The day-to-day mode choice analysis under Mobility-as-a-Service bundle subscription

Manlian Pan, Haoyu Mo, and Xiaotong Sun*
Intelligent Transportation Thrust, Systems Hub, The Hong Kong University of Science and Technology (Guangzhou), China
xtsun@ust.hk
* Corresponding author

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1 INTRODUCTION

The emerging Mobility-as-a-Service (MaaS) transport model is distinguished by its capability to deliver integrated mobility solutions through subscription plans, commonly known as MaaS bundles (Ho *et al.*, 2020). These MaaS bundles encapsulate a wide variety of transportation modes, from public transit to ride-hailing/sourcing, ride-sharing and micro-mobility, with the goal of providing users with seamless, efficient, and sustainable mobility experiences (Hensher *et al.*, 2021, Caiati *et al.*, 2020). However, doubts and controversies have arisen regarding whether MaaS can achieve its potential benefits. While a growing number of MaaS-like pilot schemes have been promoted and trialed globally (Daniela *et al.*, 2023), some well-known MaaS schemes have been terminated, e.g., the first MaaS trial, Ubigo in Gothenburg, the only cross-country operated MaaS scheme, Whim owned by MaaS Global, Tripi in Sydney, Zipster in Singapore and etc.

The simultaneous burgeon and termination of MaaS trials raise concerns about the feasibility of MaaS. Inconclusive findings over the MaaS adoptions were disclosed by studies based on stated preference: Ho *et al.* (2018) revealed that more than half of the sample respondents will accept MaaS, while Caiati *et al.* (2020) indicated that the public merely intend to subscribe to MaaS bundles at the current moment. Similarly, no consensus has reached regarding on MaaS's impact on private car usage: Hensher *et al.* (2021) demonstrated that an increase in choosing the MaaS bundle leads to reduced car-kilometres-travelled in Sydney Tripi trial, though no evidence is found on car ownership reduction. Wright *et al.* (2020), on the other hand, demonstrated that MaaS can reduce both private car usage and ownership among the respondents. Nonetheless, theoretical studies by Hörcher & Graham (2020) unveiled that MaaS can reduce car ownership but not necessarily the car usage measured by vehicle-miles-traveled.

We hypothesize that the conflicting findings in literature arise from the insufficient consideration of the intricate interplay between bundle subscription and daily mode choices, which differ in frequency and are based on perceived rather than realized travel costs. To test this hypothesis, this extended abstract first outlines the static bundle and mode choices based on the stochastic user equilibrium principle. It then explores the periodic bundle subscriptions and daily mode choices of passengers using a two-level day-to-day (DTD) dynamic model. Drawing on the insights from this abstract, the full paper will further demonstrate the stability of mode and bundle choice dynamics, particularly when MaaS operators implement optimal control strategies through bundle pricing. We anticipate that stabilizing travelers' bundle and mode choices will enable MaaS operators to allocate transport resources more effectively and yield valuable insights for the design and implementation of MaaS bundles.

2 THE BUNDLE AND MODE DYNAMICS

This section first introduces the static problem of bundle and mode choices, capturing commuters' perception errors in travel time through the stochastic user equilibrium principle. Then, a two-level DTD model is employed to describe the evolution over commuters' mode behaviors within the bundle subscription period and the progression in bundle subscriptions from period to period.

2.1 The Problem Setting

Consider a linear city, one long-trip OD and one short-trip OD are served by either transit-based mode (Mode A, green), or vehicle-based mode (Mode B, yellow), or both with a finite number of transfers (see Fig.1). Mode A and Mode B are both available as part of MaaS bundle services, offering a total of four bundle options indexed by $j \in J$, where $J = \{0:$ no subscription, Pay-as-you-go (PAYG); $1:$ subscription to A only; $2:$ subscription to B only; $3:$ subscription to both A and B$\}$.

