Evolutionary process of self-financed shared mobility systems

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1 INTRODUCTION

In rural areas, traditional mass transit is often ineffective due to low and sparse demand, leading to a reliance on private cars that limits mobility for non-car users (e.g., elderly and children). While on-demand shared services could be a viable alternative, private providers may hesitate to invest due to profitability concerns.

We propose a community-owned on-demand shared service (CST) as a viable alternative. In this paper, we define CST as a means of transport that is established by sharing resources for mobility within a community. Achieving CST solely through a residents' initiative requires strong communication and consensus, which can be challenging. While it's feasible if a group aligns on a cost-sharing scheme, organizing community discussions to agree on cost distribution is often time-consuming and complex.

Given the difficulty to establish an agreement within the community prior to commencing CST, it is likely that CST will need to begin operating, with the hope that patronage will subsequently increase. However, with this approach, the initial number of users might be small and hence user fares will not cover the costs of CST. Therefore, it may be necessary to allow the CST to accrue some debt in its early stages, to be repaid once sufficient patronage is established.

To achieve this goal, this study aims at developing rules that encourage CST usage assuming that users make myopic decisions with no coalition or agreement among them. Specifically, the study emphasises the establishment of pricing rules that meet the following criteria;

1) It should allow for initial deficit, with the potential to achieve profitability over time.
2) It must converge to a level where income and costs balance out to maximize the social welfare.
3) It should be applicable without knowing the details about personal traits of potential users.
4) It should be easy for public to understand so that everyone can agree with the rule.

These criteria are selected with the goal of integrating such pricing rules into a web-based service that could facilitate the organic emergence of CST, especially if implemented by the public sector or representatives of rural communities. In the present study, we propose an example of a rule that fulfils these criteria, and demonstrate its effectiveness applied to a simple traffic system via numerical simulation.

Existing works have considered how to share the cost of a transport system such as CST among users, using either cooperative games such as Bistaffa *et al.* (2017) or non-cooperative games such as Fielbaum *et al.* (2022). Other studies have analysed the effects of collective information using a dynamical model (Thaithatkul *et al.*, 2019). This study is novel in that it proposes a dynamical policy that promotes cooperation between users that do not have social interactions, and demonstrates its effectiveness.

2 METHODOLOGY

2.1 Transport system

We consider many-to-one origin-destination demands in a rectangular area with length R and width L, as shown in Figure 1. An arterial road runs horizontally across the middle, connecting to the unique destination (e.g., transit station) located at the centre of the left edge. Local roads branch vertically from the arterial road at fixed intervals g, and users' origins are randomly located along these local roads.

The set of users is denoted by $\mathcal{N} \equiv \{1, \dots, N\}$. The origin location of the i-th user can be represented by the horizontal and vertical distances from the unique destination, and they are denoted by r_i and l_i, respectively. We only consider users travelling to the station by car or CST. Assuming people will walk to the station from some distance w, no origins are generated for $r_i < w$. We also assume that there are no users whose origin locations are the same.

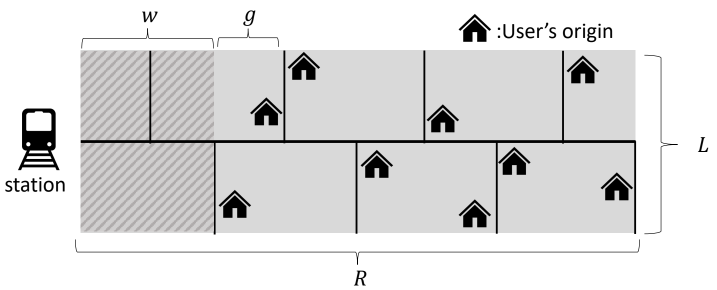

Figure 1 – *An example of the network*

A mode choice pattern of all users is denoted by a vector $\mathbf{a} \equiv (a_1, \dots, a_N)$. a_i represents the mode choice of user $i \in \mathcal{N}$,where $a_i = 0$ if the user chooses the private car and $a_i = 1$ if the user chooses CST. All trips from and to the origin start by first reaching the arterial road and then travelling to the destination. Thus, the travel distance for a user $i \in \mathcal{N}$ when using the private car is $r_i + l_i$. A user's travel distance via CST depends on the number of CST users located downstream toward the destination. The CST picks up users starting with those located farthest from the station. When multiple origins share the same local road, the CST collects users from the farthest point, moving toward the arterial road.

