tr(Dr) + Twr(Dwr)\} . \quad (5)$$

t_0 : the time for the negative-bit check (Const.) Tr : the time for reading the IC card
 t_n : the time for the negative-ID check Dr : the amount of the data to be read (const.)
 t_s : the time for seeking the fare data Twr : the time for writing the IC card
 t_c : the time for calculating "FAJ" Dwr : the amount of the data to be written (const.)

In Equation 5, t_0 is the constant time for the negative-bit check. t_n is the time for the negative-ID check and it is governed by the volume of the "negative" DB, which can be estimated from the number of transactions P .

$$t_n = \beta P t_1 = \beta t_1 \int_{\text{Suica start} \rightarrow \text{now}} p dt \quad (6)$$

β : the rate of "negating" per transaction (const.)
 P : the total number of transactions
 t_1 : the time for checking a negative card (const.)
 p : dP/dt (the number of transactions at a period)

As each AFCG has the fare data from the station to the other stations, t_s is proportional to the number of whole the stations ($j-1$) while t_c is targeted on the stations only within the free-ride area ($n-1$).

$$t_s = \gamma(j-1), \quad t_c = \delta(n-1) \quad (7)$$

γ : the time for picking up a fare datum from the fare DB (const.)
 δ : the time for comparing a fare with another (const.)

Then, Equations 5 to 7 deliver Equation 8.

$$T_A = t_0 + \beta t_1 \int_{\text{Suica start} \rightarrow \text{now}} p dt + \gamma j + \delta n + Tr(D_r) + Twr(D_{wr}) - \gamma - \delta \quad (8)$$

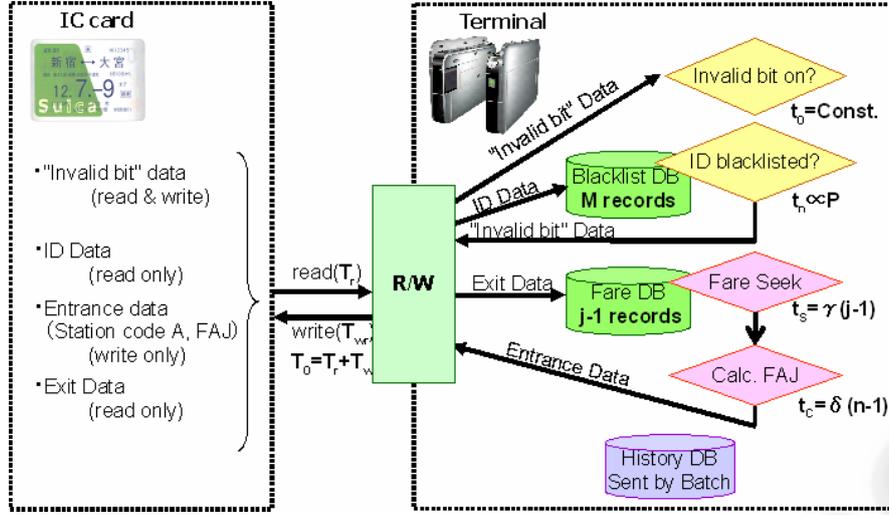


Fig. 3. Card-terminal autonomous decentralized processing (at station A).

In the post-boarding process at the station B (Fig. 4), the processing time T_B has been shown in Equation 4. T_{1B} and T_{0B} are considered in the same way as the Equation 5 while extra processes have to be taken into consideration on T_{2B} :

$$T_{2B} = t_s + t_c + t_{\text{sum}2} + t_c + t_2. \quad (9)$$

$t_{\text{sum}2}$: the time for summation of the fares (const.)

t_2 : the time for calculating the balance (const.)