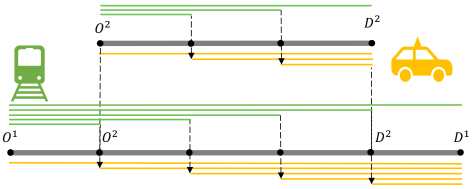


Figure 1 – *Illustration of linear city network*

When subscribing a bundle j, the subscription fee b_j is uniform across OD pairs and path utilization. Without a bundle, they pay the PAYG price, which is p_A or p_B per link. The link travel time cost of vehicle-based mode, $t_a(x_a)$, is flow-dependent due to congestion, while that of transit-based mode t_a remains fixed. To capture the discomfort on transit, a link body congestion cost function $c_a(x_a)$ is introduced with $c'_a(x_a) > 0$ and $c_a(0) = 0$. Consequently, the generalized cost of a traveler with bundle subscription j choosing path p for OD pair w is expressed as:

$$g^w_{jp} = \sum_{a\in E^A} \Big(t_a + c_a(x_a) + \phi^a_j p_A\Big)\delta^{wa}_{jp} + \sum_{a\in E^B} \Big(t_a(x_a) + \phi^a_j p_B\Big)\delta^{wa}_{jp} + \frac{\alpha}{2f}\psi^A_p, \tag{1}$$

where the first and second terms are the travel costs of using mode A and B, respectively. The third term accounts for the waiting time cost incurred if transit mode is utilized along path p. The binary indicator ϕ^a_j equals to one if link a belongs to the link set of bundle j, and zero otherwise, and the binary indicator δ^{wa}_{jp} equals to one if link a lies on path p between O-D pair w under bundle j.

2.2 Stochastic User Equilibrium

In the mode choice analysis under a determined bundle subscription, we employ the Path-Size Logit Model to address the issue of path overlapping (Ben-Akiva & Bierlaire, 1999), resulting in the probability of selecting path $p \in P^w$ within bundle j for O-D pair w:

$$\pi^w_{jp} = \frac{\bar{w}^w_{jp}\exp(-g^w_{jp}/\mu_m)}{\sum_{r\in P^w} \bar{w}^w_{jr}\exp(-g^w_{jr}/\mu_m)},\ p \in P^w,\ w \in W. \tag{2}$$

The path-size factor $\bar{w}_{jp}^{w} \in (0,1]$ measures the extent to which path p overlaps with other paths in bundle j for O-D pair w, defining as $\bar{w}_{jp}^{w} = \sum_{a \in A_{jp}^{w}} \frac{l^a}{L_{jp}^{w}} \frac{1}{\sum_{k \in P^w} \delta_{jk}^{wa}}$, where l_a represents the length of link a, and L_{jp}^{w} is the length of path p between the O-D pair w under bundle j, and A_{jp}^{w} denotes the set of links on path p between the O-D pair w under bundle j.

In the bundle choice analysis, we employ the dogit model proposed by Gaundry & Dagenais (1979), which captures the bundle loyalty stating that individuals consistently choose a specific product regardless of other product attributes. Assume that a bundle period is T days, let V_j^w denote the daily expected perceived travel cost of bundle j and OD w, the corresponding total travel cost is expressed by

$$g_j^w = V_j^w + \frac{b_j^w}{T} = -\mu_m \ln \left(\sum_{p \in P^w} \exp(-g_{jp}^{w}/\mu_m) \right) + \frac{b_j^w}{T},\ j \in J, w \in W. \tag{3}$$

Then, the probability of choosing bundle j with the consideration of bundle loyalty is

$$\pi_j^w = \frac{\eta_j^w}{1 + \sum_{j \in K} \eta_j^w} + \frac{1}{1 + \sum_{j \in K} \eta_j^w} \cdot \frac{\exp(-g_j^w/\mu_b)}{\sum_{k \in K} \exp(-g_k^w/\mu_b)},\ j \in J, w \in W, \tag{4}$$

where $\eta_j^w \geq 0$ is the captivity parameter representing bundle loyalty.

