INTRODUCING RELIABILITY INTO TRAVEL DEMAND MODELS

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1. INTRODUCTION

The theory of departure time choice suggests that an acceptable approximation for the impact of unreliable travel times is to use the traveller's valuation of the standard deviation (SD) of journey time. This valuation can be determined by Stated Preference techniques, and despite some difficulties, particularly in terms of the presentation of variability to respondents, reasonable progress has been made, and the existing corpus of studies indicates a range of plausible values (Bates *et al*, 2001).

However, for this to be useful for travel demand modelling, it is necessary to develop supply-side models which will calculate the amount of travel time variability consequent on other inputs, parallel to the way an assignment model delivers a matrix of zone-to-zone times and costs. This is, in fact, a much more challenging task.

In October 2001, the UK Department for Transport (DfT) commissioned the authors to carry out a programme of research into frameworks for modelling the variability of journey times on the UK highway network (Arup, 2002; Arup 2004).

We define journey time variability (JTV) as unpredictable variation in journey times. Hence JTV is confined to random effects. It excludes predictable variation relating to varying levels of demand by time of day, day of week, and seasonal effects.

One of the components of JTV is due to "incidents", while what remains is referred to as "day-to-day variability" (DTDV), which in turn can be divided into two components: one due to unpredictable variations in demand, and the other due to random fluctuations in capacity, as represented in the following "equations":

JTV = DTDV + Incident-related variability
DTDV = Demand-related variability + Capacity-related variability

In order to model JTV, we need in principle to model the distribution of journey time, but in practice most previous work has been confined to models of the mean and either the variance or SD. While this will normally be acceptable, it is important to bear in mind that the valuation of the SD is not in fact independent of the shape of the distribution, particularly in the case of extreme events, as we have demonstrated in an earlier report (Arup, 2002: Chapter 4 and Appendix B).

Ideally, JTV should be related to the whole journey. Most work, however, has been confined to individual links, or small sequences of links. There are potential problems in moving from JTV for a link to JTV for a journey, and we have conducted some investigation into this in the urban context, which has identified the key issue as the need to allow for the correlation between link journey times.

Our work has concentrated on two distinct environments - interurban motorways, and "primary" roads within urban areas. While there are many differences in these two situations, a particular feature is the reduced routeing possibilities in the motorway environment, which is the product of the high speeds that are (normally) possible and the limited entry/exit opportunities. In fact, because of this, it becomes harder in the urban case to separate out the effect of incidents from DTDV, without a system-wide data collection and analysis framework.

This paper concentrates on the motorway investigation, where a substantial data-base is available. Two models have been developed to represent the impacts on journey time variability under conditions of transient excess demand. Both apply a simulation approach (of repeated randomly generated "days") to deal with variability, but the two models generate journey times in different ways. In both cases the general approach was to build a model of journey time arising from the observed demand profile, and to calibrate the model against data for mean journey times.

2. COMPONENTS OF JOURNEY TIME VARIABILITY

DfT had previously commissioned the development of a model (INCA) to evaluate the impacts of JTV on motorways due to "incidents" – notably accidents and major fires, load sheds and spillages. We have clarified and endorsed the methodology within INCA (Van Vuren, 2002) for use when demand is below capacity. In this context, incidents are the main source of JTV: DTDV is less important, and speed-flow relationships can be used to develop straightforward formulae to predict it.

However, there are occasions when demand exceeds capacity; we refer to this as "transient excess demand". This is a growing phenomenon, particularly on certain sections of motorway. Such excess demand can lead to flow breakdown and queuing, particularly near motorway merges when flows exceed the merge capacity.

When excess demand occurs there will be variation in the extent of the excess, and in the time(s) at which it occurs. Attempts to derive a relationship between the standard deviation of journey time and the mean have suggested that the dynamic process of queue formation leads to the phenomenon of "serial correlation" (correlation between journey times in successive time intervals). This is manifested by a graph in the form of a loop, when a temporal sequence of points relating to a measure of variability is plotted against a variable relating to the level of demand to capacity (eg the mean difference between the average journey time and the free-flow journey time).

Typically in these conditions, the average journey time, allowing for variations in demand, is different from the time the time that would be obtained if average demand conditions always occurred. While in general JTV increases with average journey times, in the presence of occasional extreme conditions very high levels of JTV can be found, even though average journey times are below the maximum. Thus a dynamic analysis is required, which allows for lagged effects of demand in previous "time-slices" whenever queues arise.

To develop a methodology for predicting JTV in such conditions, we designed a major survey to collect data over a 13 Km section of the M6 Motorway north of Birmingham. This section was chosen because it has three merges which exhibit excess demand on most weekdays. We needed to collect comprehensive demand data, to be able to identify incidents, to be able to factor out "predictable" (eg seasonal and daily) variation and sufficient data to enable us to deduce the remaining DTDV.

Hence the data collection exercise was primarily designed to deliver:

- route times between five camera sites, from matched automatic number plate recognition (ANPR) data;
- count data on each link and slip road, mainly from the Motorway Incident Detection System (MIDAS);
- speed data for all working MIDAS loops along the route; and
- MTV plots (graphical representations of speeds on each loop, showing the location and progression of flow breakdown).

Additional data was collected on a range of factors that might explain the observed JTV, including data on incidents (from police records), roadworks, wide loads, weather and events (eg sports and leisure events).

3. MODELS OF JTV ON MOTORWAYS

Given the anticipated difficulties in carrying out this work, we adopted two different approaches to representing the impacts on JTV under conditions of transient excess demand. Both apply a simulation approach (of repeated randomly generated "days") to deal with variability, but the two models generate journey times in different ways. The general approach was to build a model of journey time arising from the observed demand profile, and to calibrate the model against ANPR data for mean journey times.

One approach involved the development and application of a Paramics microsimulation model (M6SIM) which was "embedded" within a more general simulation process (M6FRAME) to perturb the input demand matrices. The other approach modelled journey times at an aggregate level, using speed-flow relationships when demand is below capacity, and a model of random flow breakdown, based on the volume/capacity ratio, to generate queueing conditions. Only the first approach is described here.

Our aim was to develop a model for the likely impact on JTV of a) the pattern of demand variation and b) the occurrence of incidents. M6SIM had to be shown to replicate the flow breakdown phenomenon when demand is high. Then M6FRAME had to be validated against the complete M6 dataset, given the **actual** pattern of demand variability and incidents, to see how well it reproduces the JTV based on **independent** ANPR observations.

In the work described here, we are using **two** types of simulation - the microsimulation for the supply model, and a more general simulation approach, random sampling from distributions to generate results arising from the interaction between different distributions, for the framework. The aim is to develop a tool which could ultimately lead to an **analytical** model, though the construction of such a model was outside the scope of our contract.

For each of the relevant matrix cells between entry and exit points, the temporal pattern of demand needed to be specified. This was done firstly by specifying the matrices separately for each hour, and secondly, within each hour, defining a "profile" at 5 minutes intervals. Four vehicle types were distinguished, based on the length variations detected by MIDAS. The simulation runs through from 0600 to 2200.

The motorway section was coded into the M6SIM network, making use of Ordinance Survey mapping and aerial photographs of the key junctions to allow for lane distribution etc.. The network also contained the locations of a) the ANPR cameras and b) relevant MIDAS interception points (loops), to allow for the calibration/ validation against data from these sources.

The model was tested on a preliminary subset of 11 “neutral” days’ data. Essentially the demand data, based on MIDAS counts, was input to the model, and the predicted journey time profiles were then compared with the ANPR data. Account also needed to be taken of incidents. The comparisons led to adjustments in the model to reflect local traffic behaviour characteristics. A close fit was obtained, which is reassuring, given that the ANPR “validation data” is quite independent of the input demand data.

On the basis of the work done we were confident that we were producing an adequately representative account of the impact of demand and incidents on travel time. In particular, we confirmed the ability of the microsimulation approach to give a realistic account of flow breakdown which had not been conclusively demonstrated before. We therefore proceeded to construct the M6FRAME framework, which involves an input module to generate suitably randomised data for “days” which can then be run through M6SIM, plus an output processing module to collect the simulated ANPR data.

As noted, the M6SIM input distinguishes, separately for each vehicle length category, the all day demand, the hourly proportions, and the five minute period proportions by hours. Although there is no special reason to keep within the M6SIM input format, a general specification of the demand profile D_{hp} in hour h and sub-period p as a random variable along the following lines seems quite sensible:

$$D_{hp} = A.\, B_h.\, C_{p|h}$$

in which A is a random variable relating to the traffic volume for the whole day (0600-2200), B_h is a random variable relating to the proportion of total daily volume in hour h, and $C_{p|h}$ is a random variable relating to the proportion of hourly volume for hour h falling in period p. Further, it was proposed that the overall demand be taken across all vehicle types, and an additional random variable L used to assign vehicle length proportions.

Each of the random variables A, B and C can be specified in terms of the observed mean and an appropriate distribution. The framework allows for a limited choice of two-parameter distributions (eg normal, lognormal, uniform). For those random variables representing proportions, the sampled values are summed and then factored so that they add to 1 in the relevant dimensions.

The data observations from the 11 days were not really sufficient to obtain (a) mean values for the various quantities (A, B, C, L), (b) some indication of the shape of the distributions, and (c) information on correlations as discussed above, at any definitive level, and reliable input will have to await an analysis of variance when the complete M6 dataset is available. Nevertheless, we considered it important to test the framework on realistic data, and for this purpose we accepted the limitations of the available data.

For each simulated "day", the output from M6SIM was processed along the lines previously carried out for the validation of M6SIM. For each usable pair of camera points, the individual simulated vehicle data was collected into 5 minute periods for the purpose of calculating mean travel times. For each period, treating the mean for a simulated day as a separate observation, we then calculated the output profile of the coefficient of variation over the number of simulated days.

We first compared the average journey time profile for 10 simulated days with the average ANPR profile for the days to which the dataset relates, and the general impression was of considerable similarity. The ANPR times were somewhat higher in the period 0900-1500, and this turns out to be largely the effect of incidents.

We concluded that:

- the M6SIM model, based on actual MIDAS counts for a given day, reasonably reproduces the independently measured journey time profile for that day as derived from ANPR data;
- a single M6SIM run based on simulated input data produces plausible results for the journey time profile;
- an average of 10 M6SIM runs (the minimum number that would be required) based on different simulated "days" taken from the same underlying population delivers a journey time profile which is comparable to the average ANPR data over the period to which the data relates.

The final test was to examine the implications for DTDV from the same 10 M6SIM runs. Apart from a small peak between 0800 and 0910, the predicted CV on the basis of the demand variation is generally less than 0.1, until about 14.30 where it starts to rise. Note the typical pattern in the later part of the day, indicating that the mean is falling more rapidly than the standard deviation in the "decline" period. CV values greater than 0.1 are generally associated with high average V/C ratios, the tendency for the CV to carry on increasing even though demand and mean travel times are generally falling is reminiscent of the "looping" pattern due to serial correlation.

4. SUMMARY

All the investigations confirm strongly that JTV on a stretch of motorway is strongly related to capacity utilisation. We have distinguished two key contributions - incidents, and the ratio of demand to capacity. With no incidents, and a low ratio of demand to capacity, JTV is at a low level (CV $\approx$ 0.05), essentially due to what we term "variations in capacity". When the ratio of demand to capacity reaches a level equivalent to the "breakpoint" on the standard COBA curve (ie about 65%, when the proportion of HGVs is 20%), the combined effect of variation in demand and capacity starts to increase, but the CV does not typically exceed 0.1 provided no queues occur.

If an incident occurs under these circumstances, the modelling approach incorporated in INCA is generally adequate to produce estimates of consequent delay and variability.

In the later stages of the research, we concentrated on transient excess demand. To model this we require reasonable information on the average demand profile, as well as the level of day-to-day variation in demand. The level of this variation appears to be quite low, based on the four weeks' data that we have used. For the whole day, the CV is about 0.05, though the variation within a particular 5-minute period can be much greater. However, even this can lead to significant DTDV: values of up to 0.4 for the longest journeys on the section, and even higher for individual links.

Given the average demand profile and the variation in demand, we have been able to reproduce the characteristic "looping" pattern for JTV. This means that the pattern of JTV is not merely a reflection of "peak vs off-peak", and requires a dynamic analysis.

What is now required is to validate the modelling framework using the complete M6 data set. Firstly, concentrating on DTDV, it would be valuable to understand the average pattern of the profile of demand, plus its variability. Previous work indicates that there are certainly "day of week" effects, and we expect other sources of variation (eg seasonal) to be found. The aggregate and microsimulation models should then be validated against the ANPR data for chosen "day-types", after removing incidents.

We have indicated how incidents can in principle be taken into account, but, particularly under conditions of transient excess demand, some more effort would be required to establish how best to incorporate them within the overall modelling framework, with a view to forecasting JTV from all possible sources. This would then need to be validated against the ANPR data without incidents removed.

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AN EVALUATION OF RELIABILITY OF TAXI SERVICE QUALITY

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1. INTRODUCTION

In many towns and cities, taxis offer a speedy, comfortable, and direct transportation service. Regarding the demand for taxi services, which is dominated by either street hailing or telephone requests, potential customers will consider the taxi service quality as well as travel time and fare in making their mode choice decisions. However, passengers face uncertainty about the availability of taxis, which varies by time of the day. An impatient customer cannot effectively communicate with the supplier to express his willingness to pay more for a reduced wait, but has to accept the stochastic wait given by the equilibrium of the taxi market (Douglas 1972). Furthermore, the customer may also not be able to make an accurate estimate of the taxi fare, which depends on the travel time and distance, as this in turn depends on the state of the road network.

The modelling of taxi services has been extensively studied and a network equilibrium approach has recently been proposed (Yang and Wong 1998; Wong *et al.* 2001). The model was formulated as a simultaneous optimization model of two equilibrium sub-problems to incorporate congestion effects and customer demand elasticity (Wong et al., 2001), for which one sub-problem is a combined network equilibrium model (CNEM) that describes the simultaneous movements of vacant and occupied taxis, as well as normal traffic in a user-optimal manner. The other sub-problem is a set of linear and nonlinear equations (SLNE) that ensure the satisfaction of the relationship between taxis and customer waiting times, and the relationship between customer demand and taxi supply.

Studies so far have simplified the problem by considering only the mean waiting and travel time, ignoring the reliability of taxi services. This study of the reliability of the taxi services will add greater realism. Concerning the reliability issue, several methodologies are commonly used to study travel time reliability. Travel time reliability, which is commonly defined as the probability that a trip can be successfully finished within a specified time, has been discussed in many papers (see Bell *et al.*, 1999; Nicholson *et al.*, 2003). Monte Carlo simulation is often used to study the effects of variation of some variables on other dependent variables, when their relationship is complex (Chen *et al.*, 1999). A more efficient way would be to approximate the equilibrium response by sensitivity analysis (Bell *et al.*, 1999).

In this paper, the model of Wong *et al*. (2001) is adopted to study travel time and taxi waiting reliability. The objective is to assess the reliability of taxi services while considering passenger demand elasticity with respect to traffic congestion and service quality. The aspect of service quality of particular interest is the variance of passenger waiting time. A Monte Carlo simulation approach is proposed to estimate the reliability measures of the taxi service and road network. A numerical example is used to demonstrate the effectiveness of the proposed methodology.

2. ESTIMATING THE TAXI SERVICE RELIABILITY

To study the characteristics of the taxi movement, the taxi model (Wong *et al.* 1999), which considers demand elasticity and network congestion, is used in this paper. The model is formulated as a simultaneous optimization of two equilibrium sub-problems, CNEM and SLNE. A solution to the simultaneous optimization model is a set of values which can satisfy both sub-problems simultaneously. The model is briefly presented as follows.

Let I and J be the sets of customer origin and destination zones, respectively, and O_i and D_j are the total customer demands from origin zone $i \in I$ and to destination zone $j \in J$. $t_a(v_a)$ is the travel time on link $a \in A$. N is the number of taxis operating in the network, T_{ij}^{o} is the occupied taxi movements (veh/h) from zone $i \in I$ to zone $j \in J$, T_{ji}^{v} is the vacant taxi movements (veh/h) from zone $j \in J$ to zone $i \in I$, and $w_i, i \in I$ is the taxi waiting/search time at zone $i \in I$.

