

## Research Article

# Analysis of Parking Reliability Guidance of Urban Parking Variable Message Sign System

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Operators of parking guidance and information systems (PGIS) often encounter difficulty in determining when and how to provide reliable car park availability information to drivers. Reliability has become a key factor to ensure the benefits of urban PGIS. The present paper is the first to define the guiding parking reliability of urban parking variable message signs (VMSs). By analyzing the parking choice under guiding and optional parking lots, a guiding parking reliability model was constructed. A mathematical program was formulated to determine the guiding parking reliability of VMS. The procedures were applied to a numerical example, and the factors that affect guiding reliability were analyzed. The quantitative changes of the parking berths and the display conditions of VMS were found to be the most important factors influencing guiding reliability. The parking guiding VMS achieved the best benefit when the parking supply was close to or was less than the demand. The combination of a guiding parking reliability model and parking choice behavior offers potential for PGIS operators to reduce traffic congestion in central city areas.

## 1. Introduction

With the development and application of information transportation systems, urban Parking Guidance and Information System (PGIS) has become an important method to alleviate parking problems. Parking guidance information is primarily distributed via the Variable Message Sign (VMS) [1, 2]. Studies have shown that optimizing the number and locations of VMS can efficiently guide the parking flow [3, 4], through which the driving distance or the queue length can be minimized [5–7]. Through this method, VMS not only reflects the operating condition of the parking lots but also forecasts the parking berths. However, the display information provided by VMS tends to be inconsistent with the actual usable berths

of the parking lots [8–11], making parking guiding less reliable. Lower reliability lowers VMS acceptance among drivers, thus decreasing the benefits that PGIS can offer.

Although studies and applications of reliability in transportation have often used reliability to estimate travel time and network capacity [12, 13], it has been seldom employed in studies estimating parking time [14]. Li et al. proposed the concept of parking reliability and quantitatively analyzed factors influencing guiding reliability. However, they did not mention methods to dynamically estimate parking arrivals and to calculate the guiding reliability. The influence factors of guiding reliability were also not analyzed quantitatively [15]. Chatterjee et al. surveyed the actual responses of drivers to message activation in London, but no model of driver behavior was constructed [16]. Mei and Tian presented an optimized combination model and algorithm of parking guidance information configuration but did not consider the guiding reliability of VMS [17]. Thus, determining the best availability status to display on the signs to obtain higher reliability has become a common problem, particularly during periods when demand levels are approaching capacity.

To address the aforementioned issues, the present study focuses on the following:

- (1) defining Guiding Parking Reliability and related basic assumptions,
- (2) analyzing parking choice behavior and parking arrivals estimation, and establish a Guiding Parking Reliability model and algorithms,
- (3) analyzing factors influencing Guiding Parking Reliability using a numerical example network.

## 2. Analysis Foundations

### 2.1. Definition of Guiding Parking Reliability

Drivers choose parking lots based on information provided by VMS. Upon arriving at a parking lot, a driver must choose between two existing conditions: presence or absence of berths. The guiding parking reliability refers to the ratio between parking flow and total parking flow, where parking flow is controlled by the parking guiding information. The parking reliability can be denoted by  $\psi$ :

$$\psi = \frac{Q_m}{Q}, \quad (2.1)$$

where  $\psi$  is the guiding parking reliability of VMS. The larger the  $\psi$ , the higher the reliability.  $Q_m$  is the parking flow that chooses parking lots using parking guiding information.  $Q$  is the total parking flow.

### 2.2. Basic Assumptions

The present research is based on following assumptions.

- (1) Drivers passing by a VMS look at the displayed information and consider that information as correct.
- (2) Drivers decide on the parking choice upon seeing the VMS. Drivers never change their minds once a decision is made. Upon arriving at the parking lots, drivers must still wait for berths if none is available. A first-come, first-served service rule exists at parking lots.