Thus, T_B is expanded as Equation 10.

$$\begin{aligned} T_B &= T_{1B} + T_{2B} + T_{0B} \\ &= (t_0 + t_n) + (t_s + t_c + t_{\text{sum}2} + t_c + t_2) + T_{0B} \\ &= (t_0 + \beta P t_1) + \{\gamma(j-1) + \delta(n-1) + t_{\text{sum}2} + \delta + t_2\} + \{T_r(D_r) + T_{wr}(D_{wr})\} \\ &= t_0 + \beta t_1 \int_{\text{Suica start} \rightarrow \text{now}} p dt + \gamma j + \delta n + t_{\text{sum}2} + t_2 - \gamma + T_r(D_r) + T_{wr}(D_{wr}) \end{aligned} \quad (10)$$

Equations 2, 8, and 10 lead to the time for the decentralized procession, which is the function of P and j . That is, the total number of transactions and the total number of stations decides the total processing time. T_{AB} follows up when P and j increase.

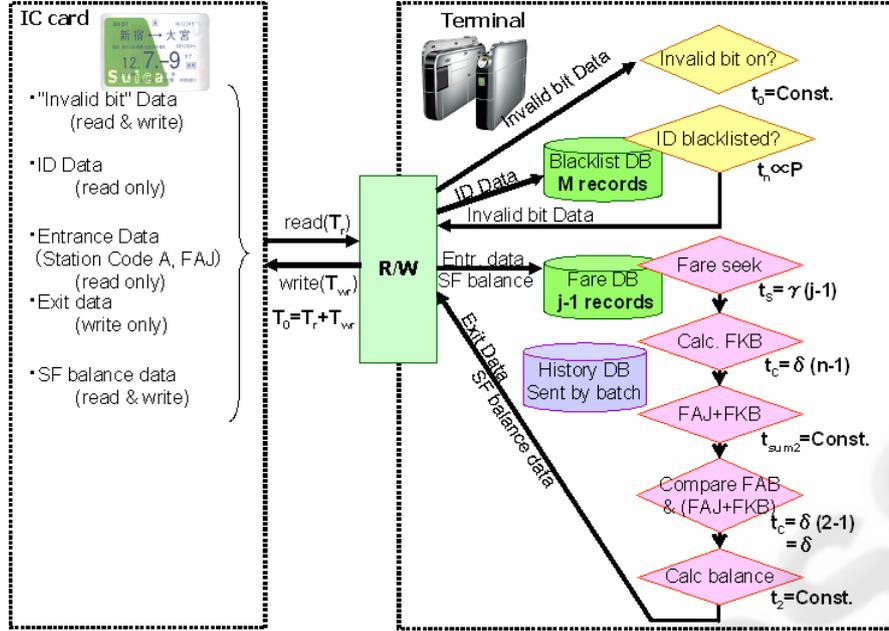


Fig. 4. Card-terminal autonomous decentralized processing (at station B).

4.2 Centralized Model

T_C , the time for the centralized processes on a center server is broken down in the same way as the Equation 1. In case of the centralized procession at the center server, only the "negative" cards are checked at the entrance in the station A. Another check and the fare calculation are done at the station B (Fig. 5). In this case, the processing time is written as Equation 11, with the expansions as in the decentralized processes.

$$\begin{aligned}
 T_C &= T_{IC} + T_{2C} + T_{0C} \\
 &= (t_0' + t_n') + (t_s' + t_c' + t_{sum}' + t_c' + t_2') + (T_0 + T_1) \\
 &= T_r(D_r) + T_{wr}(D_{wr}) + T_r'(D_r) + TW(p, n, cw) + T_{wr}'(D_{wr}) + TR(p, n, cr) + t_0' \\
 &\quad + \beta p t_1' + \frac{\gamma j(j-1)}{2} + 2\delta(n-1) + t_{sum}' + \delta + t_2' \\
 &= \beta t_1' \int_{Suicart \rightarrow now} p dt + \frac{\gamma j^2}{2} - \frac{\gamma j}{2} + 2\delta n + TW(p, n, cw) + TR(p, n, cr) \\
 &\quad + T_r(D_r) + T_{wr}(D_{wr}) + T_r'(D_r) + T_{wr}'(D_{wr}) + t_0' - \delta + t_2'
 \end{aligned} \tag{11}$$