<u>Combined network equilibrium model (CNEM)</u>

The mathematical formulation on the CNEM model is as below.

$$\text{Minimize } Z = \sum_{a\in A}\int_0^{v_a} t_a(\omega)\,\mathrm{d}\,\omega + \frac{1}{\theta}\sum_{j\in J}\sum_{i\in I} T_{ji}^{\mathrm{v}}\left(\ln T_{ji}^{\mathrm{v}} - 1\right) - \sum_{i\in I}\sum_{j\in J}\int_0^{T_{ij}^{\mathrm{o}}} D_{ij}^{-1}(\omega)\,\mathrm{d}\,\omega \tag{1a}$$

subject to: $$\sum_{j\in J} T_{ji}^{\mathrm{v}} = O_i,\ i \in I, \tag{1b}$$

$$\sum_{i\in I} T_{ji}^{\mathrm{v}} = D_j,\ j \in J, \tag{1c}$$

$$\sum_{k\in R_{ij}} f_{ij}^{k} = T_{ij}^{\mathrm{n}} + T_{ij}^{\mathrm{o}} + T_{ij}^{\mathrm{v}},\ i \in I,\ j \in J, \tag{1d}$$

$$v_a = \sum_{i\in I}\sum_{j\in J}\sum_{k\in R_{ij}} \delta_{ij}^{ak} f_{ij}^{k},\ a \in A, \tag{1e}$$

$$f_{ij}^{k} \ge 0,\ i \in I,\ j \in J,\ k \in R_{ij}, T_{ji}^{\mathrm{v}} > 0,\ i \in I,\ j \in J. \tag{1f}$$

where $$D_{ij} = \widetilde{D}_{ij}\exp\left\{-\gamma\left[F_0\left(1+\kappa h_{ij}\right) + \nu_1 h_{ij} + \nu_2 W_i\right]\right\},\ i \in I, j \in J, \tag{2}$$

and $\widetilde{D}_{ij}$ is the potential customer demand from zone $i \in I$ to zone $j \in J$, W_i is the expected customer waiting time at zone $i \in I$, $F_{ij} = F_0\left(1+\kappa h_{ij}\right)$ is the monetary cost that a customer pays for a taxi ride from zone i to zone j, and h_{ij} is the travel time of the taxi ride from zone i to zone j. ν_1 and ν_2 are the monetary values to the customer of unit in-vehicle travel time and waiting time respectively, and γ is a scaling parameter which indicates the sensitivity of demand to full trip cost.

A set of linear and nonlinear equations (SLNE)

To eliminate the internal inconsistency, the temporarily relaxed constraints are enforced at the SLNE to ensure that the desirable characteristics of the taxi model are satisfied. Assume that D_z is an arbitrarily chosen dependent variable in the deleted constraint that satisfies $D_z = \sum_{i \in I} O_i - \sum_{j \in \{J-z\}} D_j$. The control variables of the SLNE are $\mathbf{r} = (r_i, i \in I)$, $\mathbf{W} = (W_i, i \in I)$, $\mathbf{O} = (O_i, i \in I)$, $\overline{\mathbf{D}} = (D_j, j \in \{J-z\})$, and $c = (c)$. The results that are obtained from the CNEM include $\boldsymbol{\alpha} = (\alpha_i(\mathbf{r}, \mathbf{W}, \mathbf{O}, \overline{\mathbf{D}}), i \in I)$, $\mathbf{h} = (h_{ij}(\mathbf{r}, \mathbf{W}, \mathbf{O}, \overline{\mathbf{D}}), i \in I, j \in J)$, $\mathbf{T}^{\mathrm{o}} = (T_{ij}^{\mathrm{o}}(\mathbf{r}, \mathbf{W}, \mathbf{O}, \overline{\mathbf{D}}), i \in I, j \in J)$, $\mathbf{T}^{\mathrm{v}} = (T_{ji}^{\mathrm{v}}(\mathbf{r}, \mathbf{W}, \mathbf{O}, \overline{\mathbf{D}}), j \in J, i \in I)$. The SLNE can be formulated as follows,

$$R_{1i}(\mathbf{W}, \mathbf{O}, \overline{\mathbf{D}}, c) = (\alpha_i(\mathbf{W}, \mathbf{O}, \overline{\mathbf{D}}) + c) W_i \sum_{j \in J} T_{ij}^{\mathrm{o}}(\mathbf{W}, \mathbf{O}, \overline{\mathbf{D}}) - \eta \Omega_i = 0, i \in I, \quad (3a)$$

$$R_{2i}(\mathbf{W}, \mathbf{O}, \overline{\mathbf{D}}, c) = O_i - \sum_{j \in J} T_{ij}^{\mathrm{o}}(\mathbf{W}, \mathbf{O}, \overline{\mathbf{D}}) = 0, \quad i \in I, \quad (3b)$$

$$R_{3j}(\mathbf{W}, \mathbf{O}, \overline{\mathbf{D}}, c) = D_j - \sum_{i \in I} T_{ij}^{\mathrm{o}}(\mathbf{W}, \mathbf{O}, \overline{\mathbf{D}}) = 0, \quad j \in \{J-z\}, \quad (3c)$$

$$\begin{aligned} R_4(\mathbf{W}, \mathbf{O}, \overline{\mathbf{D}}, c) &= \sum_{i \in I} \sum_{j \in J} T_{ij}^{\mathrm{o}}(\mathbf{W}, \mathbf{O}, \overline{\mathbf{D}}) h_{ij}(\mathbf{W}, \mathbf{O}, \overline{\mathbf{D}}) \\ &+ \sum_{j \in J} \sum_{i \in I} T_{ji}^{\mathrm{v}}(\mathbf{W}, \mathbf{O}, \overline{\mathbf{D}}) \{h_{ji}(\mathbf{W}, \mathbf{O}, \overline{\mathbf{D}}) + (\alpha_i(\mathbf{W}, \mathbf{O}, \overline{\mathbf{D}}) + c)\} - N = 0 \end{aligned}. \quad (3d)$$

where Ω_i is the area of zone $i \in I$ and η is a common model parameter for all zones. Denote $\mathbf{X} = \mathrm{Col}(\mathbf{r}, \mathbf{W}, \mathbf{O}, \overline{\mathbf{D}}, c)$ as the solution vector, and $\mathbf{R} = \mathrm{Col}(\mathbf{R}_1, \mathbf{R}_2, \mathbf{R}_3, \mathbf{R}_4)$ as the column residual vector containing all the residues, where $\mathbf{R}_1 = (R_{1i}, i \in I)$, $\mathbf{R}_2 = (R_{2i}, i \in I)$, $\mathbf{R}_3 = (R_{3j}, j \in \{J-z\})$ and $\mathbf{R}_4 = (R_4)$. The problem becomes one of finding a solution vector $\mathbf{X}$ such that the residual vector $\mathbf{R}(\mathbf{X}) = \mathbf{0}$.

Having defined the taxi model, the approach of estimating reliability can be defined as follows.

Step 1. Set sample number $k = 1$.
Step 2. Generate the link travel times with the variations, $\tilde{t}_a$.
Step 3. Perform the taxi model with the link travel time $\tilde{t}_a$.
Step 4. Collect the information for the computation of the reliability analysis.
Step 5. If the sample size is less than the required sample size, set $k = k + 1$ and go to Step 2. Otherwise, terminate the procedure.

3. CUSTOMER WAITING TIME AND TRAVEL TIME VARIATIONS

The network equilibrium approach assumes that all travellers have perfect information of network conditions. However, the travel time may vary from time to time and the actual average travel times obtained from the deterministic models is different from the stochastic one. We assumes that the stochastic travel times on a link a can be determined as

$$\tilde{t}_a = t_a + \varepsilon_a$$

where t_a is the (average) travel time on link a, $\tilde{t}_a$ is the stochastic travel time on link a, ε_a is the corresponding variation, which is assumed to follow a normal distribution of $\varepsilon_a \sim N\left(0, \alpha t_a\right)$, and α is the coefficient of variation.

4. NUMERICAL EXAMPLE AND RELIABILITY ANALYSIS

Consider a network with 4 zones as shown in Figure 1. The travel impedance functions for the links are given as $t_a = t_a^0\left(1 + \left(v_a / s_a\right)^2 / 2\right)$, which is a form of the Bureau of Public Roads function. The parameters are shown in Table 1. The O-D matrices for normal traffic and potential taxi customer demand are given in Table 2. Where not otherwise specified, the input data used in the example are as follows: θ=5.0(1/hr); ηZ_i=0.3(veh·hr^2), $i = 1 \sim 4$; $\nu_1 = 120$ (HK\$/hr), $\nu_2 = 200$ (HK\$/hr); κ=10.0(1/hr); $\gamma = 0.01$(1/HK\$); N=250(taxi); and $F_0 = 8.0$ (HK\$).

A Monte Carlo simulation approach is proposed to estimate the reliability measures of the taxi service and road network. The coefficient of variation of travel time, α, is set at various levels, and the simulation is run for the sample size of 500 for each case. The results are shown in Figures 2 to 3. It can be seen from Fig. 2 that the total travel-time is decreased when the coefficient of the variation increases. The total travel time is also an indicator of total revenue collected by the taxi market. When the travel time variation increases, customer demand decreases due to uncertainty of taxi fare and waiting time. On the other hand, when the customer demand decreases with increasing variation, the overall network has more vacant taxis, and thus the customer waiting time decreases. The corresponding result for the reliability of customer waiting time is displayed in Fig. 3. As a result, the graphs of total travel time and total waiting time have a different intersection point with variation (0.9 for travel time and 0.4 for waiting time) as in Figures 2 and 3.

5. CONCLUSION

We have proposed a Monte Carlo simulation procedure to assess the reliability of taxi services. Numerical experiments have been performed using a simple network with travel time variations, and the variations of taxi services in terms of waiting time across the network are evaluated. These measures are useful for the management of the provision of taxi service in areas where reliability impacts on network performance. For the purposes of efficient implementation, another methodology that could be used to study the problem is the sensitivity analysis approach, where the reliability measures are explicitly calculated with respect to the travel time variation. Similar work on the taxi model has been done in Wong *et al.* (2002), in which a sensitivity analysis has been carried out on the combined network equilibrium problem. This could be further extended for the reliability assessment purpose, although the problem size may be too large to be solved for practical networks.

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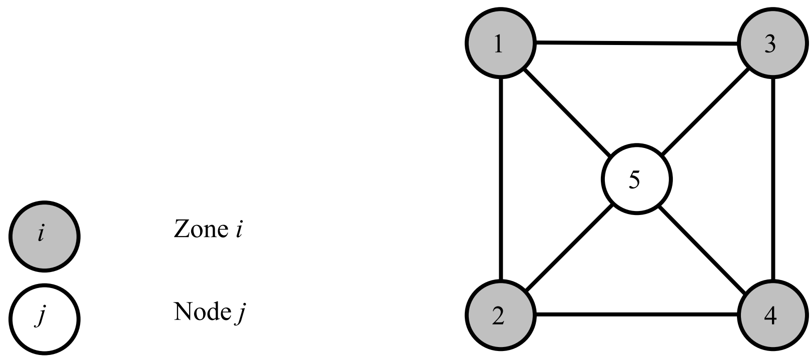

Figure 1: The example network

Link	Start node	End node	t_a^0 (h)	s_a (veh/h)	Link	Start node	End node	t_a^0 (h)	s_a (veh/h)
1	1	2	0.25	250	9	3	5	0.15	150
2	1	3	0.30	300	10	4	2	0.20	200
3	1	5	0.20	200	11	4	3	0.25	250
4	2	1	0.25	250	12	4	5	0.15	150
5	2	4	0.20	200	13	5	1	0.20	200
6	2	5	0.15	150	14	5	2	0.15	150
7	3	1	0.30	300	15	5	3	0.15	150
8	3	4	0.25	250	16	5	4	0.15	150

Table 1: Data input for the example network

	O-D matrix for normal cars					O-D matrix for potential taxi customer demand				
	1	2	3	4	Total	1	2	3	4	Total
1	0	200	300	100	600	0	65	35	35	135
2	300	0	200	200	700	55	0	30	40	125
3	100	50	0	350	500	35	25	0	65	125
4	50	100	100	0	250	35	35	45	0	115
Total	450	350	600	650	2050	125	125	110	140	500

Table 2: The origin-destination matrices for normal cars and potential taxi customer demand

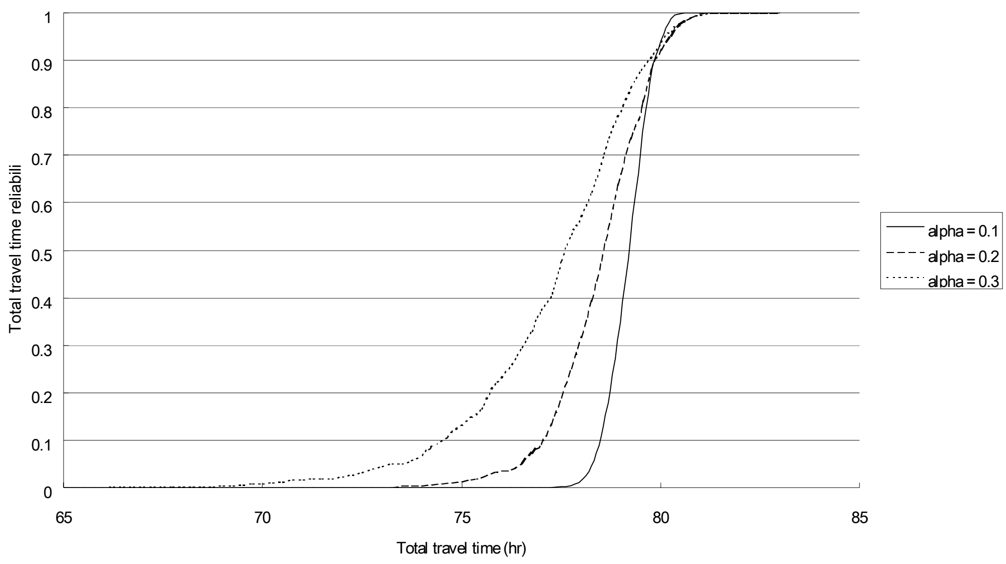

Figure 2: Total travel time reliability for different variations

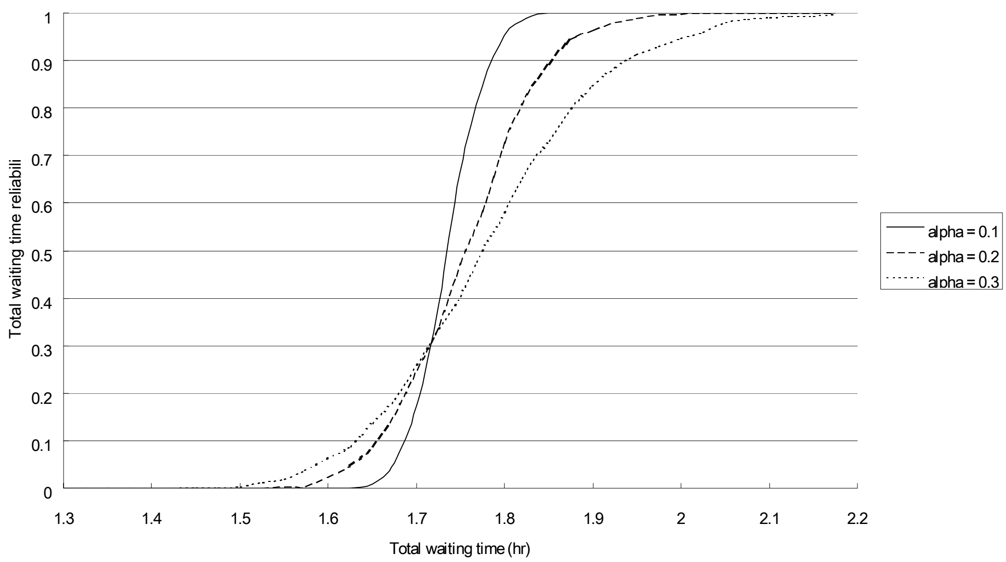

Figure 3: Total waiting time reliability for different variations

RISK ASSESSMENT FOR HAZARDOUS MATERIALS TRANSPORTATION IN A ROAD NETWORK

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1. INTRODUCTION

Two types of uncertain factors have been previously considered in transport network reliability studies. One is the supply side uncertainty due to natural disaster or system failure, and the other is the demand side uncertainty due to day-to-day fluctuation of travel behavior of network users. Previous studies [1], [2] generally assumed that a moving object in a network did not have any external risk factors, and would not cause any negative effects on socio-economic activities and natural environment. In an actual network, however, hazardous materials such as poisonous or explosive characteristics are frequently transported by using several transport modes. Even though the probability of the occurrence of serious accident involving the leakage of hazardous materials may be small, the consequence of the accident will be extremely large. Thus, it seems necessary to consider the additional uncertain factors in transport network reliability studies. That is to discuss the moving risk due to hazardous materials transportation in a network.