### 3. Guiding Parking Reliability

#### 3.1. Parking Choice Model

Drivers use parking lots to minimize vehicle disutility [18]. From this information, the parking choice model could be established as follows:

$$P_{ijk} = \frac{l^{kj} \cdot \exp(-\theta U_{ijk})}{\sum_{k=1}^K l^{kj} \cdot \exp(-\theta U_{ijk})} \quad (i = 1, \dots, I; j = 1, \dots, J; k = 1, \dots, K), \quad (3.1)$$

$$U_{ijk} = \alpha_m t_m^{ik} + \alpha_w t_w^{kj} + \frac{\alpha_f f^k}{t_f}, \quad (3.2)$$

where  $P_{ijk}$  is the probability of selecting parking lot  $k$  from deciding node  $i$  with destination  $j$ .  $U_{ijk}$  is the utility for drivers from deciding node  $i$  to destination  $j$ , choosing parking lot  $k$ .  $t_m^{ik}$  is the driving time from the deciding node  $i$  to parking lot  $k$ , which could be calculated from the VMS to the parking lot.  $t_w^{kj}$  is the walking time from parking lot  $k$  to destination  $j$  and  $f^k$  is the fee at parking lot  $k$ .  $t_f$  is the value of time.  $\alpha_m$ ,  $\alpha_w$ , and  $\alpha_f$  are relatively important weighing coefficients.  $\theta$  is the scale parameter.  $I$ ,  $J$ , and  $K$  are the sets of the deciding nodes, the destinations of the drivers, and the parking lots. Availability of parking lots is defined as the walking time after parking from parking lot  $k$  to destination  $j$ , which is within the range of the maximum acceptable walking time  $T_w$ .  $l^{kj}$  is used to denote the efficiency of the parking lots.

$$l^{kj} = \begin{cases} 1, & t_w^{kj} \leq T_w, \\ 0, & t_w^{kj} > T_w. \end{cases} \quad (3.3)$$

With the parking guiding information, when the VMS displays that the parking lot  $k$  is full, the parking lot is no longer available. The available variable of VMS display  $\delta^{ik}$  is used to revise the parking choice utility [19]:

$$P_{ijk}(o) = \frac{\delta^{ik} l^{kj} \exp(-\theta U_{ijk})}{\sum_{k=1}^K [\delta^{ik} l^{kj} \exp(-\theta U_{ijk})]}, \quad (3.4)$$

where  $P_{ijk}(o)$  is the probability of selecting parking lot  $j$  from deciding node  $i$  with destination  $k$  under the parking VMS.  $\delta^{ik}$  is the Boolean variable:

$$\delta^{ik} = \begin{cases} 1, & \text{if message sign } i \text{ displays parking lot } k \text{ available} \\ 0, & \text{other.} \end{cases} \quad (3.5)$$

When the VMS displays the *Full* sign for all covered parking lots, vehicles are forced to wait, resulting in queues. Thus, the parking choice behavior is consistent with the behavior even without considering the parking guiding information.

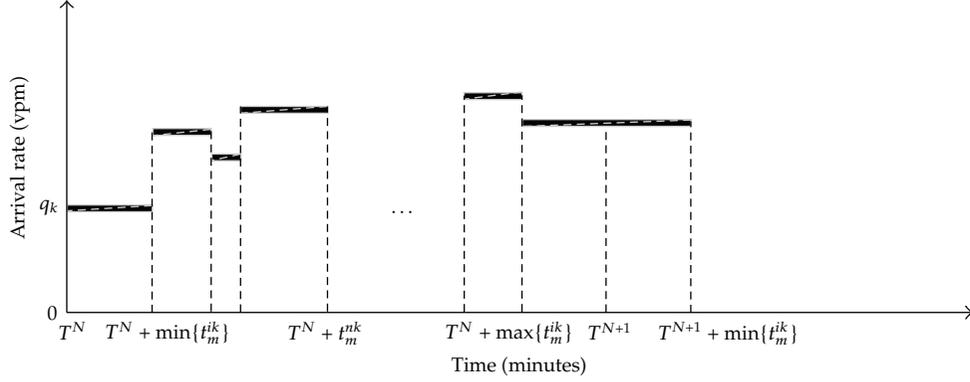


Figure 1: Arrival of parking flow  $T^N \sim T^{N+1}$  in parking lot  $k$ .

