Estimating benefits of travel demand management measures

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Abstract

This paper presents models for estimating benefits considering the uncertainty of travel times by implementing travel demand management measures including park and ride systems and road pricing. The models are composed of drivers’ behavioural model and dynamic traffic simulation. The models were applied to a test road and railway network in Kyoto-Osaka area, Japan. Results indicated that commuting drivers can expect both benefits by reducing travel times as well as reducing variation of travel times by implementing park and ride systems.

1 Introduction

We are currently faced with increasing level of traffic congestion and environmental problems in urban areas due to increase of transport demands. Some travel demand management (TDM) schemes including park and ride systems and road pricing have been proposed and implemented in many cities around the world. However, it is required to evaluate effects of these schemes before the implementation. Network modelling becomes a key issue in the evaluation of effects of these schemes on traffic conditions. In particular the uncertainty of travel times within networks plays an important role for modelling, as the traffic conditions on the network vary with time.
Traffic congestion increases the uncertainty of travel times as well as the travel times themselves. It is expected that implementing TDM schemes will reduce the variation of travel times and the amount of travel times. If the reliability of travel times is improved, drivers can cut the time margin of travelling and take later starting time for a trip. Moreover, providing alternatives of travel modes and routes by TDM schemes allows traffic congestion to be alleviated and the reliability on road network to be improved.

The reliability on road network has become more important, given the ongoing increases in the time value of people involved in business and other activities. There are three types of reliability of road network; connectivity reliability, time reliability and capacity reliability (Bell et al. [1]). This paper focuses on the time reliability of networks that is related to the uncertainty of travel times within the network.

Normally constructing new roads or implementing TDM schemes can reduce travel times. The benefits generated by the reduction of travel times are estimated in the traffic planning. However, the measures can contribute to decrease the variation of travel times as well as the reduction of mean travel times. This leads to the reduction of risk of arriving late at the destination, which is beneficial to drivers. This type of benefits should be incorporated in estimating economic benefits by implementing some measures for improving road traffic conditions (Taniguchi et al. [6]). It becomes essential in an information-oriented society, since the trips on the road network are then increasingly associated with a designated arrival time. A typical example can be seen in the Just-In-Time delivery system for freight transport.

There have been intensive studies on drivers' choice behaviour on starting time for a trip. Many of them assume drivers behave by maximising their utility (or minimising their disutility) under the uncertainty of travel times that can be represented by a probabilistic distribution. Hall [5] presented a model for identifying the starting time for a trip of drivers by minimising the loss function of drivers. Chang et al. [3] analysed drivers' choice behaviour on starting times for daily commuting by an experimental approach. Ben-Akiva [2] presented a model for simultaneously identifying the starting time and route by applying the maximisation of drivers' utility.

This study presents a simulation model that incorporates drivers' behaviour under the uncertainty of travel times. After applying the model to a test network, benefits by reducing travel times and improving the reliability of travel times can be estimated for commuting drivers by means of TDM schemes. As well the changes in traffic conditions on the network can be evaluated after implementing TDM schemes.
2 Models

2.1 Drivers' behavioural model

2.1.1 Models for adjusting starting time
The drivers' behaviour of adjusting the starting time for commuting by car under the uncertainty of travel times can be formulated as given below. A driver who is expected to arrive at his/her office at a designated time identifies the starting time by minimising the expected disutility taking into account the early arrival and delay penalties as shown in Figure 1. If a driver arrives at the office later than the designated time $t_d$, he/she needs to pay the penalty that is proportional to delay time. If he/she arrives earlier than the designated time $t_d$, he/she needs to wait for the work starting time and incurs the time costs. Multiplying the distribution of arrival time at the office with the penalty function in Figure 1 gives expected disutility of early arrival and delay.