2.2 Evolutionary process of mode choices and fares

Given a day-to-day time sequence $\mathcal{D} \equiv (1, \dots, d, \dots, D)$; on each day $d \in \mathcal{D}$, each user reconsiders their mode choice with a fixed probability of $q \in (0, 1)$. The conditional probability that user $i \in \mathcal{N}$ chooses the CST under the condition that the user reconsiders the mode choice is given by the following logit model;

$$p_i^d = \frac{\exp(\theta EU_{i,s}^d)}{\exp(\theta EU_{i,s}^d) + \exp(\theta EU_{i,p}^d)}, \tag{1}$$

where $EU_{i,s}^d$ and $EU_{i,p}^d$ are, respectively, the expected utility for the shared service (CST) and private car on day d. The logit parameter is θ.

In this study, the private car is assumed to be driven by a user's partner. After dropping the user off at the destination, the partner must return to the origin. It implies that when using a private car, the household (i.e. the user and his/her partner) spends three times the value of the one-way travel time. Therefore, the expected utility for a user $i \in \mathcal{N}$ is formulated as follows:

$$EU_{i,p}^d = -3\alpha(r_i + l_i)/v_p \tag{2}$$

where α is the value of time and v_p is the average speed for a private car which is constant as congestion is not considered in this study.

The expected utility of using the CST consists of the expected travel time with the CST and the fare for CST on the day, f_d, given by;

$$EU_{i,s} = -\alpha\delta_d(r_i + l_i)/v_s - f_d \tag{3}$$

where v_s is the mean speed for CST. For simplicity, the expected travel time on day d for user i is estimated by multiplying direct travel distance to the destination with the "expected detour factor" on the day, δ_d. Here, δ_d is defined as the average ratio of the experienced travel distance using CST to the direct distance to the station for all users who chose CST on the previous day.

The fare is updated at regular intervals of γ days (when $d \bmod \gamma = 0$) to approximate the average operational cost per CST user. Let the operational cost for day d be the distance travelled on that day, K_d, multiplied by a constant η. The service operator updates the fare as follows:

$$f_d = \min\left\{(1-\beta)f_{d-1} + \beta\sum_{h=d-\gamma}^{d-1}\frac{\eta K_h}{\sum_{i\in\mathcal{N}} a_i^h},\ f^{max}\right\}, \tag{4}$$

where $\beta \in (0,1)$ represents the weight given to the target fare; f^{max} represents the fare cap set to prevent the fare from becoming extremely large. On other days where $d \bmod \gamma \neq 0$, $f_d = f_{d-1}$.

3 NUMERICAL EXPERIMENTS

Numerical experiments are conducted using the proposed model to explore conditions under which the CST achieves a self-financing state. 100 demand patterns are randomly generated with parameter settings in Table 1 to represent a rural area in Japan. For each demand pattern, 152 scenarios are run for different combinations of maximum fare, $f^{max} = [100, ..., 1000]$ [JPY], and cost per km, $\eta = [50, ..., 400]$ [JPY/km]. The fare is updated every 20 days. The same random seed is used for each simulation run.

R	L	g	w	N	α
10 [km]	1 [km]	0.5 [km]	1 [km]	30 [ppl]	2400 [JPY/h]
v_p	v_s	D	β	q	θ
40 [km/h]	30 [km/h]	1000[days]	0.1	0.1	0.01