There have been studied on hazardous materials transportation in the area of optimum vehicle routing [3] and decision support systems [4]. Location management systems of hazmat vehicles were also studied as one of the ITS (Intelligent Transport Systems) service function. However, there were little studies of extending those related studies to network reliability analysis.

The objective of this paper is to develop a risk evaluation model when hazardous materials are moving along a route in a road network. Using on-board GPS (Global Positioning System) data, the movement of hazmat vehicles in an actual road network is analyzed. Through the comparison of the risk minimization route and the transport cost minimization route in a network, we show how much risk could be avoidable by diverting a hazmat vehicle on the cost minimum route to the risk minimum route. It could be possible to discuss the relations between the transport cost of diverting traffic and the acceptable risk for the society.

2. RISK EVALUATION MODEL OF HAZARDOUS MATERIALS TRANSPORTATION

A risk evaluation model [5] is developed for calculating a potential risk of a hazardous material vehicle moving along a route in a road network. The assumptions are as follows. Cities and towns are discretely distributed in an area. A city locating at the coordinates (x_i, y_i) has a level of activity N_i, which is for example the population of the city. A vehicle loading hazardous materials moves at constant speed along $x-$axis in a network. Probability density function of the occurrence of accident between section $a \le x \le b$ is denoted by $\phi_{ab}(x)$. Assuming that a hazmat vehicle is involved in an traffic accident at the position of $(x,0)$, the distance between the city i and the vehicle is calculated as $d_i(x) = \sqrt{(x-x_i)^2 + y_i^2}$. Due to this accident, the city may be damaged.

The probability of whether the city suffers damage is shown by $p(d_i(x))$ when an accident occurs at a distance of $d_i(x)$ from the city. The probability is assumed to decrease in proportion to the distance. An example of the function is written as $p(d_i(x)) = \exp(-\alpha d_i(x))$. Here α is a parameter depending on the hazardous material. Figure 1 shows a location of a city and a hazmat vehicle, and the damage probability of the city.

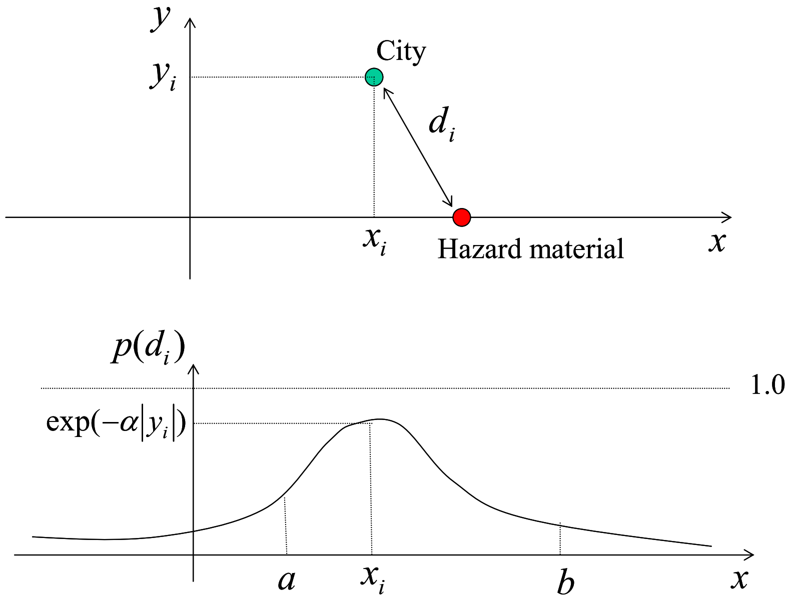

Figure 1: Location of a Hazardous Vehicle and the Probability of Damage

When a hazmat vehicle travels the section $a \le x \le b$, the expected probability of suffering damage of the city is represented by $P_{ab}[i] = \int_a^b \phi_{ab}(x) p(d_i(x)) dx$. When road and traffic characteristics are constant in the section between $a \le x \le b$, the probability of accident is assumed constant and written as $\phi_{ab}(x) = \phi_{ab}$. Then, the suffering probability of the city becomes $P_{ab}[i] = \phi_{ab} \int_a^b p(d_i(x)) dx$.

When there are a number of cities $(i = 1,2,..., I)$ in an entire area, the total expected amount of damage of the cities suffered by the accident in the section $a \le x \le b$ can be represented by $D_{ab} = \sum_{i=1}^{I} N_i P_{ab}[i]$. A road section corresponds to a link and D_{ab} becomes a link-based risk evaluation index. When the functional form of $p(d)$ and the relative value of ϕ_{ab} are determined, the link-based risk index can be evaluated. Route-based risk index is also defined as the sum of link-based indexes along the route. It is written as $R_k = \sum_{ab} \delta_{k,ab} D_{ab}$, here $\delta_{k,ab} = 1$ when the route k includes link ab.

3. RISK MINIMIZATION VERSUS COST MINIMIZATION IN A NETWORK

Two routes can be identified between an origin and destination (OD) pair in a network. One is the risk minimization route and the other is the transport cost minimization or utility maximization route. The risk minimization route can be calculated by applying the shortest path algorithm when the link-based risk index is used as the length of a link. The transport cost along the risk minimum route is easily calculated. $R[R_{\min}]$ and $C[R_{\min}]$ denote the risk and the transport cost along the risk minimization route. On the other hand, the risk and the cost along the transport cost minimum route are represented by $R[C_{\min}]$ and $C[C_{\min}]$, respectively. Obviously, $R[R_{\min}] \le R[C_{\min}]$ and $C[R_{\min}] \ge C[C_{\min}]$. The equality condition is for the case when the risk minimization route is equivalent to the cost minimization route.

As shown later, a vehicle with hazardous material generally uses the cost minimization route. Thus, it has a potential risk of $R[C_{\min}]$. If the vehicle is diverted from the cost minimum route to the risk minimum route, the amount of avoidable risk becomes $\Delta R = R[C_{\min}] - R[R_{\min}]$. However, transport cost increases by $\Delta C = C[R_{\min}] - C[C_{\min}]$ due to this diversion. The ratio of the reduced risk to the increased cost $\Delta R / \Delta C$ indicates the degree of effects of diversion. The diversion to the risk minimization route is recommended when the risk-cost ratio becomes larger.

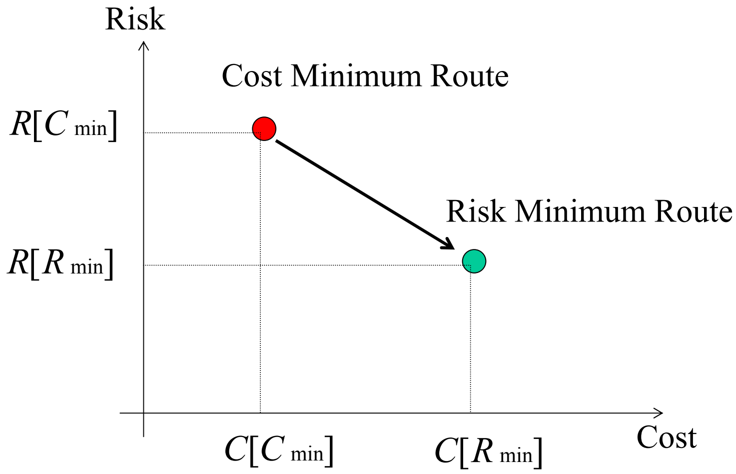

Figure 2: Reduction of Risk versus Increase of Transport Cost

It seems very important to show the amount of avoidable risk and the transport cost for each OD pair in a network. When the amount of avoidable risk is larger enough and transport carriers do not intend to pay additional transport cost for diversion, the increased transport cost could be paid by the society who might prefer the reduced risk rather than the increased transport cost. This corresponds to discuss the acceptable risk for the society.

4. HAZARDOUS MATERIALS TRANSPORTATION IN AN ACTUAL ROAD NETWORK [6],[7]

Road Traffic Census data in Hokkaido, the northern island in Japan, were analyzed to know the amount of hazardous materials transportation including volatiles, petroleum products and chemicals. Number of vehicle trips of those hazardous materials in Hokkaido was 95,000 trips per day. This amount is about 1% of total generated trips in the area. Since the averaged trip length of hazardous materials vehicles are longer than the ordinary vehicles, the share in the total vehicle kilometers in a network becomes about 2%.

Location positioning data were collected using GPS receiver equipped on vehicles of hazardous materials in Hokkaido area in Japan. The actual travel routes of 67 trips were calculated in DRM (Digital Road Map) network and the averaged trip distance was 80 kilometers. It was found that the averaged ratio of the trip distance along actual path with that of the shortest path was 1.1. Just 10% of the hazardous materials vehicles used the route with the distance of 1.2 times longer than the shortest path. This suggests that hazardous materials vehicles tend to use the shortest path as normal goods transportation, and the risk and the consequence of accident of hazardous materials might not be considered in route choice.

For evaluating the risk index, we assume that the probability of accident per unit length is constant for all links in a network. This means that the value of ϕ_{ab} is set proportional to the link length. The mesh data of population in Hokkaido is used for calculating the activity level N_i of mesh *i*. The averaged direct distance between mesh *i* and both terminal nodes of link *ab* is used as the distance between mesh *i* and link *ab*. The exponential function is applied for $p(d_i(x))$ and the parameter value is set as $\alpha = 1$.

Before analyzing the effects of diversion, the transport cost and the risk of actual routes were calculated. Then they were divided by the risk of the risk minimum route and the transport cost of the cost minimum route, respectively. Figure 3 shows the distribution of the ratios of $R[real]/R[R_{\min}]$ and $C[real]/C[C_{\min}]$. Here, $R[real]$ and $C[real]$ denote the risk and the cost of actual route obtained through GPS data. It is found that the risk ratios are widely distributed. There are 10 routes whose risk values exceed more than ten times of that of the risk minimum route. On the other hand, the cost ratios are almost less than 1.2. It is estimated that the actual hazardous materials transportation in Hokkaido has some potential risk and it could be reduced if hazardous vehicles diverted to the risk minimum route.

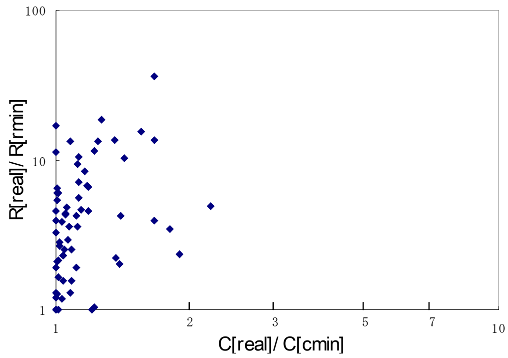

Figure 3: Risk and Cost Ratios of Actual Route in Hokkaido (n=67)

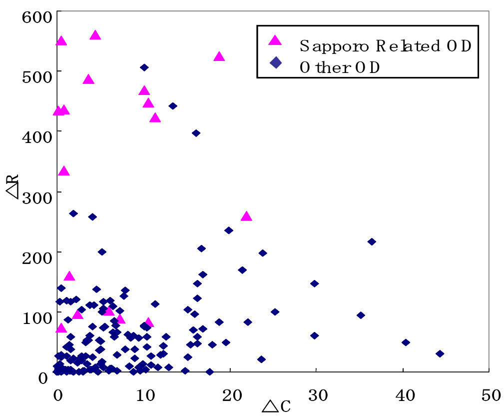

Figure 4: Reduced Risk versus Increased Cost by Diversion

For the OD pairs with actual vehicle trips of hazardous materials transportation, the risk minimum route and the cost minimum route were calculated. Then, the amount of reduced risk ΔR and increased cost ΔC of each OD pair were estimated when hazardous materials vehicles could be diverted from the cost minimum route to the risk minimum route. Figure 4 depicts the distribution of the reduced risk and the increased cost of each OD pair. For those OD pairs distributed in the upper left of the figure, it could be possible to reduce large amount of risk with small increase of transport cost. Those OD pairs include OD pairs related with Sapporo city, the capital of Hokkaido. On the other hand, it would not be effective to divert hazardous vehicles to the risk minimum route for those OD pairs in the lower right in the figure. Those OD pairs are relatively long distanced OD pairs. For those OD pairs, the alternative route in a network is limited and a longer diversion is required to avoid risk.

5. CONCLUSION AND FUTURE DISCUSSION

In this paper, we have shown a network risk evaluation model of hazardous materials transportation. Using the proposed model framework, it becomes possible to discuss the potential risk of mobile objects in a network. In addition to evaluate the risk of actual transport route of an OD pair, the route-based risk evaluation model can be applied to compare the risk of alternative routes of the OD pair. The cost versus risk evaluation of diverting hazardous materials vehicles would be one of the important issues for risk management of hazardous materials transportation in a network. The reduced risk and the increased cost can be used for discussing “effective” or “acceptable” diversion of hazmat vehicles.

As well as to improve the risk evaluation model shown in this paper, there are some important topics to discuss in the future. One is to evaluate the effects of link closure to hazardous materials transportation. Diversion of hazardous materials vehicles due to the closure of a link may increase the risk of a network. The links with larger increases of network risk should be found for network wide risk management.

In addition to the uncertainty due to network system failure and demand fluctuation, it seems important to consider the potential risk of mobile objects such as hazardous material vehicles in a network. This would become one of the interesting topics in network reliability studies.

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ASSESSING THE EFFECT OF CONGESTION ON BUS SERVICE RELIABILITY

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1. INTRODUCTION

Bus reliability has long been considered an important factor affecting the attractiveness of bus travel [Chapman 1976], and various engineering countermeasures (e.g. bus lanes, traffic signal pre-emption) and operational countermeasures (e.g. bus location and control systems) have been implemented to assist buses to maintain schedules. However, there is much doubt regarding how reliability should be measured, and Chapman identified sixteen potential indices, as follows:

- indices of interest to operators; ratio of actual to scheduled bus mileage, total deviation in round trip time, ratio of buses running to buses scheduled, ratio of mean actual headway to scheduled headway, range of deviation from scheduled time leaving terminus;
- indices of interest to passengers; mean waiting time, day-to-day variations from timetable, proportion of passengers encountering full bus, probability of completing journey within specified time, proportion of passengers saying service unreliable, passenger perception;
- indices of interest to transport system analysts; standard deviation of headways at a stop, sum of deviations from schedule, weighted proportion of early or late arrivals, mean variance of headway weighted by passenger numbers, size of tail of headway distribution.

Chapman noted that an improvement in some indices (e.g. the ratio of actual to scheduled bus mileage) may not mean an improvement in the reliability for users. This paper considers one aspect of bus service reliability, namely the formation of bus bunching and the effect on the variability of bus headways.