Proposition 1 *Under assumption that the generalized link cost function $t_a(x_a)$ and $c_a(x_a)$ is continuous differentiable and the generalized path cost is additive, the static bundle and mode choice problem has at least a solution, denoted as $q^* \in \Omega$, which is an equilibrium pattern of bundle and mode choice.*

2.3 The Day-to-day Dynamics

As the static equilibrium serves merely as a benchmark and does not reflect real-world scenarios accurately, we further track evolution of travelers' bundle subscription q_j^w and mode usage q_{jp}^w through a day-to-day dynamic model. In particular, Logit-based Smith dynamics (Smith & Watling, 2016) is adopted:

$$\frac{dq_{jp}^w}{dt} = \sigma^t (y_{jp}^w(t) - q_{jp}^w(t)),\ \frac{dq_j^w}{dT} = y_j^w(T) - q_j^w(T). \tag{5}$$

Here, the parameter σ^t denotes the mode change rate and also reflex the inertia for mode change. Variables $y_{jp}^{w*}(t)$ and $y_j^{w*}(T)$ are the solutions to mode choice problem (**Eqs.** (1)-(2)) bundle choice problem (**Eqs.** (3)-(4)), respectively.

The convergence of bundle and mode to equilibrium within a given period is contingent upon the unit cost of bundle service (β_A, β_B) and PAYG price (p_A, p_B), as detailed in Table 1. In scenarios where bundle convergence occurs, several key insights emerge:

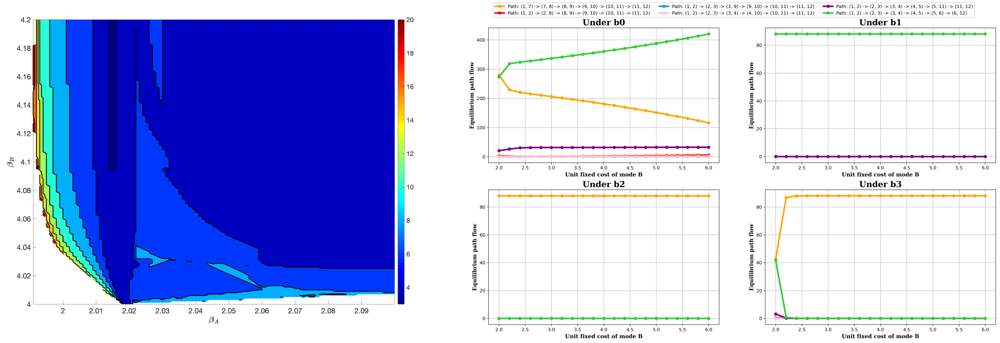
- Bundle prices make no difference on the bundle flow distribution, where non-MaaS users occupy the main population (see fig.(2a)), echoing the findings by Caiati *et al.* (2020).

- PAYG prices minimally affect solo subscribers (Bundle 1 & 2) but significantly impact others (Bundle 0 & 3), pushing multi-subscribers (Bundle 3) to vehicles and non-subscribers (Bundle 0)to transit(see fig.(2b)). In comparison, subscribing to MaaS bundles with vehicle-based travel options can leads to more vehicle-miles traveled, validated the conclusions by Hörcher & Graham (2020).

Table 1 – *Conditions for bundle convergence*

	$\beta_B < p_B + \epsilon$	$\beta_B \geq p_B + \epsilon$
$\beta_A < p_A - \delta$	NC	NC
$\beta_A \geq p_A - \delta$	NC	C

NC: bundle does not converge; C: bundle converge.



(a) *Bundle convergence period* (b) *Long-trip OD*

Figure 2 – *Equilibrium bundle and path dynamics*

3 NEXT STEP

To complete this paper, we will assess the stability of the controlled DTD mode and bundle choice dynamics and examine the optimal control policies for MaaS operators. Preliminary results indicated that when the MaaS operators aim to minimize the total travel time, bundle subscriptions do not favor transit-based mode. Therefore, different objectives, such as total transit ridership maximization, total emission minimization will also be studied.

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