Figure 1: Identification of expected disutility using the distribution of travel times and penalty function
The expected disutility of using car can be given as the sum of disutility of early arrival and delay penalty, time costs of moving by car and costs incurred by the road pricing scheme. It can be formulated as:

$$EDU_c(t_0) = C_p(t_0) + C_m(t_0) + \delta \cdot C_r$$  \hspace{1cm} (1)$$

where,

$$C_p(t_0) = \int_{-\infty}^{t_0} c_f \{t_d - (t_0 + t)\} f(t) dt + \int_{t_0}^{\infty} c_d \{(t_0 + t) - t_d\} f(t) dt$$  \hspace{1cm} (2)$$

$$C_m(t_0) = \int_{-\infty}^{t_0} c_m \cdot t \cdot f(t) dt = c_m \cdot E(f(t))$$  \hspace{1cm} (3)$$

$t_0$: starting time
$t_d$: designated time to be arrived
$f(t)$: probability density function of travel time $t$
$c_f$: coefficient for time cost due to early arrival (yen/min.)
$c_d$: coefficient for delay penalty (yen/min.)
$c_m$: coefficient for time cost due to the increase of travel time (yen/min.)
$\delta$: $= 1$; if vehicle passes cordon line, $= 0$; otherwise
$C_r$: cost for road pricing (yen)

Let us consider park and ride systems in which travellers use trains after leaving their cars at car park attached to the railway station. The expected disutility of using park and ride systems is the sum of the disutility of early arrival and delay and time cost of moving by car and train and cost for car park and train ticket. It can be formulated:

$$EDU_p(t_0) = C_p'(t_0) + C_m(t_0) + c_i \cdot t_i + C_c + C_t$$  \hspace{1cm} (4)$$

where,

$$C_p'(t_0) = \int_{-\infty}^{t_d - t_i} \{t_i \cdot c_f + c_w(t_d - t_i - t)\} f(t - t_0) dt$$
$$+ \int_{t_d - t_i}^{t_d} c_w(t_d - t) \cdot f(t - t_0) dt$$
$$+ \int_{t_d}^{\infty} [t_i \cdot c_d + c_w \{t - (t_d + t_i)\}] \cdot f(t - t_0) dt$$  \hspace{1cm} (5)$$

$t_i$: time interval of train operation (min.)
\( C_w \): coefficient for time cost due to waiting at station (yen/min.)

\( C_t \): coefficient for time cost for taking train (yen/min.)

\( t_t \): time for riding train (min.)

\( C_c \): cost for car park (yen)

\( C_t \): cost for train ticket (yen)

Equation (5) incorporates the time cost for waiting for trains at station. Here, it is assumed that each train is operated at the same interval of \( t_t \). Drivers try to determine the optimal route and starting time by choosing the latest starting time that can be given by

\[
 t_0^* = \min_{t_0} EDU(t_0) \tag{6}
\]

where, \( EDU(t_0) \) indicates \( EDU_c(t_0) \) or \( EDU_p(t_0) \)

The model formulated here can also be applied for describing travel behaviour under other TDM schemes than park and ride systems and road pricing.

2.1.2 Models for choosing transport mode

Drivers are to choose optimal transport mode and route by minimising the expected disutility. Then the probability of choosing park and ride systems based on the equation (6) can be given by

\[
P_r = \frac{\frac{1}{EDU_p}}{\frac{1}{EDU_p} + \frac{1}{EDU_c}} \tag{7}
\]

Note that drivers can update travel times based on their experience on travelling in the previous day. The model used in this study only allows travel times on a route that a driver actually used to be updated.

2.2 Dynamic traffic simulation model

This study used a dynamic traffic simulation model based on BOX model (Fujii et al. [4]). The BOX model is essentially a macroscopic model but because the origin and destination of each vehicle is defined, it is actually a hybrid macroscopic/microscopic model. Vehicles are assumed to choose the shortest path when they arrive at a node using an estimated average travel time. The BOX
model consists of two components, flow simulation and route choice simulation as shown in Figure 2. A sequence of boxes is used to represent each link. Groups of vehicles flowing out of a box and into the next box during the scanning interval represent the flow on links. The BOX model was combined with the drivers' behavioural model that was described in the previous section to estimate benefits of reducing travel times and improving the reliability of travel times as well as traffic conditions.