### 3.2. Parking Arrivals Dynamic Estimation

We first deduce the arrival parking flow in parking lot  $k$ . A driving time delay from the deciding node with VMS  $i$  to parking lot  $k$  is found. At time  $t$ , the vehicle from the deciding node  $i$  must reach the parking lot  $k$  at  $t + t_m^{ik}$ , based on the assumption,  $\Delta T > \max\{t_m^{ik}\}$ . Thus, the arrival parking flow  $r^k(t)$  between the varied cycle  $\Delta T = T^{N+1} - T^N$  is shown as in Figure 1.

At time  $T^N$ , each message sign displayed on the VMS is changed. At time  $T^N \sim T^N + \min\{t_m^{ik}\}$ , the arrival rate of parking lot  $k$  is influenced by the parking redistribution in the last variety cycle. From time  $T^N + \min\{t_m^{ik}\}$ , the arrival rate is affected by both the last and the corresponding parking redistribution with parking guiding information until time  $T^N + \max\{t_m^{ik}\}$ . From  $T^N + \max\{t_m^{ik}\}$  to  $T^{N+1} + \min\{t_m^{ik}\}$ , the arrival rate of parking lot  $k$  is only affected by the parking guiding information in this cycle. When arranging  $t_m^{ik}$  from the smallest to the largest, the arrival rates of parking lot  $k$  are affected individually by each parking flow from the deciding nodes in this varied cycle. Therefore, the arrival rate of parking lot  $k$  ( $r_k(t)$ ) in time  $T^N \sim T^{N+1}$  could be deduced as follows:

$$r_k(t) = \begin{cases} \sum_{i=1}^I \sum_{j=1}^J q_{ij}^{N-1} P_{ijk}^{N-1}, & t \in (T^N \sim T^N + \min\{t_m^{ik}\}), \\ \sum_{i=x+1}^I \sum_{j=1}^J q_{ij}^{N-1} P_{ijk}^{N-1} + \sum_{i=1}^x \sum_{j=1}^J q_{ij}^N P_{ijk}^N, & t \in (T^N + t_m^{xk} \sim T^N + t_m^{(x+1)k}), \\ \sum_{i=1}^I \sum_{j=1}^J q_{ij}^N P_{ijk}^N, & t \in (T^N + \max\{t_m^{ik}\} \sim T^{N+1}), \end{cases} \quad (3.6)$$

where  $x = 1, 2, \dots, I$ , and  $t_m^{xk}$  is sequenced  $t_m^{ik}$  from the smallest to the largest,  $\min\{t_m^{ik}\} = t_m^{1k} \leq t_m^{2k} \leq \dots \leq t_m^{Ik} = \max\{t_m^{ik}\}$ . Thus, in a varied cycle of VMS, the number of arrival rate might be  $I + 1$ .  $q_{ij}^N$  is the parking flow rate from the deciding node  $i$  to destination  $j$  in the variety cycle  $N$ .

The arrival parking flow volume of parking lot  $k$  ( $R_k(t)$ ) from  $T^N$  to  $T^N + t$  could be calculated as

$$R_k(t) = \int_{T^N}^{T^N+t} r_k(t) dt. \quad (3.7)$$

With the departing rate of parking lot  $k$  designated as  $d_k(t)$ , the depart parking flow volume of parking lot  $k$  ( $D_k(t)$ ) from  $T^N$  to  $T^N + t$  could be calculated as

$$D_k(t) = \int_{T^N}^{T^N+t} d_k(t) dt. \quad (3.8)$$

Finally, parking flow volume of parking lot  $k$  ( $S_k(t)$ ) from  $T^N$  to  $T^N + t$  is equal to the arriving amount  $R_k(t)$  minus the depart amount  $D_k(t)$ :

$$S_k(t) = R_k(t) - D_k(t). \quad (3.9)$$

This time, the number of total parking vehicles in parking lot  $k$  ( $Q_k^N(t)$ ) is

$$Q_k^N(t) = Q_k^N(0) + S_k(t), \quad (3.10)$$

where  $Q_k^N(0)$  is the number of parking vehicles at the beginning of variety cycle  $T^N$ .