Table 1 – *Parameter settings*

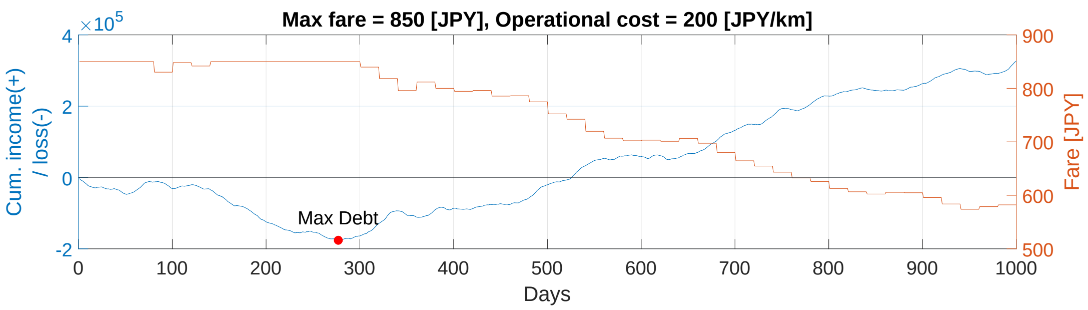

Figure 2 – *Evolution of cumulative income/loss and fare over 1000 days*

Figure 2 illustrates how the system transitions, indicating that it incurs the debt on earlier days before achieving self-financing on later days. Figure 3 (left) shows how many demand scenarios out of 100 reached a self-financing state. Here, a self-financing state is considered achieved when the cumulative income of the CST remains positive for the final 100 consecutive days of a 1000-day period. Figure 3 (right) shows the max debt averaged across those scenarios achieved self-financing. Black cells represent cases where self-financing is not achieved in any demand scenario. In general, higher costs per kilometre tends to increase debt levels, reducing the likelihood that the system will achieve self-financing.

The exception is some edge cases especially with lower max fare (e.g., max fare = 250 [JPY] and operational cost = 150 [JPY/km]) which show lower max debt but lower chances to achieve self-financing state compared to some cases (e.g., max fare = 300 [JPY] and operational cost = 150 [JPY/km]. These edge cases were investigated further, with 100 additional simulations for the same demand scenarios, each with a unique random seed. Unlike the cases shown in Figure 3, most combinations of maximum fare and cost per kilometre either consistently achieve or fail self-financing. However, there are still a few edge cases where the outcome remained unstable.

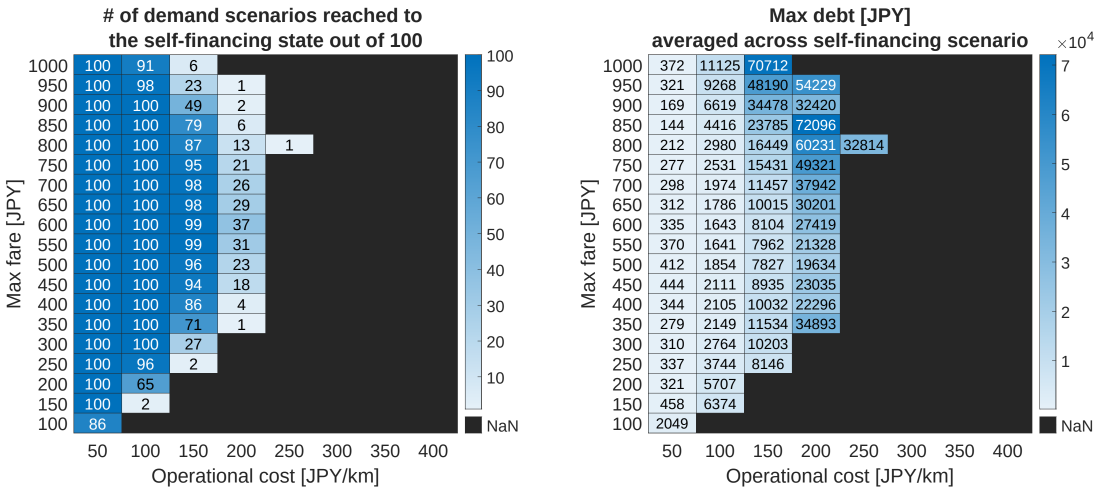

Figure 3 – *The number of demand scenarios achieving self-financing (left) and the maximum debt averaged across self-financing scenarios (right)*

4 DISCUSSION

In this study, we proposed a dynamic pricing scheme that promotes the use of the CST, which aims at achieving the self-financing state and confirmed its performance by a numerical calculation. We found that a simple pricing scheme that defers the burden of the fixed fare at the initial stage until the patronage increases can achieve the spread of the CST under self-financing conditions with appropriate parameters. In future studies, the impact of θ, β and q should be investigated to see if those values will change how the system evolves. Additionally, the characteristics of edge cases (in Figure 3) should be further analysed to identify the factors that lead the system to either achieve or fail to reach a self-financing state.

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