2. A SIMPLE MODEL OF BUS BUNCHING

Newell and Potts [1964] developed one of the first models for analysing bus service reliability. They assumed that the passenger arrival rate, bus loading rate, scheduled headway and travel time between successive stops did not vary between stops or buses. They also assumed that passengers arrived at random. They derived the following expression for the time (t_{mn}) at which bus m (m=0,1,2,3,...,M) departs from stop n (n=0,1,2,3,...,N), assuming t_{00} is zero:

$$t_{mn} = (m + nk)\tau + nT + \alpha \frac{(n+m-2)!}{(n-1)!(m-1)!}\left[\frac{1}{1-k}\right]^{n-1}\left[\frac{k}{k-1}\right]^{m-1} \quad \text{(Eq. 1)}$$

where T = the bus travel time between successive stops;
k = the ratio of passenger arrival rate to bus loading rate ($0 \le k < 1$);
τ = the scheduled headway between buses;
α = the delay of bus #1 at stop #1 ($\alpha \ge 0$).

Newell and Potts assumed that the number of passengers disembarking at a stop was similar to the number boarding, with simultaneous loading and unloading at separate doors, and the unloading rate exceeding the loading rate. Hence, the unloading rate did not appear in the model.

If α equals zero, $t_{mn} = [(m + nk)\tau + nT]$ (i.e. all buses run according to schedule), but if α exceeds zero, bus #1 and following buses will deviate from the schedule. The magnitude and direction of the deviation (i.e. whether behind or ahead of schedule) depend respectively upon

$$\alpha \frac{(n+m-2)!}{(n-1)!(m-1)!}\left[\frac{1}{1-k}\right]^{n-1}\left[\frac{k}{k-1}\right]^{m-1} \text{ and } \left[\frac{k}{k-1}\right]^{m-1}. \text{ (Eq. 2)}$$

Hence, the magnitude of the deviation increases as α, m, n and k increase, and for $n>1$, approaches infinity as k approaches unity. For $0<k<1$, the direction of the deviation alternates between being positive and negative as m increases from 1 to M (i.e. successive buses alternate between being behind and ahead of schedule).

This accords with what has been observed in reality, where a bus subject to unexpected delay at a stop will be further delayed at subsequent stops, due to the extra time taken by the additional waiting passengers to board, and falls further and further behind schedule as it progresses along the route. The following bus will encounter fewer passengers at the stops, due to their having boarded the preceding bus, and the boarding times will be less, enabling the following bus to progress faster than scheduled and catch up with the preceding bus.

While the Newell and Potts model predicts pairs of buses bunching, it does not predict what happens subsequently. In addition, the model considers a delay to only one bus at one stop, with the travel times between stops being the same for all pairs of stops and all buses. The model therefore does not accurately reflect reality, where all buses are susceptible to being delayed, with the delay varying between buses. This research involved extending the Newell and Potts model, to include consideration of what happens after buses form into bunches of two, and to allow for all buses being subject to exogenous delay (e.g. delay due to traffic conditions).

3. THE EXTENDED MODEL

An Excel spreadsheet model of a new bus service in Christchurch was developed. This service entails buses running around a roughly circular route about 36.1 km long and incorporating 96 stops, with buses running at 10 minute headways during peak periods and completing the circuit in 60 minutes. The spreadsheet model was initially based on the same assumptions as the Newell and Potts model, and the results were found to agree with those obtained using their equation.
Information about the passenger arrival rate at each stop was not available. It was assumed that the passenger arrival and bus loading rates were 0.1 persons/min and 5.0 persons/min respectively (i.e. k=0.02). With no delay to any bus and a bus speed between stops of 53 km/h, the spreadsheet model predicted a circuit time equal to the scheduled 60 minute circuit time (i.e. k equal to 0.02 and bus speed equal to 53 km/h represent actual conditions without bus delay well).

Newell and Potts suggested that if $0<k<0.5$, the headways will tend to return to the scheduled value, but if $k>0.5$, the initial perturbation will increase in magnitude (i.e. the deviations from the schedule will continue increasing). However, the extended model predicted bus bunching for much lower values of k (even as low as 0.02). It seems that whether bunching occurs does not depend only on k (i.e. the values of α, m, n, T and τ may also affect the propensity for bunching).

It was assumed that once buses formed into pairs, they would continue to progress around the circuit together, with the buses 'leap-frogging' (i.e. stopping at every second stop). This gives a somewhat different set of trajectories for buses 0,1,…,10 than if strictly applying the Newell and Potts equation, as shown in Figures 1 and 2. Note that bus #0 is subject to zero delay, while bus #1 is subject to a one minute delay at stop #1 only, as assumed by Newell and Potts.

As k increases, the models predict that bunching will occur earlier in the circuit. Figure 3 shows the trajectories for buses 0,1,…,10 for k=0.04 for the extended (spreadsheet) model, and it can be seen that the model predicts bunches of two forming into bunches of four. This result is consistent with what has been observed to occur in peak hours. Note that the spreadsheet model was unable to deal with the situation where a bunch of four had formed, and was stopped once this occurred.

The standard deviations of bus headways at stops around the circuit (one of the indices of interest to transport system analysts suggested by Chapman) were calculated using both models. The results are shown in Figures 4 and 5, and it can be seen that the Newell and Potts model predicts a steadily increasing standard deviation as the stop number increases, while the extended model predicts the standard deviation will increase until a 'threshold' value is achieved. This threshold corresponds to buses travelling in pairs, when headways are either about zero or about twenty minutes.

The above-mentioned results for the spreadsheet model did not allow for buses other than bus #1 being subject to exogenous delay. It was decided to investigate the effect of allowing all buses to be subject to random delay, by allowing the bus speed between stops to vary randomly about the mean speed of 53 km/h. That is, the exogenous delay was assumed to occur between stops, rather than at stops, the purpose being to represent the delay experienced by buses as a result of interaction with other vehicles on the road.

4. THE PROBABILISTIC MODEL

A probabilistic model was achieved by importing the Excel spreadsheet into the @RISK program, which incorporates a Monte Carlo simulation facility. The major advantage of a probabilistic approach is that it is possible to allow for stochastic variations in traffic conditions. At this stage, the model assumes the bus travel speeds for each segment of the route (i.e. between consecutive stops) are governed by the same probability distribution. For this study, the Truncated Normal distribution was used, with the mean speed being 53 km/h, the standard deviation of the speed being 5.3 km/h, the minimum speed being 20 km/h, and the maximum speed being 60 km/h. The minimum and maximum speeds represent the bus speeds in congested flow and free-flowing traffic conditions respectively.

Simulations were done for various values of k, with each simulation comprising 10,000 iterations (i.e. for each value of k, a total of 10,000 travel speeds were randomly selected for each route segment). During each of the 10,000 iterations, the standard deviation of the bus headways was calculated for each stop, and 90% confidence intervals for the standard deviation of bus headways at the stops were estimated (Figure 6). The confidence intervals clearly widen as the stop number increases.

5. CONCLUSION

The Newell and Potts model has been extended to predict the behaviour of buses once they have formed into bunched pairs, and predicts the formation of four-bus bunches for a bus route in Christchurch. This is consistent with observations of bus bunching on that route. The extended model also predicts bus bunching in circumstances where the ratio of the passenger arrival rate to the bus loading rate is much less than 0.5 (the threshold value suggested by Newell and Potts), suggesting that bus service stability depends upon other variables.

The extended model has been further extended to allow for all buses being subject to stochastic exogenous delays between stops, as might be expected in practice, where buses interact with other vehicles and are affected by any traffic congestion. Confidence intervals for the standard deviation of bus headways at individual stops can then be estimated, providing information on the reliability of the service experienced by bus users boarding at those stops.

The probabilistic model currently assumes the same traffic conditions (i.e. the same probability distribution of bus speed for each segment of the route). It should be possible to have different probability distributions for different route segments, to reflect the variations in traffic conditions around the route. This would then enable the identification of those segments where bus speed variation contributes substantially to bus service unreliability, and where some traffic engineering countermeasure should be implemented to improve bus system reliability.

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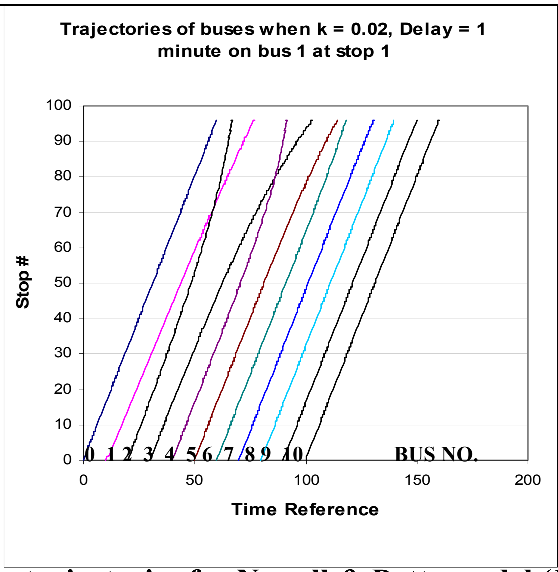

Figure 1: Bus trajectories for Newell & Potts model (*k*=0.02)

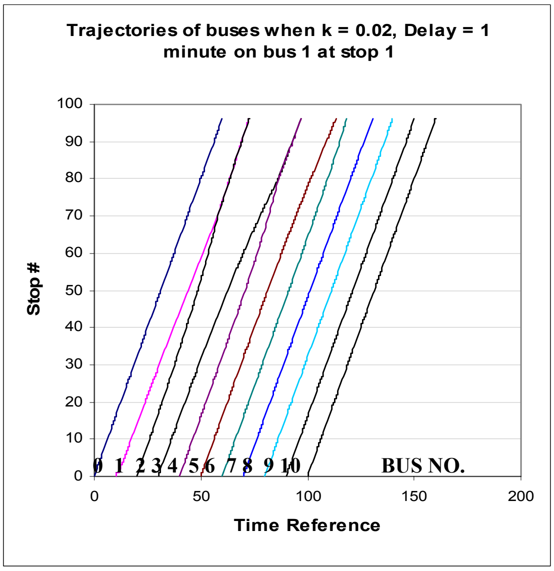

Figure 2: Bus trajectories for extended model (*k* = 0.02)

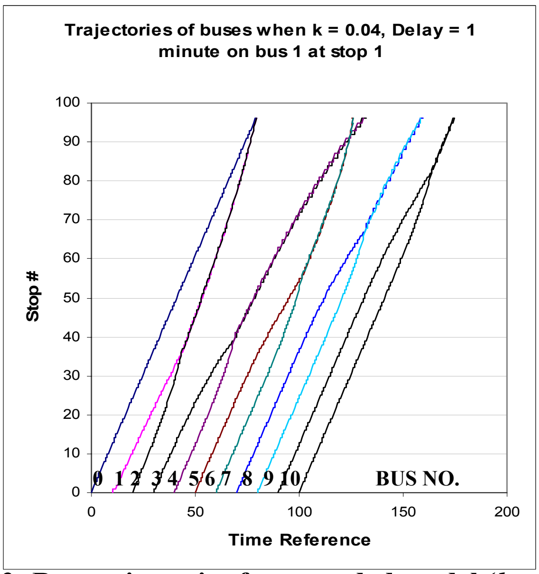

Figure 3: Bus trajectories for extended model (*k* = 0.04)

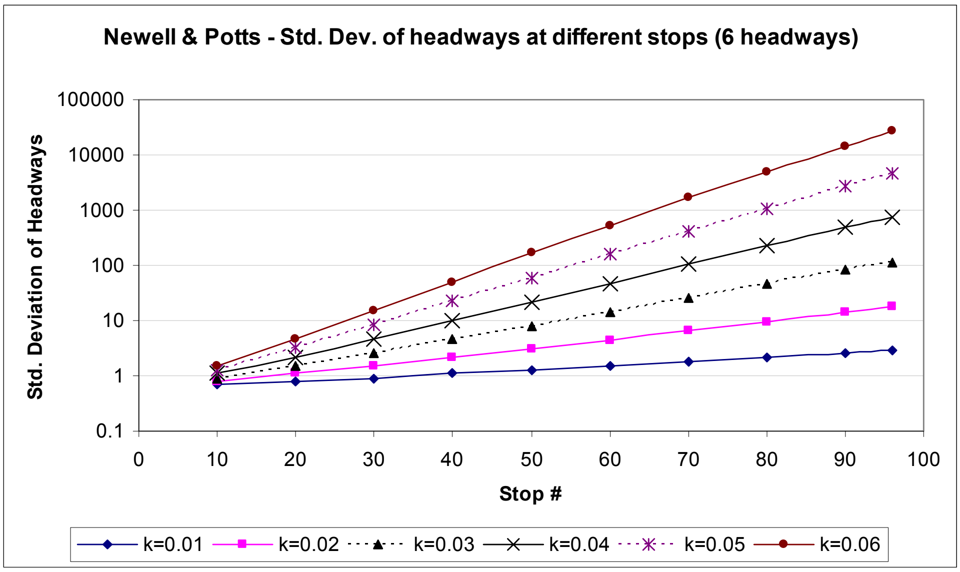

Figure 4: Standard deviation of headways (Newell & Potts model)

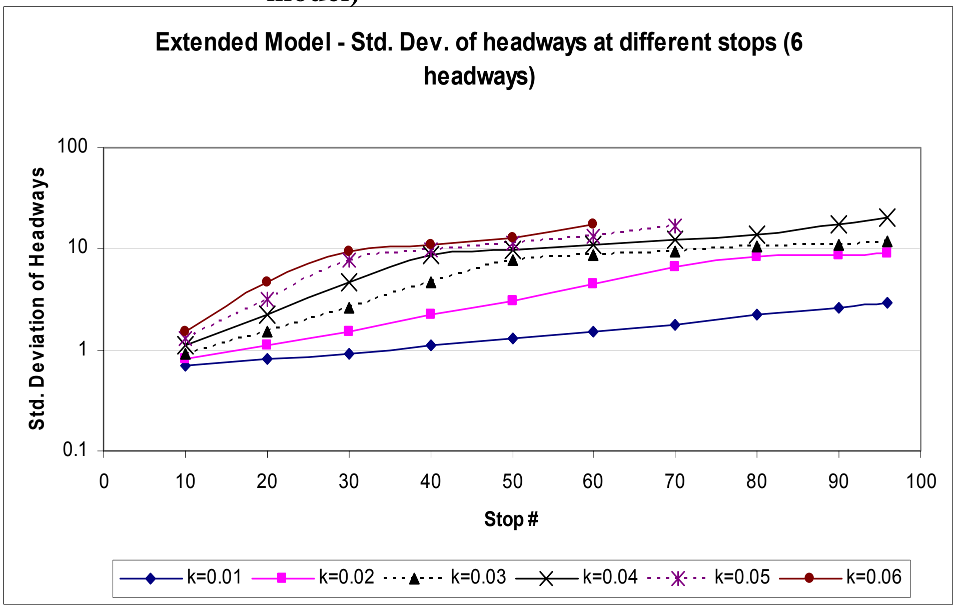

Figure 5: Standard deviation of headways (Newell & Potts model)

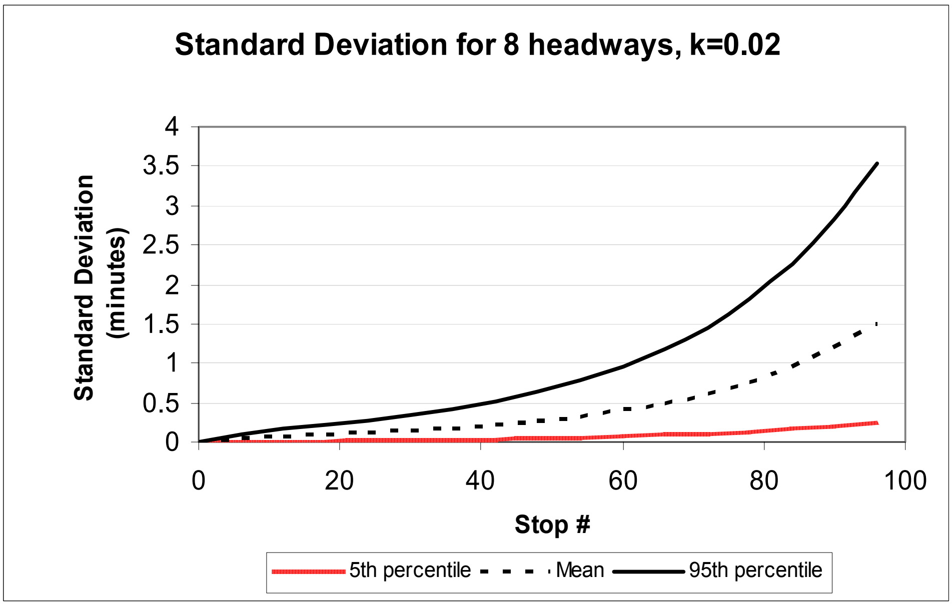

Figure 6: 90% confidence intervals for standard deviation of bus headways

THE IMPACT OF RECOVERY STRATEGIES ON PLATFORM CROWDING

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1. CROWDING AND CAPACITY PROBLEMS FOR COMMUTERS

The problem of full or nearly full transit vehicles is known to many commuters using public transport during peak hour. Overcrowding can be experienced daily on buses, trains and underground systems in most major cities all around the world. With growing urbanisation the problem is increasing. At certain locations, it is common that passengers interchanging in the CBD during peak hours have to let some vehicles pass before they manage to board, because of overcrowding. The reaction to overcrowding differs between the public transport operators. Tokyo Metro for example adjusts the speed of the ticket gates to control the influx of passengers but most other metros do not have this facility. At London's Victoria underground station the whole station is often closed for a few minutes during the morning peak hour to control the queues on the platforms.