### 3.3. Guiding Parking Reliability Model

The present paper analyzed the guiding parking reliability within a one-time cycle, from  $T^N$  to  $T^{N+1}$ , due to the various cycles of VMS of PGIS.

According to (3.10), the available berths of parking lot  $k$  at  $T^N + t$  are as follows:

$$V_k(t) = C_k - Q_k^N(t), \quad (3.11)$$

where  $V_k(t)$  is the number of vacant berths. When  $V_k(t) > 0$ , vacant berths are available; thus parking reliability is achieved. When  $V_k(t) \leq 0$ , no vacant berth is available, and parking reliability cannot be achieved, denoted by  $\varphi_k(t)$ :

$$\varphi_k(t) = \begin{cases} 1, & V_k(t) > 0, \\ 0, & V_k(t) \leq 0. \end{cases} \quad (3.12)$$

According to Formula (3.6), there could be  $I + 1$  arrival rates of parking lot  $k$  in  $T^N \sim T^{N+1}$ . The parking flow that achieves parking reliability of parking lot  $k$  in  $T^N \sim T^{N+1}$  could be calculated as

$$Q_m(k) = \int_{T^N}^{T^{N+1}} r_k(t) \varphi_k(t) dt. \quad (3.13)$$

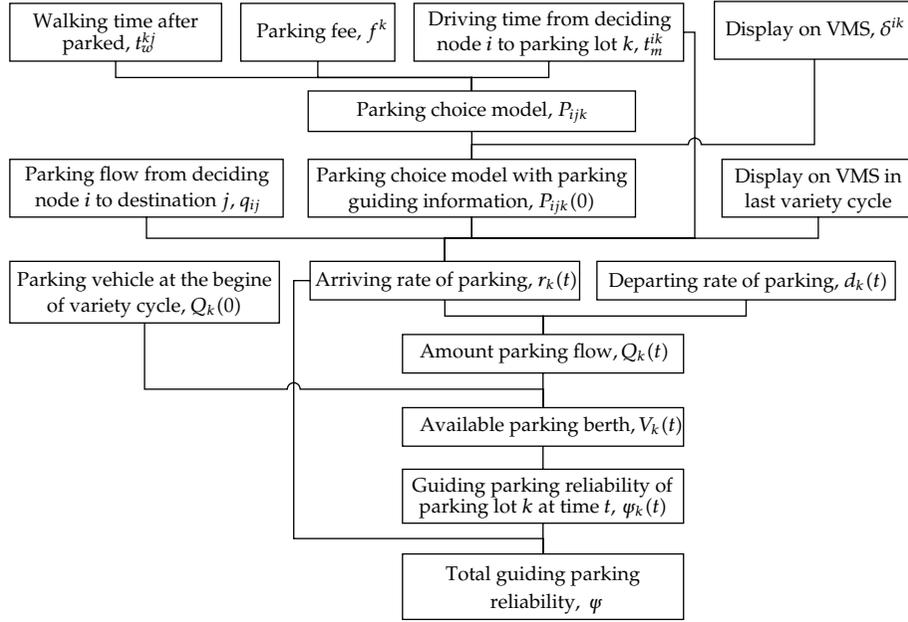


Figure 2: Calculation flow chart of guiding parking reliability.

In the parking guiding zone, the guiding parking reliability in the variety cycle  $T^N \sim T^{N+1}$  of VMS could be given as follows:

$$\psi = \frac{\sum_k Q_m(k)}{Q}. \quad (3.14)$$

Combining (3.1) to (3.14), the guiding parking reliability in various cycles  $T^N \sim T^{N+1}$  of VMS could be calculated, which could optimize the configuration of VMS of PGIS.