T_C : the processing time at the center server

T_{1C} : the time for checking and processing the negative cards at the center server

T_{2C} : the time for calculating the fares at the center server

T_{0C} : the time for communicating and the others at the center server

TW : the waiting time for the center server

TR : the waiting time for the R/W

nl : the number of the communications lines at the center server (const.)

cw : the average processing rate of a communications line at the center server (const.)

nl' : the number of the communications lines at the R/W (const.)
 cr : the average processing rate of a communications line at a R/W (const.)
 TW and TR, the waiting times at the center server and the R/Ws, are delivered from the queuing theory (Equation 12).

$$TW = \frac{\rho(nl\rho)^{nl}}{nl!(1-\rho)^2 \sum_{i=0}^{nl-1} \left\{ \frac{(nl\rho)^i}{i!} + \frac{(nl\rho)^{nl}}{nl!(1-\rho)^2} \right\} p}, TR = \frac{\rho'(nl'\rho')^{nl'}}{nl'!(1-\rho')^2 \sum_{i=0}^{nl'-1} \left\{ \frac{(nl'\rho')^i}{i!} + \frac{(nl'\rho')^{nl'}}{nl'!(1-\rho')^2} \right\} p} \quad (12)$$

$$\rho = \frac{p}{nl \cdot cw}, \quad \rho' = \frac{p}{nl' \cdot cr}$$

From the Equations 11 and 12, the time for the centralized procession is estimated. It is also the function of P and j.

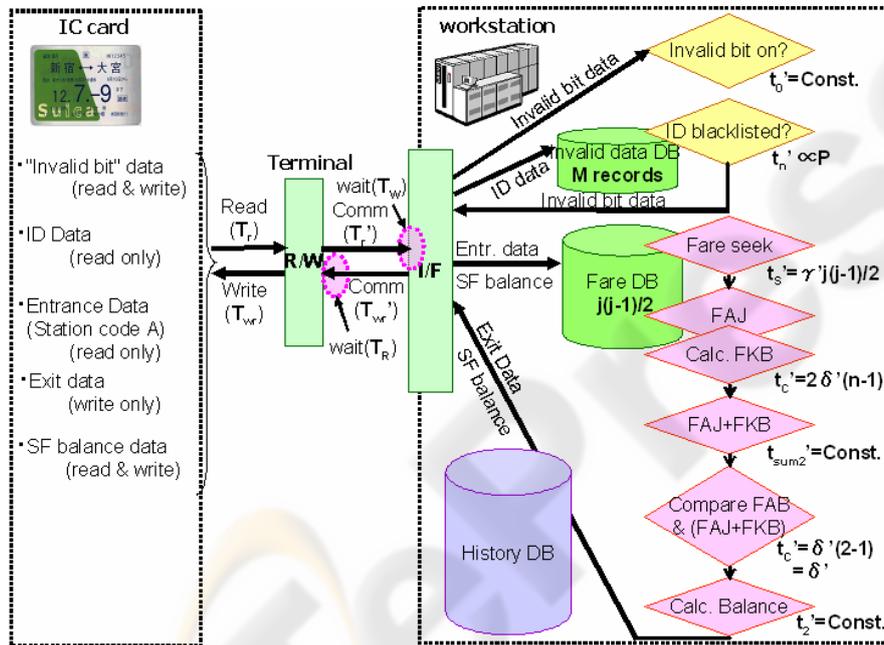


Fig. 5. Centralized processing (at station B).

5 Evaluation

Fig. 6 and 7 are the results of the simulations according to the two models defined in the previous sections. Fig. 6 shows the relationship between the processing time and the number of the stations while the Fig. 7 shows the one between the processing time and the number of the transactions. Both the figures insist that the decentralized process is more effective at middle-sized transportation and bigger though the centralized process wins at fewer stations; 43 stations and 42,700 transactions are the thresholds. The IC card ticket system was started at 424 stations and the number of

the transactions is reaching about 6 million a day. It suggests the decentralized architecture is more suitable for the actual system.