The social cost resulting from overcrowded public transport systems is considerable. The BBC quoted the social cost arising through public transport delays and congestion during the morning peak hour as £230 Million for London alone (BBC, 2003). In London, capacity problems are focused on a few stations. At most stations, even in the city centre, passengers seldom have problems boarding the trains even during the peak hour. Capacity problems in the underground network arise mainly at the major interchanges between rail and tube (like Victoria and Kings Cross). Figure 1 shows the available capacity and demand during peak hour in some major metro systems around the world (Adeney and Schmöcker, 2004). However, one needs to look at the matrix of trips in order to understand where the capacity problems are. In London, for example, the Victoria Line is at some stations far more congested than the Piccadilly Line, even though Figure 1 might suggest the opposite.

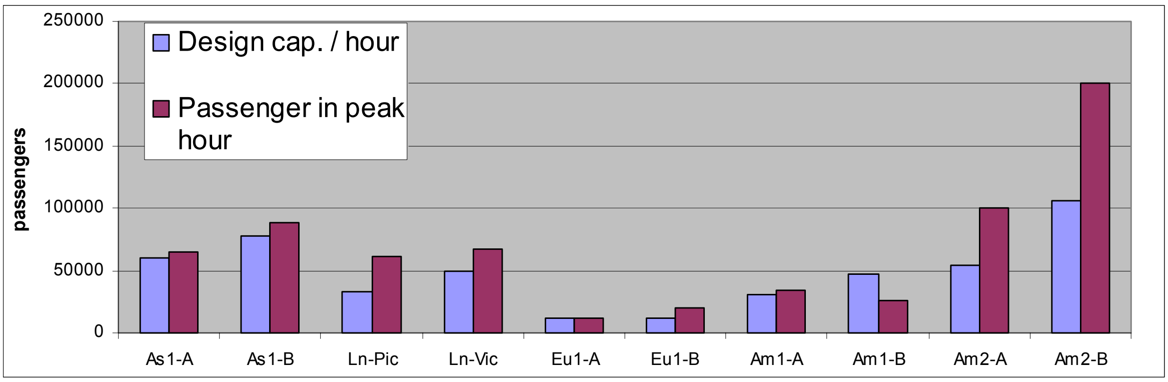

Figure 1: Passenger crowding on selected lines of some major metros around the world

2.RELIABILITY AND REGULARITY PROBLEMS ON UNDERGROUND NETWORKS

The problem is amplified if any disturbances occur during the peak hour that lead to train cancellations and therefore a reduction in the available capacity. Even if trains are not cancelled but arrive with uneven headways, this will result in platform congestion and passengers having to miss trains. The result is an increase in passenger waiting time, severe platform congestion and with this a higher risk of accidents on the platforms. Incident prone lines are more likely to have capacity problems, on the other hand it can be argued that the impact of a single incident on an incident prone line will be reduced because of improved passenger behaviour (higher awareness of alternative routes) and better handling of the incident. This thesis is difficult to prove but Adeney and Schmöcker (2004) report that a South American metro with very few incidents takes much longer to clear up the incident than most other lines.

If the cause of the incident has been resolved, capacity problems might continue for a while near the location of incident and knock-on effects might cause problems all along the line through longer dwell times and the resulting "bunching effect". This in fact means a reduction in capacity. Discussions with London Underground revealed that even small peak-hour delays are often un-recoverable until after the peak period and lead to enormous capacity problems and delays for the whole line. Further, delays often spread to other lines that are connected with the primarily affected line through one or more major interchanges. Every metro operator will try to avoid this.

3. RECOVERY STRATEGIES

Besides avoiding incidents and reducing the duration of an incident, it is important to choose an appropriate strategy to avoid knock-on effects and to recover a normal service quickly. Adeney and Schmöcker summarise the different strategies used by 6 metro operators and discuss advantages and disadvantages of each strategy:

1. **Stacking (Do-nothing):** Let all following trains run as close as possible to the affected train.
2. **Stacking (De-train):** Remove passengers from the affected train, let all following trains run as close as possible to the affected train
3. **Freezing:** Hold all trains on the lines. "Instant freezing" (stop all trains immediately, regardless of their current position) and "Soft freezing" (let trains run into next station) can be distinguished.
4. **Holding some trains:** Hold trains in the vicinity of the affected one.
5. **Removing trains:** Take trains out of service (but not the affected one)
6. **Adding a gap train:** Add a train from sidings to close gaps in the service
7. **Turning short:** Turn selected trains short, prior to scheduled terminus.
8. **Station skipping:** Let a train not stop at one station where it is scheduled to stop.
9. **Diverting:** Let trains bypass the affected train(s) on other routes. This strategy is not possible on many networks.
10. **Shuttle Service:** Split line into two or more sections and run a separate service between the new termini.

4. PUBLIC TRANSPORT ASSIGNMENT AND INCIDENT MODELLING

Several frequency-based and schedule-based assignment models have been developed in order to predict passenger loading and to give the planner a tool to optimise the schedule (see Wilson and Nuzzolo, 2004; Lam and Bell, 2003, for a summary). Stochastic models have been developed in order to recognize the variation in demand and run-time. Most of these models have significant shortcomings when it comes to modeling capacity constraints. The most common way to handle congestion in frequency-based assignment models is the "effective frequency approach" as introduced by Spiess and Florian (1989). In this approach, the service frequency is reduced as demand approaches capacity in order to reflect the fact that some passengers will fail to board and will have to wait for a following service. This approach does not allow a system to be permanently overloaded so equilibrium cannot be reached. Schedule-based models are significantly more computational demanding and Wilson (2004) doubts if they are suitable for large scale models. Schedule-based models such as in the new EMME/2 version can handle capacity problems but not changes in the OD composition of passengers on-board if passengers from a certain stop cannot board. Within schedule-based models this is currently only possible through a combination of microscopic passenger simulation and assignment, as proposed by Tong *et al* (2001).

Bell (2002) introduced a new approach to public transport assignment using absorbing Markov chains. This approach assumes that passengers mingle on platforms, that passengers on-board have priority over passengers wanting to board, and that demand might exceed capacity, i.e. some passengers may not be able to board. The suggested framework can be used for deterministic as well as stochastic assignment. Kurauchi *et al* (2004) extended the model in order to handle the common line problem.

The models discussed so far do not consider knock-on effects from incidents such as bunching effects of vehicles due to dwell time variations. At MIT, a disruption control model for real-time control was developed (Eberlein, 1996; Shen and Wilson, 2001) in order to specifically model these effects and to test the impact of different strategies. The MIT simulation model moves trains by time-steps through the network and considers all important constraints like minimum dwell time, dwell time depending on boarders/ alighters, minimum distance between trains, etc. The model does however not consider the priority of passengers on-board compared to those wishing to board and does not include passenger route choice.

The following describes an extension to the "Capacity Constrained transit assignment model" as described in Bell and Schmöcker (2004) and Schmöcker *et al* (2001). Schmöcker *et al* presented a dynamic version of the CapCon model that explained how the excess demand is carried over from one time slice to the next. The model as described here is able to predict changes in passenger route choice in response to capacity problems resulting from incidents and in response to the operator's delay recovery strategy. The passenger's route choice is dependent on $d_{ij,min}$, the direct cost of the link and f, the risk of that trip failing to board at the origin or any interchange. Eq. 1 shows the cost of travel between i and j during time interval τ

$$c_{ij\tau} = d_{ij,min} - \beta \, ln\,(1 - f_{j\tau}) \qquad (1)$$

where β is a weight. If the direct costs of all arcs were zero, the minimum cost route would be the most reliable route. The capacity constrained, dynamic assignment problem is then solved with the Time Dependent Correction Algorithm (Schmöcker *et al*, 2001).

5. MODELLING DISRUPTIONS

Discussions with metro operators revealed that it is sufficient to distinguish three types of incidents in order to choose the best strategy (minor incidents, slow moving delays and major incidents).

Minor incidents are often caused by passengers (for example, obstruction of doors, sick passengers needing to alight, or a police investigation) whereas major incidents are often due to problems with the rolling stock or the infrastructure. From the operator's point of view the main difference between these two is that when notified of an incident, the line manager expects a minor incident to be cleared quickly, thus requiring a different recovery strategy to be selected compared to a major incident. Typical causes of slow moving delays are track circuit or signal failures (Adeney and Schmöcker, 2004).

In the enhanced CapCon model, each line segment has a time-dependent capacity. Minor disruptions can be modelled by reducing the capacity to zero for one time-slice. Major disruptions are equivalent to setting the capacity to zero for several time intervals. Slow moving delays mean a reduction in frequency and increased travel cost on one or more line segments. Further, the link cost function is adjusted to reflect bunching effects:

$$d_{ij\tau} = d_{ij,min} + const_1 * (b_{i\tau} + a_{i\tau}) \tag{2}$$

where $b_{i\tau}$ and $a_{i\tau}$ are the number of passengers boarding and alighting at station i. $const_1$ reflects the system's ability to cope with high demand. A lower constant means a better possibility to keep the dwell times constant even during peak hour services. Eq. (2) will only be applied in two cases: Either $b_{i\tau} + a_{i\tau} > const_2$ (busy station) or $b_{i\tau} / s_{i\tau} > const_3$ (passengers wishing to board a nearly full train) must apply. If this is not the case, $d_{ij\tau} = d_{ij,min}$ can be assumed. The three constants reflect the system's ability to cope with high demand. A lower $const_1$ for example means a better possibility to keep the dwell times constant even during peak hour service. Following loss of capacity through longer dwell times in case of high demand is considered:

$$c_{i\tau+1} = c_i - \delta_{ij}(d_{ij\tau} - d_{ij,min}) \tag{3}$$

with $c_{i\tau+1}$ the capacity at platform i during time interval τ and c_i the nominal, scheduled capacity. $\delta_{ij} = 1$ if there is a service connecting i and j, otherwise 0. Note that because $c_{i\tau+1}$ reduces with an increased number of passengers wishing to board / alight, a bunching effect is modelled.

6. EVALUATING RECOVERY STRATEGIES IN CAPCON

The impact of the above mentioned recovery strategies in response to a minor delay can be estimated. In particular, the following strategies are compared:

- Do-nothing
- Turning trains short: Decrease capacity at end of line during τ, increase nominal capacity on return line segment and move capacity increase through line in subsequent time-intervals.
- Station skipping / prohibit boarding: Reduce available spaces to 0 during one time interval.

In order to evaluate the success of the recovery strategies following evaluation measures are proposed:

$$NF = \sum_{\tau}\sum_{j}\frac{b_{j\tau}f_{j\tau}}{1-f_{j\tau}} \tag{3}$$

with $f_{j\tau}$ the probability that a trip fails to board at platform j within τ, which is calculated with the time-dependent correction algorithm as described in Schmöcker *et al* (2001). *NF* is therefore a measure of how many passengers failed to board in the simulation interval. And secondly

$$TT = \sum_{\tau}\sum_{i}\delta_{i\,j}d_{ij,\min}(b_{i\tau}+o_{i\tau}-a_{i\tau}) \tag{4}$$

with $o_{i\tau}$ the number of passengers who stay on board (vehicle occupancy) at platform j within τ. Eq. (4) is therefore a measure of the in-vehicle time spent by all passengers. *TT* increases if passengers start to reroute in order to avoid boarding at busy stations.

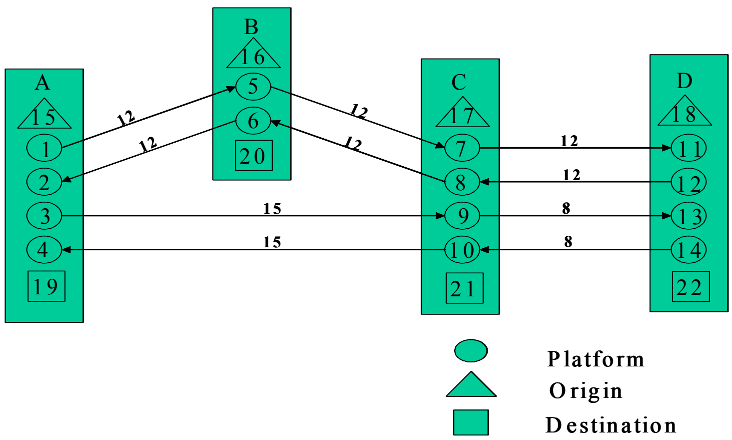

Figure 2: Example network

7. NUMERICAL EXAMPLE

The approach is tested on a small example network (Figure 2). An asymmetric demand matrix is assumed with station C being the major attractor for passengers from all other stations. Eight time periods are modeled. During the first time intervals, the demand slightly exceeds the capacity, but in the later time periods the demand is reduced so that all passengers can arrive within the simulated time intervals. Further, a delay in the second time interval at platform 3 is modeled leading to severe overcrowding. The impact of different recovery strategies, for different levels of passenger risk-averseness β regarding the possibility of not being able to board the first train, and for differences in $const_1$ are shown in Table 1. In this case turning some trains destined for D short at C would yield benefits in terms of “Number of passengers failing” as well as “Total in-vehicle time”.

	Number of passengers failing to board (*NF*)	Total in-vehicle time (*TT*)
No incident		
No bunching effect ($const_1$= 0), no passenger risk-averseness (beta = 0)	2150	10900
$const_1$= 0, β = 10	1280	13000
$const_1$=0.1, β = 0	2650	10900
Incident at platform 3: $c_{j=3,\tau=2} = 0.5c$ $const_1$= 0.1, β = 10		
Do-nothing	1580	13400
Turning short of trains at C (in τ=3)	1510	13100
Skip Station B (in τ=3)	1860	13300

Table 1: Evaluation results of different scenarios

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EVALUATION OF DELAY PROPAGATION AND NETWORK RELIABILITY OF AIRLINE SCHEDULES

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1. INTRODUCTION

An airline schedule is operated by a fleet of aircraft to fly to certain destinations. Each aircraft in the fleet is assigned a daily rotation schedule to carry out specific flights at planned departure/arrival times. An aircraft rotation schedule is illustrated in Figure 1 showing an aircraft flying from Airport A to Airport B, Airport C, Airport B, then finishing the schedule duty at Airport D. Aircraft turnaround operations are carried out at airport gates to prepare the aircraft for a following departure. A number of duties in aircraft turnaround operation need to be done in a period of time, namely scheduled turnaround time, including disembarking/embarking passengers, cabin cleaning, catering, baggage handling, fuelling, routine maintenance check and so forth. Some duties are sequential, e.g. cabin cleaning after disembarking passenger, while some are carried out independently such as routine engineering check and fuelling aircraft.