According to (3.11) to (3.13), as the number of vacant berths decreases, especially when the parking supply cannot meet the demand, the guiding parking reliability declines. To precisely depict the guiding benefit of a parking VMS, a relative guiding parking reliability is adopted, which is the comparison of the parking reliability with and without VMS,  $\phi$ , denoted as follows:

$$\phi = \frac{\psi - \varphi}{\varphi}, \quad (3.15)$$

where  $\phi$  is the relative guiding parking reliability of parking VMS. The larger the  $\phi$ , the bigger the benefit of parking guidance.  $\varphi$  is the parking reliability without parking guiding information. In contrast to  $\psi$ , calculating  $\varphi$  adopts the parking choice model (3.2), which does not need to be revised by (3.3).

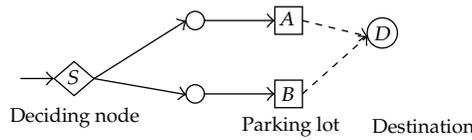


Figure 3: Numerical example network.

Table 1: Parking reliabilities under different conditions.

$Q(0)$	$q_N$ VMS	1	2	3	4	5	6	7	8	9	10
		Parking reliabilities									
$Q_A^N(0) = 40$	(1,1)	1	1	1	1	1	1	1	0.924	0.841	0.783
	(1,0)	1	1	1	0.853	0.752	0.696	0.661	0.636	0.618	0.604
$Q_B^N(0) = 80$	(0,1)	1	1	1	1	1	0.840	0.705	0.624	0.570	0.532
	NO	1	1	1	1	1	1	1	0.924	0.841	0.783
$Q_A^N(0) = 20$	(1,1)	1	1	1	1	1	0.851	0.725	0.666	0.620	0.575
	(1,0)	1	1	1	1	1	1	1	0.944	0.884	0.839
$Q_B^N(0) = 90$	(0,1)	1	1	1	0.920	0.610	0.507	0.410	0.348	0.307	0.277
	NO	1	1	1	1	1	0.851	0.725	0.666	0.620	0.575

(1, 1) means that parking lots A and B are available. (1, 0) means that parking lot A is available but B is not. "NO" means no VMS is available.

### 3.4. Model Algorithm

The key to solving the previous model is determining the connection between the different models. The calculation flow chart is as shown in Figure 2.

Figure 2 indicates that the key factors influencing guiding parking reliability are the driving time from the deciding node  $i$  to parking lot  $k$  ( $t_m^{ik}$ ), the displayed information on VMS ( $\delta^{ik}$ ), the parking flow ( $q_{ij}$ ), and the departing rate ( $d_k(t)$ ).

## 4. Numerical Example

A simple numerical network is presented in Figure 3 to explain how to calculate the guiding parking reliability. This example also shows how the factors affect guiding parking reliability, where S is the deciding node, that is, the location of VMS, A and B are the parking lots, which are all within the walking limitation,  $l^{AD} = l^{BD} = 1$ , and D is the destination. The values of basic variables and parameters are  $t_m^{SA} = 5$  min,  $t_m^{SB} = 3$  min,  $t_w^{AD} = 2$  min,  $t_w^{BD} = 3$  min,  $f^A = f^B = \$1$ ,  $t_f = 4$ \$/h,  $\alpha_m = 1$ ,  $\alpha_w = 0.7$ ,  $\alpha_f = 0.05$ ,  $\theta = 1$ ,  $\Delta T = T^{N+1} - T^N = 10$  min,  $C_A = 50$ , and  $C_B = 100$ .

The parking arrival rate in the last variety cycle is assumed to be known ( $q_{N-1} = 6$  veh/min), and the availability of each parking lot is displayed on the VMS. To explain the effect of the influence factors, the reliabilities under different conditions of parking supply, demand, and display of VMS are calculated. The results are shown in Table 1.