![Figure 2: Dynamic traffic simulation (BOX model)](image)

### 3 Case studies for Kyoto-Osaka area network

#### 3.1 Test conditions

Models described in the previous section were applied for the test road and railway network in Kyoto-Osaka area, Japan as shown in Figure 3. A railway line with 14 railway stations in Figure 3 facilitates park and ride systems at each
Figure 3: Test road and railway network in Kyoto-Osaka area, Japan

station. We consider commuters whose homes are randomly located in nodes and commute to their office in the city centre of node 27. Each commuter has designated arrival time at the office. Simulation was performed during 5:00-11:00 a.m. The total vehicle generation during the period was 120,000 vehicles and hourly generation rate was determined based on the traffic census in 1994. Eight percent of those were assumed to take opportunity for choosing park and ride systems, which is referred to as "commuting drivers" in this paper. The commuting drivers have their cognitive travel times that are composed of historical data of 30 days.

Some parameters required for analysis are assumed to be:
(a) Designated arrival time: 8:00, 8:30, 9:00 and 9:30 a.m.
(b) Coefficient for
   - Delay penalty: 300 yen/min
   - Time cost of early arrival: 30 yen/min
   - Time cost of trip by car: 65.5 yen/min
   - Time cost of trip by train: 80 yen/min
   - Time cost of waiting for train: 90 yen/min
It is assumed that travellers who use park and ride systems will choose the nearest station, since car parks at stations are to have enough capacity for all users. Commuting drivers can choose a route with the minimum disutility on the previous day and follow the route on current day. On the other hand other drivers will follow the route choice procedure in BOX model based on the updated average travel times. We considered three cases:

- Case 1: without any TDM measures
- Case 2: Park and ride systems are implemented
- Case 3: Park and ride systems and road pricing are implemented

### 3.2 Results

Figure 4 compares the expected disutility of cases with and without TDM (park and ride systems). This figure indicates that expected disutility of early arrival and delay with park and ride systems (Case 2) is smaller than that without park and ride systems (Case 1). In Case 2 commuters who have chosen park and ride systems enjoy smaller expected disutility than car users. These results are attributed to reduction of variation of travel times in Case 2 compared with Case 1.

![Figure 4: Comparison of expected disutility of early arrival and delay](image)

Table 1 shows benefits in Case 2 of implementing park and ride systems for users of park and ride systems as well as cars. Note that these figures are average of 20 days from 81st-100th day of iteration. Both users of park and ride systems as well as cars can expect benefits by not only reducing average travel times but also by reducing variation of travel times. Users of park and ride systems can get
larger benefits than car users in both benefits.

Table 2 shows the change of vehicle hours of travel by implementing park and ride systems. Vehicle hours of travel in this table include all vehicles of commuting vehicles and other vehicles. It is essential that vehicle hours of travel can be decreased by implementing TDM measures.

<table>
<thead>
<tr>
<th>Benefits by implementing park and ride systems (Case 2)</th>
<th>Car</th>
<th>Park and ride</th>
</tr>
</thead>
<tbody>
<tr>
<td>Benefits by reducing average travel times (Yen/person) (A)</td>
<td>445.2</td>
<td>598.7</td>
</tr>
<tr>
<td>Benefits by reducing variation of travel times (Yen/person) (B)</td>
<td>16.6</td>
<td>30.3</td>
</tr>
<tr>
<td>Percentage (B/A)</td>
<td>3.7</td>
<td>5.1</td>
</tr>
</tbody>
</table>

Table 2 Change of vehicle hours of travel by implementing park and ride systems

| Vehicle hours with park and ride (Case 1) (hours) | 20,328 |
| Vehicle hours without park and ride (Case 2) (hours) | 20,133 |
| Change (%) | -1.0 |

Figure 5: Conversion rate to park and ride systems by road pricing
Figure 5 shows the conversion rate to park and ride systems when implementing road pricing of 500 and 1,000 yen. The charge was incurred for all vehicles crossing the cordon line in Figure 3. The conversion rate to park and ride systems was increased by charging higher price at cordon line.

4 Conclusions

This paper presented models for estimating benefits considering the uncertainty of travel times by implementing TDM measures including park and ride systems and road pricing. The models were applied to a test road and railway network. Results indicated that commuting drivers can expect both benefits by reducing travel times as well as reducing variation of travel times by implementing park and ride systems. Moreover, road pricing stimulates more drivers to use park and ride systems.

References