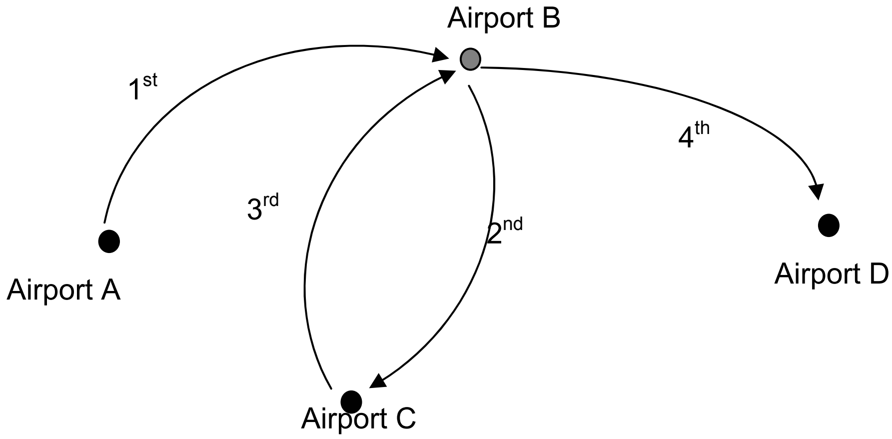

Figure 1: A single aircraft rotation in a network

Implementing airline schedules, like running bus or railway schedules, is influenced by various stochastic disruptions such as airport capacity constraints, airspace/enroute air traffic control, aircraft turnaround operations and metrological conditions. Major disrupting events, e.g. snowstorms around airport area may seriously disrupt airline schedules, while minor disruptions can delay flights and may cause down-stream delay propagation. This paper is aimed at studying the delay propagation phenomenon in an airline network caused by minor disruptions, i.e. delays less than one hour and the associate issue of airline network reliability.

2. MODELLING AIRCRAFT ROTATION IN A NETWORK

The process of a complete aircraft rotation is a sequential combination of ground operations (turnaround) and enroute operations. Accordingly, the Aircraft Rotation model to be developed is composed of two sub-models, namely Turnaround model and Enroute model. Some assumptions are necessary to narrow down the scope of the model. First of all, only operations carried out by airlines are modelled including passenger processing, crewing, cargo/baggage processing and aircraft services. Second, delays due to airport and enroute airspace congestion are aggregately modelled by stochastic functions. By doing this, the aircraft rotation model is able to describe aircraft turnaround operations to a required extend and meanwhile consider external variables in the operating environment. Third, this model has an emphasis on turnaround operations, so potential delays due to crew and passenger transfer is not yet included. A brief description of the Aircraft Rotation model is given as follows. Readers interested in the modelling process may like to consult a paper by the author (Wu & Caves 2004).

There have been a few attempts in the literature to model the complex aircraft turnaround operation. Some of them approached this issue by using Critical Path Method (CPM) to identify critical workflows (Braaksma and Shortreed, 1971; Hassounah and Steuart, 1993), while others used analytical models to describe turnaround operations (Wu and Caves, 2000). Given the characteristics of aircraft turnaround operations, a hybrid approach combining a semi-Markov chain and a discrete-event simulation is employed in the Turnaround model.

1. Semi-Markov Model: Two major processes have been identified critical to the punctuality of turnaround operations, namely passenger processing and cargo/baggage processing. These operations consist of a series of sequential service activities in which delays to one activity usually cause delays to following activities. Also, the service time of each activity is itself a stochastic variable subject to aircraft types, the number of passengers, the work efficiency and availability of ground staff. In order to model the stochastic while sequential interactions between activities in these two processes, a semi-Markov chain model is developed.
2. Discrete-Event Simulation: Some aircraft services are independent from above mentioned turnaround processes, e.g. aircraft fuelling and engineering check. Considering the uncertainty of these individual activities, discrete-event driven simulations are used to supplement the Semi-Markov model.

The Turnaround model is described by following (Eq. 1) to (Eq. 4), where D_{ij}^{D} denotes departure delay of flight *(i,j)* from Airport *i* to *j*; $f_{ij}^{ATD}(t)$ is the probability function of actual departure time of flight *(i,j)*; S_{ij}^{D} is the scheduled departure time.

$$D_{ij}^{D} = f_{ij}^{ATD}(t) - S_{ij}^{D} \qquad \text{(Eq. 1)}$$

The actual departure time of flight *(i,j)*, denoted by t_{ij}^{ATD}, is a function of the actual arrival time of a previous flight (*h,i)*, denoted by t_{hi}^{ATA}, and a stochastic turnaround operation time, T_{OP}. T_{OP} is the longest time required to finish all turnaround activities as described in (Eq. 2).

$$t_{ij}^{ATD} = t_{hi}^{ATA} + T_{OP} = t_{hi}^{ATA} + \max\left[T_{cargo}, T_{pax}, T_{events}\right] \qquad \text{(Eq. 2)}$$

Individual turnaround process is modelled as a semi-Markov chain such as the cargo/baggage processing described in (Eq. 3). T_{cargo} is the summation of all sub-activities in cargo processing, which have stochastic operating times. Discrete events only delay aircraft departure when the longest time of an event exceeds the scheduled departure time. Discrete events are modelled as stochastic variables in (Eq. 4), where ε_{q}^{e} is the expected disruption time of event *q* with occurrence probability P_{q}^{e}.

$$T_{cargo} = \sum_{k=1}^{n} \varepsilon_k = \sum_{k=1}^{n} \left(\mathrm{E}[t]\right) = \sum_{k=1}^{n} \left(\int_0^{\infty} t\mathrm{A}_k(t)dt \right) \qquad \text{for activity } k \in \Omega \qquad \text{(Eq. 3)}$$

$$T_{events} = \max[\varepsilon_q^e] = \max\left[\mathrm{P}_q^e \mathrm{E}[t]\right] = \max\left[\mathrm{P}_q^e \int_0^{\infty} t\Phi_q^e(t)dt\right] \qquad \text{(Eq. 4)}$$

The Enroute model is described by (Eq. 5) and (Eq. 6). D_{ij}^A denotes arrival delay of flight *(i,j)* at destination Airport *j*; $f_{ij}^{ATA}(t)$ is the probability function of actual arrival time of flight *(i,j)* at Airport *j*; S_{ij}^A is the scheduled arrival time at Airport *j*. The actual time of arrival of *(i,j)*, t_{ij}^{ATA}, is accordingly the sum of the actual time of departure of *(i,j)* and the expected enroute flight time, denoted by $\int_0^{\infty} tf_{OP}^{ER}(t)dt$ in (Eq. 6).

$$D_{ij}^A = f_{ij}^{ATA}(t) - S_{ij}^A \qquad \text{(Eq. 5)}$$

$$t_{ij}^{ATA} = t_{ij}^{ATD} + \int_0^{\infty} tf_{OP}^{ER}(t)dt \qquad \text{(Eq. 6)}$$

3. DELAY PROPAGATION AND NETWORK RELIABILITY

Statistics from Eurocontrol show that 47% of delays are due to airline related operations, while the remaining delays are due to air traffic management and airport operations (Eurocontrol, 2002). Among delay categories of airline operations, turnaround activities and reactionary delays are two of the highest ranked delay causes. Since an aircraft flies a series of flights in a day (in a typical domestic network), delays to one departure may cause reactionary delays to following flights. Furthermore, reactionary delays may propagate in a network through resources, e.g. crewing and passenger transfers between flights. This phenomenon is particularly significant in a hub-and-spoke airline network, in which delays of an inbound flight at a hub airport may trigger reactionary delays to particular outbound flights because of late inbound crew, transfer passengers and baggage.

The operational reliability of an airline network is the outcome of a dynamic interaction between fixed schedules and stochastic flight operations. Reactionary delays in a network downgrade the reliability of airline schedules with high delay costs and may result in re-scheduling. It is generally believed by airlines that each schedule is to achieve the maximum profits possible, while maintaining required on-time performance and reliability with built-in schedule buffer times. Accordingly, the Aircraft Rotation model is used to simulate the "expected baseline" of on-time performance (in terms of delays) of a schedule. This simulated result is then used as the comparison baseline when evaluating the operational reliability of an airline schedule. Based on this methodology, a number of reliability indices are formulated by (Eq. 7) ~ (Eq. 9).

$$R_{ij}^D = \frac{ED_{ij}^D}{D_{ij}^D} \qquad R_{ij}^A = \frac{ED_{ij}^A}{D_{ij}^A} \qquad R_{ij} = \frac{(ED_{ij}^D + ED_{ij}^A)}{(D_{ij}^D + D_{ij}^A)} \qquad \text{(Eq. 7)}$$

where in (Eq. 7) R_{ij}^D and R_{ij}^A denote the departure and arrival reliability of flight *(i,j)* respectively; ED_{ij}^D and ED_{ij}^A represent the expected departure and arrival delay of *(i,j),* while D_{ij}^D and D_{ij}^A the actual departure and arrival delay of *(i,j)*. Hence, R_{ij} is used to evaluate the operational reliability of the whole flight *(i,j)*.

$$R^k = \frac{\sum_{ij}(ED_{ij}^D + ED_{ij}^A)}{\sum_{ij}(D_{ij}^D + D_{ij}^A)} \qquad \forall flight(i,j) \in Rotation_k \qquad \text{(Eq. 8)}$$

$$R^{NET} = \frac{\sum_{ij}(ED_{ij}^D + ED_{ij}^A)}{\sum_{ij}(D_{ij}^D + D_{ij}^A)} \qquad \forall flight(i,j) \in Network \qquad \text{(Eq. 9)}$$

where R^k is the reliability of rotation *k*; R^{NET} denotes the network-wide reliability.

4. MODEL APPLICATION

The Aircraft Rotation model is implemented by a simulation program using Monte Carlo simulation technique. Flight schedules and the corresponding on-time performance data of a European airline (called Airline P hereafter) are used in model application. Due to a confidentiality agreement with the carrier, airport codes and flight numbers are replaced with assigned codes. There are 17 aircraft in Airline P's fleet flying to 20 destinations in the obtained schedule. The study schedule is simulated for 1,000 days in order to reduce the effects of simulation noises, i.e. extreme samples.

To investigate the impact of delay propagation in an airline network, scenario analyses are organised as follows:

Scenario A: the real results of the schedule (obtained from Airline P)
Scenario B: the expected baseline of the schedule (from simulation)
Scenario C: longer turnaround time (10 more minutes) for early morning flights
Scenario D: longer turnaround time (10 more minutes) for mid-day flights
Scenario E: longer turnaround time at the base airport of Airline P

Operating results (departure delays) of the study schedule (Scenario A) are compared with the simulated baseline of schedule delays (Scenario B) in Figure 2. It is seen that real operating delays are significantly higher for some rotations by aircraft 1 to 8, while slightly closer to the baseline for others. The simulated baseline of schedule delays reveals the "expected" status of schedule execution, in which aircraft are turned around according to planed ground times with some buffer to tolerate stochastic disruptions. The relatively low baseline of the schedule suggests that sufficient buffer times are embedded in the schedule (both in ground time and airborne block time). If we compare the developing trends of delays between real results and the baseline, we can see that they exhibit similar patterns across the network. This observation implies that: first, the Aircraft Rotation model successfully depicts the stochastic behaviour of schedule operations; second, the real operation of the schedule suffers from either more disruptions or needing longer turnaround time.

Simulation results of Scenario B are then used to evaluate the reliability of the study schedule. The rotation reliability index, i.e. R^k in (Eq. 8), is applied and results are shown in Figure 3. The higher the R^k is in Figure 3, the closer the real operating results of the schedule is to the baseline. We can see that the operating reliability of individual rotation varies with a network average reliability (R^{NET}; the horizontal line) of 37%. Some rotations achieve 70% reliability, e.g. aircraft 4, 12 and 15, but some are low in the 10-30% range. This result reflects the situation of real-world schedule operation in which some rotations run smoothly with controlled delays, while some flights are delayed more frequently and usually trigger "schedule recovery actions" such as swapping aircraft or rescheduling partial schedules.

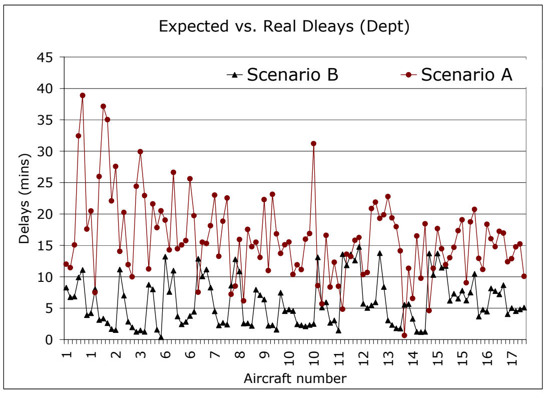

Figure 2: Scenario A and B

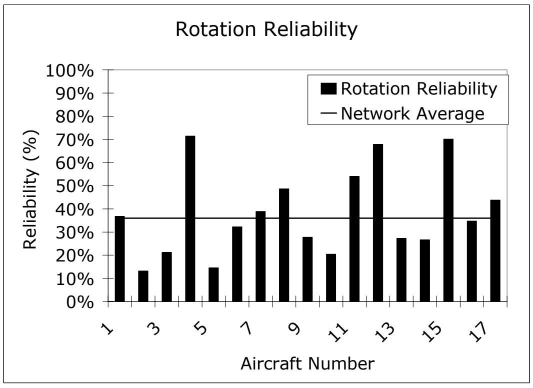

Figure 3: Reliability

To investigate the impact of delay propagation, two flights operated by aircraft 12, namely PP121 in the morning representing Scenario C and PP125 in the mid day representing Scenario D, are configured in the simulation program to take 10 minutes more than the standard turnaround time (20 mins) to finish turnaround operations. Results of Scenario C and D are compared with Scenario A in Figure 4 and Figure 5 respectively. It is seen that the longer service time for PP121 causes longer departure delays. As seen in Figure 4, delays of PP121 propagate along the rotation schedule and result in high departure delays for PP129, while some delays are absorbed by built-in buffer times of each flight ranging from 5 to 10 minutes. The reduction of delays between PP125 and PP126 is due to a long scheduled buffer time (30 mins) of PP126, which controls delay propagation to a lower level. On the other hand, it is seen in Figure 5 that departure delays start to build up after PP125 and propagate along the rotation to PP129. The long buffer time of PP126 absorbs some reactionary delays from PP125 and controls the delay level around 10 minutes for PP126.

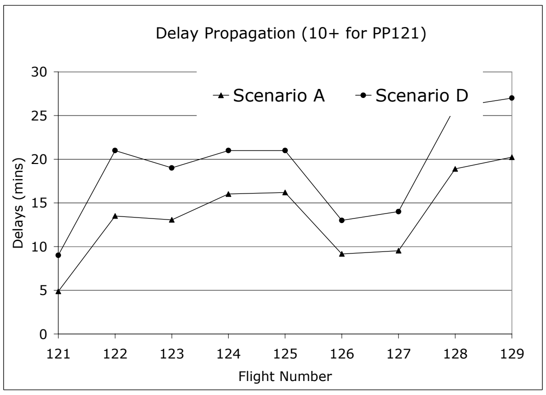

Figure 4: Scenario A and D

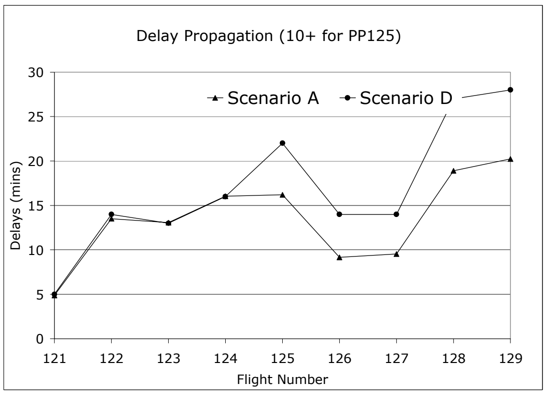

Figure 5: Delay propagation

In order to study the significance of operations control on aircraft turnaround services, results of Scenario E in Figure 6 show the scenario in which ground services at the base airport of Airline P take longer time (10 more mins in this case) to finish. It is seen that longer turnaround time at the base causes more departure delays to those flights turned around at the base. This also results in delay propagation in aircraft rotation schedules as demonstrated in Figure 6 by aircraft 2, 7 and 15. Total departure delays in Scenario E increase to 2,989 minutes from 1,816 minutes in Scenario A (the original schedule) with 65% increase of delays. The significant impact of delays in Scenario E is a result of a disruption to 82% of flights being turned around at the base airport as well as a result of delay propagation in the network.