In Figure 4, in the condition of  $Q_A^N(0) = 40$  and  $Q_B^N(0) = 80$ , the guiding parking reliability remains stable during the first three cycles. However, as the number of parked vehicles increases, the non-optimized parking guiding information or the nongiving of information offers the highest parking reliability. The parking supply of parking lots A and B is higher than the parking demand, and the optimized parking guiding information cannot

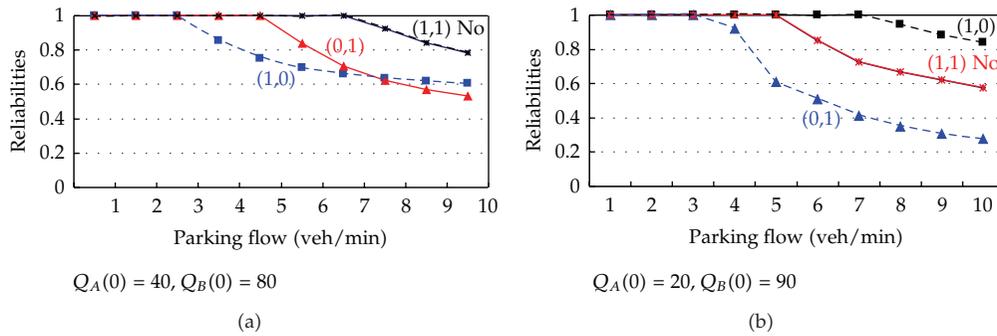


Figure 4: Parking reliability under different conditions.

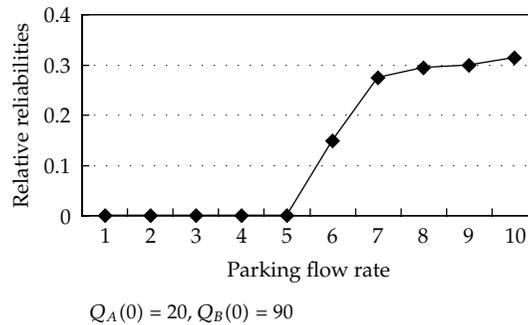


Figure 5: Relative guiding parking reliability under different parking supplies and demands.

improve the guiding parking reliability. On the contrary, the guiding parking reliability is reduced. In the condition of  $Q_A^N(0) = 20$  and  $Q_B^N(0) = 90$ , the parking supply of parking lot B is close to the parking demand, so the optimized parking guiding information offers the highest parking reliability. However, when a false parking guiding information is given, parking reliability is at its lowest.

In Figure 5, relative reliability represents the difference between the optimized and nonoptimized parking guiding information. Relative reliability shows that the optimized parking guidance information can achieve higher reliability with an increase in parking flow.

The interesting findings based on the numerical example can be summarized as follows.

- (1) The key factors that affect the guiding parking reliabilities of VMS are the quantitative changes in parking berths and the display conditions of VMS.
- (2) When the parking supply is much higher than the parking demand, the benefits of parking guiding information are limited. When the parking supply is close to or less than the demand, or when the use of parking lots is not balanced, the optimized parking guiding information can achieve the highest reliability.

## 5. Conclusions

The present paper described guiding parking reliability developed to investigate the effect of PGIS sign boards on the parking system. The guiding parking reliability model and

the algorithm were established by analyzing the parking choice behavior and estimating the parking arrival flow rate.

Providing reliable car park availability information to drivers was also discussed. A numerical example is an effective way to find solutions for identifying guiding parking reliability under different conditions. The results indicate that quantitative changes of parking berths and the display conditions of VMS are the most important factors affecting guiding reliability. PGIS operators must provide reliable and optimal car park availability information to drivers, especially when the parking demand is approaching the supply. When the parking demand is relatively low, the need to provide parking information tends to be unimportant.

Several simplifying assumptions used in the model may tend to overestimate how PGIS signs affect parking choice. In particular, if observers are assumed to be nonbelievers of the available information, the potential of PGIS to influence and manage traffic movements, as well as parking choices, is drastically reduced.

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