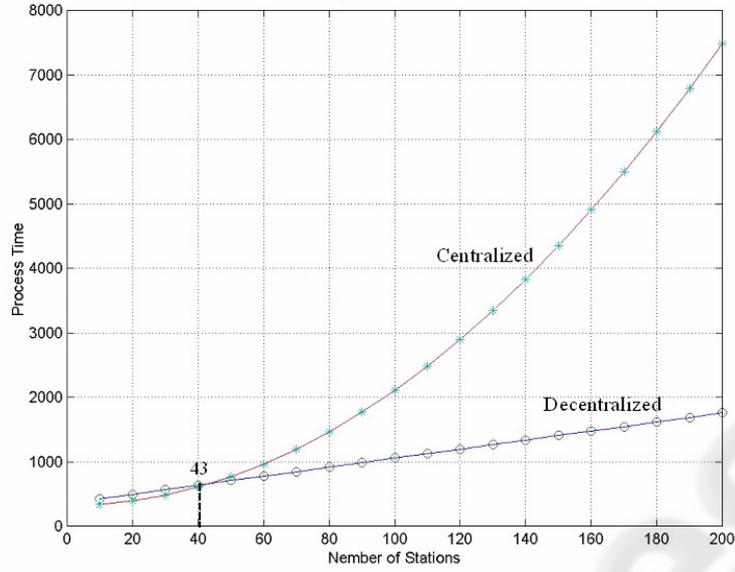


Fig. 6. Comparison: Decentralized and Centralized (by Stations).

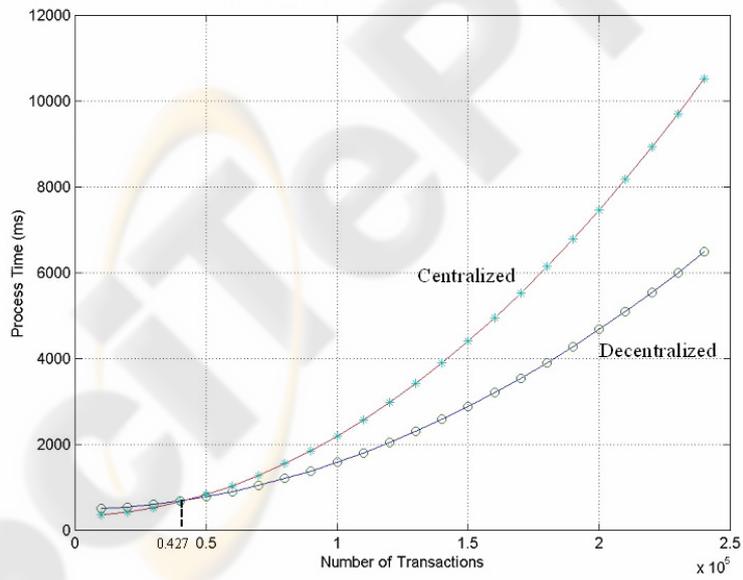


Fig. 7. Comparison: Decentralized and Centralized (by Transactions).

6 Conclusion

"The development of faster AFC machines" is one of the most important targets to handle the passengers getting on and off in high-density during the rush hours. On the other hand, reliability is indispensable to process the tickets, which are worth notes. Therefore, the ticket system requires both high performance and high reliability. To achieve these requirements, the autonomous decentralized architecture is introduced into the IC card ticket system, where "IC cards," "AFCGs," and a "center server" are constructed as the autonomous units.

This paper emphasizes the "autonomous decentralized algorithm on the fare calculations by IC cards and AFCGs." With this algorithm, the IC cards and the AFCGs calculate the fares separately to realize high performance. As a result of comparison of the two models prepared, the decentralized systems show more effectiveness than the centralized ones as the systems (the numbers of stations and transactions) get bigger. This technology has been introduced into the actual system and is performing very well [11].

Similar methods can be applied to discuss high reliability and assurance quantitatively: Modeling and quantification for high reliability and assurance shall be taken into further consideration.

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