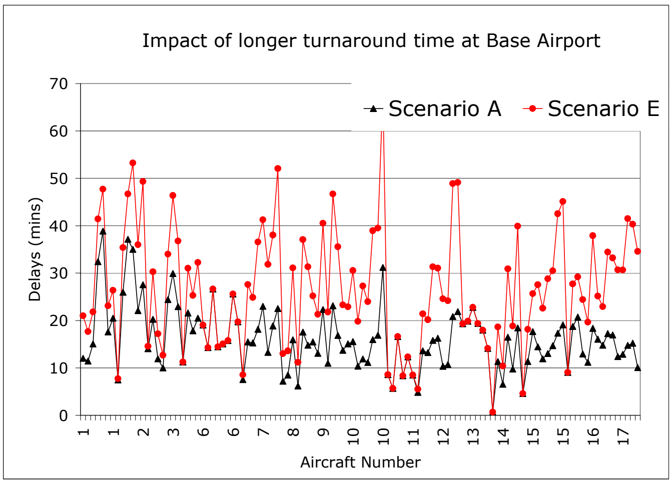

Figure 6: Impact of long turnaround time at base airport

5. CONCLUSIONS

We build a hybrid semi-Markov and event-driven simulation model to describe the operation of aircraft turnarounds and rotations between airports in a network. Real airline schedules and punctuality data are obtained and compared with simulation results of our Aircraft Rotation model. A new baseline is developed by using our simulation model to benchmark the performance of real-world schedule operation. Results show that the reliability of individual rotation varies in the network from 10% to 70% with a network-wide average of 37%. Scenario analyses are conducted regarding delay propagation. Results reveal that delays in the morning propagate along aircraft rotation and result in higher delays to later flights in the rotation. Some reactionary delays are better controlled in the network because of built-in buffer time. A higher impact to the network by increasing turnaround time at the base airport by 10 minutes results in a significant increase of total network delays by 65% due to both ground operating delays and network-wide delay propagation.

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EVALUATION OF PUBLIC TRANSPORT CONNECTIVITY RELIABILITY USING CAPACITY-CONSTRAINED TRANSIT ASSIGNMENT MODEL

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1. INTRODUCTION

The problem of full transit vehicles is experienced daily by passengers in many cities throughout the world. Where there are route alternatives, a passenger may choose a less direct or slower route to avoid a long wait. The passenger route choice strategy may therefore be influenced by the fear of having to wait, which in turn depends on the frequencies of routes and the probability of encountering a full service. Much has been written on passenger line selection strategies when a platform is shared by more than one line. The problem of full transit vehicles has received comparatively little attention in the literature. Where it has been considered, the usual approach is to define an effective frequency for an attractive line, which falls with increasing probability that the passenger encounters a full vehicle when trying to board. Based on the above considerations, the authors have proposed an approach to solving the transit network loading problem using an absorbing Markov chain analogy (Kurauchi, Bell and Schmöcker, 2003). Vehicle capacity is taken into account explicitly when considering the common lines problem. The model considers the implicit cost associated with the risk of failing-to-board. It therefore can consider the reliability of public transport network by calculating the risk of failing-to-board resulting in failing-to-arrive at the destination on time. Using the aforementioned capacity-constrained transit assignment model, this study proposes a method for evaluating public transport network reliability by the concept of connectivity reliability. Connectivity reliability is defined here as the *probability of arriving at the destination without failing to board at any stations.* Effects of public transport network improvement onto the connectivity reliability are discussed. It also handles how the reliability measures change by train arrival information.

2. NOTATION

A_p : Set of arcs on hyperpath p,
I_p : Set of nodes on hyperpath p,
R : Set of origin nodes,
$OUT_p(i)$: Set of arcs that lead out of node i on hyperpath p,
L : Set of transit lines,
$l(a)$: A transit line that is included in arc a,
S_p : Set of stop nodes on hyperpath p,
f_l : Frequency of service on transit line $l \in L$,
$\square_{ap}$: Probability that a hyperpath p traverses arc a,
$\square_{ap}$: Probability that a hyperpath p traverses node i,
c_a : Travel time on arc $a \in A$,
E_p : Set of failure nodes on hyperpath p,
WT_{ip} : Expected waiting time at stop node i on hyperpath p,

q_i : Probability that a passenger fails to board at node $i \in E$,
□ : Parameter for risk of failing to board,
Ω : Set of feasible hyperpath flows satisfying flow conservation,
$\mathbf{u}$: Vector of cost difference whose component is defined as
$u_p\left(\mathbf{y}^*,\mathbf{q}^*\right) = g_p\left(\mathbf{y}^*,\mathbf{q}^*\right) - m_{rs}^*$,
m_{rs}^* : Minimum cost from the origin of the hyperpath p (r) to the destination (s)
$\mathbf{v}$: Vector of vacancies on the line arc on line l from platform k whose component is defined as
$v_{kl}\left(\mathbf{y}^*,\mathbf{q}^*\right) = f_l z_l - x_{w_{kl}} - \left(1 - q_{h_{kl}}\right) x_{b_{kl}}$,
z_l : Capacity of transit line $l \in L$,
$x_{b_{kl}}$: Number of passengers already on board at platform k, line l,
$x_{w_{kl}}$: Number of passengers who wants to get on board at platform k, line l,
U_l : Set of platforms on line l,
y_p : Path traffic volume of hyperpath p,
P_{rs}^* : Optimal set of hyperpaths connecting r and s.

3. CAPACITY-CONSTRAINED TRANSIT ASSIGNMENT MODEL

3.1. HYPERPATH

To obtain an attractive set of transit lines that minimises expected travel time, we adopt the idea of the *hyperpath* proposed by Nguyen and Pallottino (1988). The hyperpath connecting an origin r to a destination s is defined as sets of stops, arcs and arc transition probabilities $H_p=(I_p,A_p,T_p)$, where H_p is a hyperpath connecting r to s, if:

- H_p is acyclic with at least one arc;
- node r has no predecessors and s no successors;
- for every node $i \in I_p - \{r,s\}$, there is a path from r to s traversing i, and if node $i \notin R$, then i has at most one immediate successor;
- the vector, $\mathbf{t}_p$, contains the arc split probabilities, which satisfies

$$\sum_{a \in OUT_p(i)} t_{ap} = 1, \ \forall i \in I_p, \qquad \text{(Eq. 1)}$$

and

$$t_{ap} \geq 0, \ \forall a \in A_p. \qquad \text{(Eq. 2)}$$

When we adopt the following assumptions regarding the common lines problem:

- Passengers arrive randomly at every stop node, and always board the first arriving carrier of their choice set; and
- All transit lines are statistically independent with given exponentially distributed headways, and mean equal to the inverse of line frequency,

then t_{ap} is calculated as follows:

$$t_{ap} = f_{l(a)} / F_{ip}, \ \forall i \in S_p, \qquad \text{(Eq. 3)}$$

$$F_{ip} = \sum_{a \in OUT_p(i)} f_{l(a)} \qquad \text{(Eq. 4)}$$

3.2. EXPECTED TRAVEL TIME

It is assumed that passengers try to minimise their travel time considering in-vehicle time, waiting time and the risk of failing-to-board. The expected travel time of hyperpath p, g_p can be written as follows.

$$g_p = \sum_{a \in A_p} \alpha_{ap} c_a + \sum_{k \in S_p} \beta_{kp} \cdot WT_{kp} - \theta \ln \left(\prod_{k \in E_p} (1 - q_k)^{\beta_{kp}} \right) \qquad \text{(Eq. 5)}$$

Expected waiting time at stop node k of hyperpath p, WT_{kp} can be calculated as follows:

$$WT_{kp} = 1 \Big/ \sum_{i \in OUT_p(k)} f_i \qquad \text{(Eq. 6)}$$

Since the cost of hyperpath p can be expressed as the sum of the cost of the current node and the subsequent nodes, it is possible to apply the dynamic programming method to obtain the shortest hyperpath.

3.3. FORMULATION

Let us assume that passengers use a hyperpath of minimum cost. The cost of a hyperpath is a function of the failure-to-board probability for each transit line on each platform. On the other hand, failure-to-board probability depends on boarding demand, passengers already on board, and transit line capacity, which in turn depends on the failure-to-board probability. Therefore, this can be regarded as a fixed point problem which defines the equilibrium. Eventually, the equilibrium is given by the solution to the following fixed point problem:

Find $(\mathbf{y}^*, \mathbf{q}^*)$

such that

$$\mathbf{y}^* \cdot \mathbf{u}(\mathbf{y}^*, \mathbf{q}^*) = 0, \mathbf{u}(\mathbf{y}^*, \mathbf{q}^*) \geq \mathbf{0}, \ \mathbf{y} \in \Omega, \qquad \text{(Eq. 7)}$$

$$\mathbf{q}^* \cdot \mathbf{v}(\mathbf{y}^*, \mathbf{q}^*) = 0, \mathbf{v}(\mathbf{y}^*, \mathbf{q}^*) \geq \mathbf{0}, \ \forall \mathbf{0} \leq \mathbf{q} \leq \mathbf{1}. \qquad \text{(Eq. 8)}$$

The existence of a fixed point is intuitive since any excess demand simply implies non-zero failures to board. However, because of the non-linear relationship in eqn (6) there is a possibility of multiple fixed points. A general procedure to solve fixed point problems is the method of successive averages (Bell and Iida, 1997).

3.4. CONNECTIVITY RELIABILITY

Connectivity reliability is defined here as the *probability of arriving at the destination without failing to board at any stations*. Therefore, the connectivity reliability of OD pair (r, s) can be calculated as follows.

$$CR_{rs} = \sum_{p \in P^*_{rs}} y^*_p \cdot \prod_{k \in E_p} (1 - q_k)^{\beta_{kp}} \qquad \text{(Eq. 9)}$$

3.5. EFFECTS OF TRAIN ARRIVAL INFORMATION

In many cities where they have metros, train arrival information has been provided. In this case, passengers can choose the transit line which arrives at the destination station fastest. For the case when they have two transit lines on the platform, arc split probability can be written as follows:

$$p_1 = \frac{f_1}{f_1 + f_2} \exp(-f_2 \cdot DT), p_2 = 1 - p_1, DT = t_1 - t_2 \geq 0, \qquad \text{(Eq. 10)}$$

Also the expected waiting time, WT, is,

$$WT_{ip} = \frac{1 - f_1 \cdot DT}{f_1 + f_2} \exp(-f_2 \cdot DT) + \frac{1 - \exp(-f_2 \cdot DT)}{f_2}. \quad \text{(Eq. 11)}$$

4. CASE STUDIES

In this study, a simple toy network shown in Figure 1 is used to explore the cases. Cases executed as summarised as Table 1. Demand for each OD pair is set to be 100 (passengers/min.), and □ is set to be 10 for all cases.

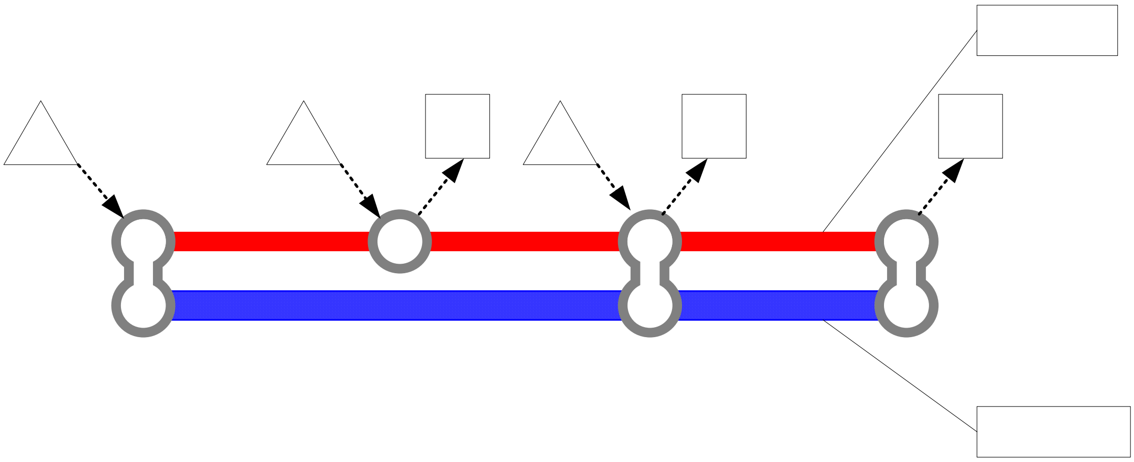

Figure 1: Example network.

	Infomation Provision	Capacity (passsenger/min.)		Frequency (minute)		Remarks
		Line I	Line II	Line I	Line II	
Case 1	No	150	125	5	10	Base Case
Case 2	No	175	125	5	10	Increasing the capacity of Line I
Case 3	No	150	150	5	10	Increasing the capacity of Line II
Case 4	No	150	125	3	10	Increasing the frequency of Line I
Case 5	No	150	125	5	8	Increasing the frequency of Line II
Case 6	Yes	150	125	5	10	Base Case + Information

Table 1: Scenario cases.

Figure 2 summarises the result of assignment for the base case (Case 1). Values in rectangles show the link traffic volumes, and values in ovals represent the fail-to-board probabilities. At station A, transit line I is rather congested, and fail-to-board probability is 0.1. The most congested station is B and fail-to-board probability is 0.550. Therefore, our target in this example is to relax the congestion on Line I of Station B. Here, we would try three strategies; 1) increasing the capacity of train, 2) increasing the frequency of lines, and 3) providing train arrival information. In general, transit line capacity is defined as *train capacity* x *frequency*, and the effects of 1) and 2) might be indifferent when we do not consider the common lines. However, when we consider the common lines, the result may differ since the arc split probability on the station will differ.

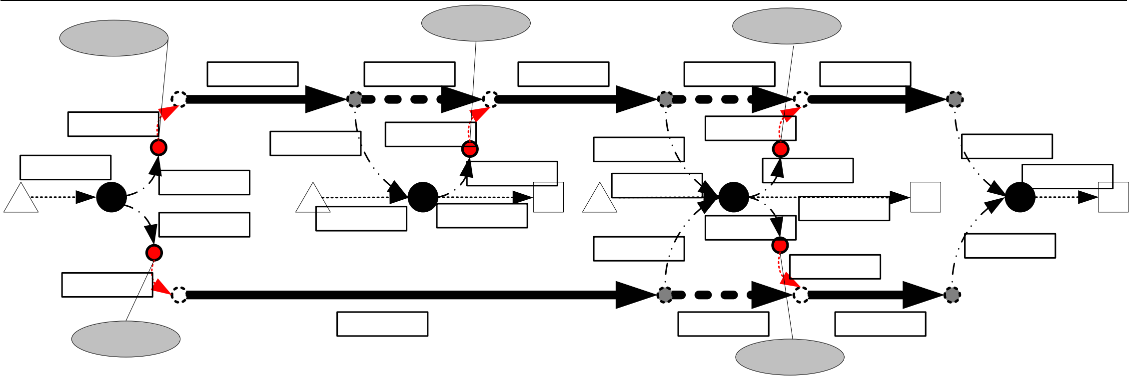

Figure 2: Result of Assignment (Case 1).

Figure 3 summarises the values of connectivity reliabilities for each case. By looking at Figure 3(a), we had better increase the capacity of line I, i.e., more congested line for improving the connectivity reliability. By increasing the capacity of Line I, all passengers can obtain the benefits. For case 3, increasing capacity of Line II only provides benefits to the passengers who can choose Line II, and connectivity reliability of OD pairs originated from station B remains the same. Looking at Figure 3(b), overall connectivity reliability improves when we increase the frequency of Line II. It is interesting to say that the connectivity reliability of OD pairs originated from station B also improves for case 5. However, the connectivity reliability of OD pair (A, D) decreases. Therefore not all passengers obtain the benefit from this improvement. When train arrival information is provided, arc split probability on station A changes so as the connectivity reliability. Since passengers boarding from Station A prefer to use Line II because the travel time is shorter, the connectivity reliability of ODs originated from station A destined to either C or D decreases. By this, the connectivity reliability of ODs originated from station B improves.

Eventually, from the simple case studies, we obtained following findings;

1) Increasing line capacity generally improves connectivity reliability, but the level of improvement may differ according to the line. Especially, increasing capacity for congested line is more effective,
2) Increasing the frequency of the congested line attracts more passengers from upstream, and it therefore may decrease the reliability of OD pairs originating from the subsequent stations,
3) Train arrival information encourages passengers to use the line of shorter travel time, which may result in decrease of the connectivity reliability.

The other results such as travel time reduction and hyperpath flow changes will be explained at the symposium.

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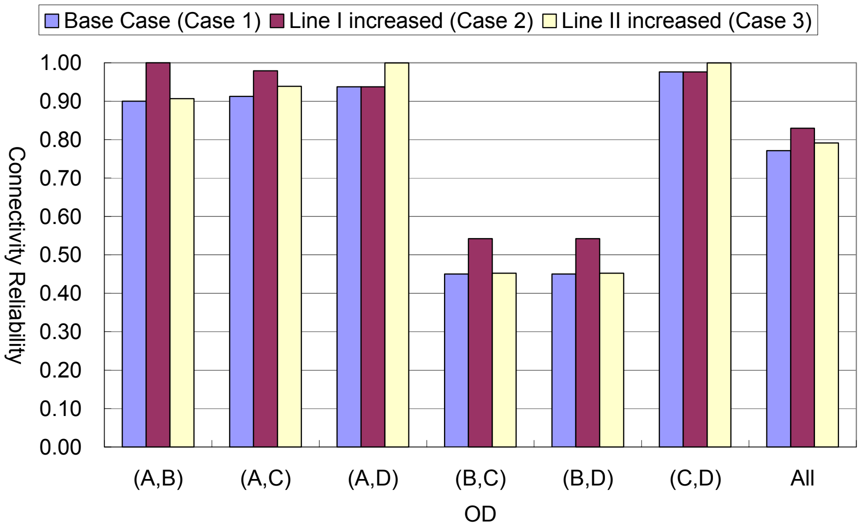
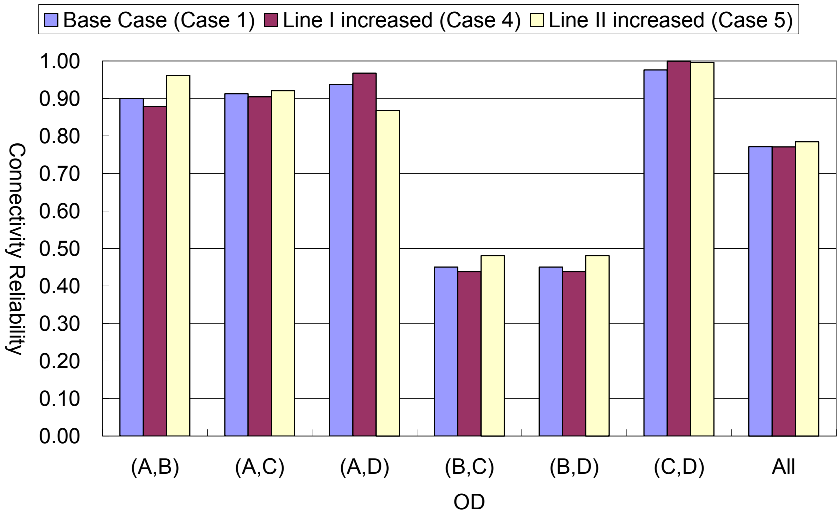
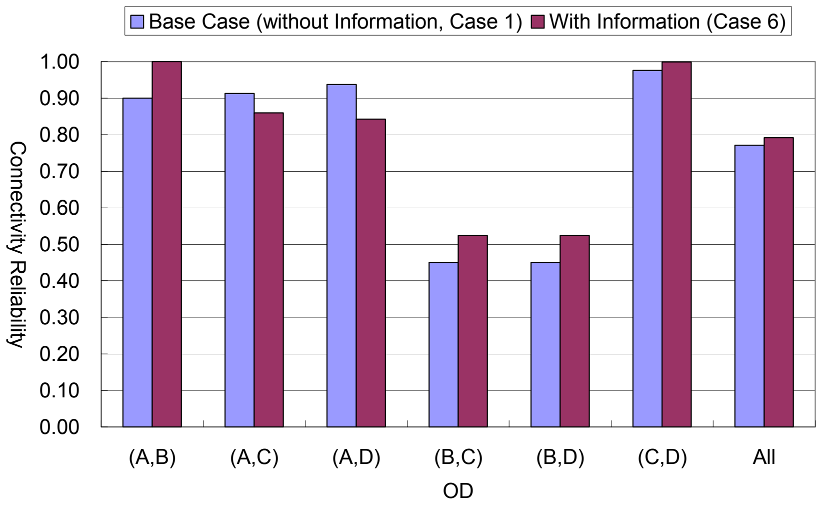


(a) Increasing Capacity



(b) Increasing Frequency



(c) Effect of Train Arrival Information

Figure 3: Calculation results.

A PRACTICAL APPROACH TO CORRECT BUS PROBE DATA FOR EVALUATING TRAVEL TIME RELIABILITY OF ROAD NETWORK

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1. INTRODUCTION

In order to make the quality of service of road network better, it is necessary to reduce uncertainty of travel time of road users. This study proposes a practical approach to correct travel time data obtained by "Bus Probe Survey", aiming at developing a methodology to evaluate travel time reliability of road network. Traditionally, the performance of road network tends to be evaluated in terms of travel time or its average value. With the rapid progress in information technology, people hope to reduce various kinds of uncertainty in their decision-making. Also the intensive progress in socioeconomic activities may lead to an increase in the value of time for each person. Under such circumstances, it becomes more important to provide travelers with stable road transport service. Accordingly, the road transport service should be evaluated from the viewpoint of travel time reliability (Iida (1999), Uno, Iida et al. (2002)).
Travel time reliability can be evaluated by the following R_{OD}, assuming travel time distribution between OD pair.

$$R_{OD} = Prob(t \leq t^{*}) \qquad (1)$$

Where, t^{*} denotes a standard travel time to evaluate travel time reliability.

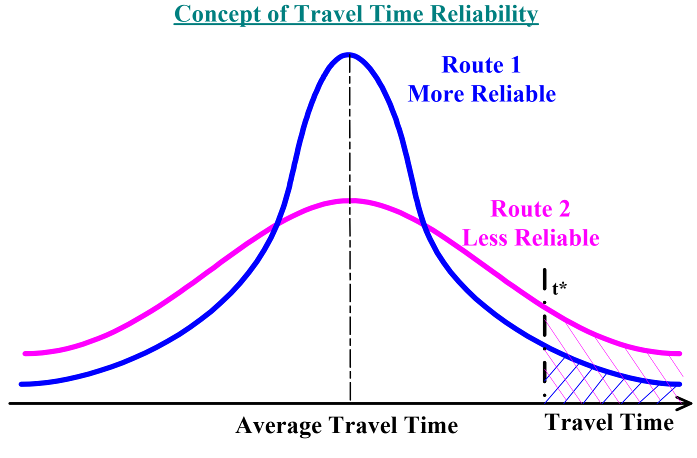

Figure 1: Travel Time Distributions of a Hypothetical Network

Equation (1) gives us the probability that a traveler can arrive at the destination less than or equal to a standard travel time t^{*}. Figure 1 shows travel time distributions of a hypothetical network composed of two alternative routes connecting an O-D pair. It is clear that the average travel time of Route 1 is the same as that of Route 2. However, in terms of travel time reliability, Route 1 is superior to Route 2, because $Prob(t_1 \leq t^{*}) > Prob(t_2 \leq t^{*})$. ($t_1$ and t_2 denote the travel time of Route 1 and 2 respectively.) In other words, Route 1 is regarded as the more reliable route in terms of travel time.

As part of putting some matured technologies of ITS into practical use, various types of probe car survey have been actively conducted in many cities in Japan for the last several years. Most of probe cars used in Japan have in-vehicle GPS (Global Position System) unit to obtain the data of real-time vehicle location measured in terms of both longitude and latitude. It is necessary to match the data of vehicle location with a kind of digital data of road network (for example, digital road map), in order for both specifying the route the vehicle travels and estimating its travel time.

This study focuses on how to utilize the data of "*Bus Probe Survey*", which is conducted in some cities mainly by Ministry of Land, Infrastructure and Transport (MLIT), Japan. The characteristics of *Bus Probe Survey* can be summarized as follows:

1) Because the bus travels along the predetermined route, it is possible for us to match the data of bus location with the digital data of road network with less inaccuracy, compared with the probe survey using passenger car or taxi.
2) Because the bus travels repeatedly along the specified route, *Bus Probe Survey* can provided us with the data of fluctuations in travel time easily.
3) However, there is a possibility that the data of *Bus Probe Survey* might be the overestimate of travel time, due to stopping at some bus stops.

In order to enhance the strong points of *Bus Probe Survey* related to the first and second characteristics above and overcome the drawback represented by the third characteristic, this study proposes the methodologies to correct the travel time and travel speed measured by *Bus Probe Survey*. In other words, it is required to develop the methodology to eliminate the increase in travel time due to stopping at bus stops.

2. SURVEYS USING PROBE SYSTEM

2.1. OUTLINES OF SURVEYS

Bus Probe Survey gives only a trajectory of bus locations measured by Global Positioning System (GPS), and does not provide any data on the stops at which the bus actually halts. Accordingly, it is necessary for us to utilize a kind of Geographical Information including the structure of road network and the location of bus stops, in order to estimate the travel modes of bus (running / stopping at bus stop / stopping at intersection). This study adopts a "*bus trip survey*" to grasp the stops at which the bus actually halts. In the *bus trip survey*, an investigator is assigned to each bus trip to observe and record its travel modes.

In addition, it is necessary for us to investigate the ordinary traffic condition, in order for developing the approaches to correct the bus probe data. This study also conducted the probe survey using passenger car. The travel time obtained by *passenger car probe survey* may be a suitable index to represent the ordinary traffic condition.

2.2. SURVEY METHODS

Both the *bus trip survey* and the *probe survey using passenger car* were conducted on December 17 and 21, 2003. The surveys on December 21 give us the data of traffic condition on weekend. This study selected four bus routes that originate at railway stations in the suburban area of Osaka. In the *bus trip survey*, each investigator got on the bus assigned with the PDA type device to collect the bus probe data. Also, the investigators were required to record the travel modes of bus manually. The investigators had to record the stops at which bus halted, stopping and resuming time, and traffic congestion occurred during they rode in the bus. In the *probe survey using passenger car*, the drivers are required to follow the vehicles traveling in a normal manner, in order for grasping the ordinary traffic condition.

3. APPROACHES TO CORRECT BUS PROBE DATA

3.1. OUTLINES OF APPROACHES

In order to confirm the necessity to develop the approaches for correcting the bus probe data, this study conducts a preliminary analysis to compare the travel time of passenger probe car and that obtained through *Bus Probe Survey*. Because of the limitation of space, only the result of preliminary analysis is explained briefly here. As the result of *t-test*, it can be said that there is a significant difference in average travel time between passenger car and bus.

This study proposes two different approaches to correct the bus probe data. The first approach is an application of multiple regression analysis for correcting travel time of bus. Based on the assumption that the travel time measured by passenger car probe can be regarded as a suitable index to represent the ordinary traffic condition, the travel time of passenger car probe is adopted as a dependent variable of the regression model. The explanatory variables of the model are travel time of bus, the possibility that the normal traffic can overtake the bus at stop and so on. The objective of the second approach is to correct the travel speed of bus along its route considering the influences of acceleration and deceleration caused by halting at bus stops. The second approach adopts *discriminant analysis* to make a model to detect halting at bus stops based on both the bus probe data and the distance to bus stops. After detecting halting at bus stops, travel speed of bus is adjusted by eliminating the dropping the speed at bus stops. Though the second approach seems more complicated than first approach, the second approach enables us to evaluate the traffic condition of any arbitrary road section along the bus route.

3.2. REGRESSION ANALYSIS FOR CORRECTING TRAVEL TIME OF BUS PROBE

Firstly, we apply the first approach mentioned above to the travel time data obtained through *Bus Probe Survey*. Table 1 shows the estimated parameters of regression model. The regression model here includes the possibility that the normal traffic can overtake the bus at stop as one of explanatory variables. In this study, it is assumed that the way to adjust the travel time of *Bus Probe Survey* might depend upon whether the bus halting at stop blocks the normal traffic or not. It is found that the estimated parameters of travel time of bus and the possibility that the normal traffic can overtake the bus at stop are statistically significant.

Figure 2 shows an example of applying the estimated regression model for correcting the travel time of bus. It is found that the dots representing the corrected bus travel time tend to shift upwards and distribute around 45-degree line. In other words, the application of the first approach might reduce the difference in travel time between the ordinary traffic and *Bus Probe Survey*.

Explanatory Variables	Estimated Parameters	Standard Error	t-statistics
Travel time of bus	**0.761**	**0.047**	**16.2**
Possibility that the normal traffic can pass the bus halting at stop	**-79.1**	**30.7**	**2.58**
Constant	**84.3**	**40.2**	**2.1**
Adjusted R^2	**0.69**	Sample Size	**120**

Table 1: Estimated Regression Model for Correcting Travel Time of Bus

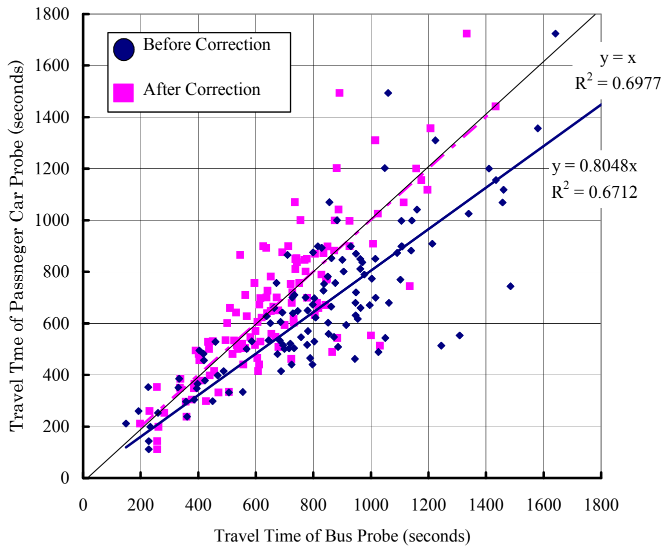

Figure 2: Relation of Travel Time between Passenger Car and Bus (1st Approach)

3.3. APPROACH TO CORRECT TRAVEL SPEED OF BUS

This study proposes another approach to correct the bus probe data. The objective of this approach is to correct the travel speed of bus along its route considering influences of acceleration and deceleration caused by halting at bus stops. In order for achieving this objective, it is necessary to prepare the way to detect halting at bus stops based on the bus probe data and the location of bus stop, the way of distinguishing deceleration and acceleration due to halting at stops and the way of adjusting the travel speed of bus.

3.3.1 Discriminant Analysis to Detect Halting at Bus Stops

This study applies *discriminant analysis* to detect halting bus at stops using the data of *Bus Probe Survey* and the data on locations of bus stops as its input. The explanatory variables of *discriminant analysis* are the travel speed of bus estimated using data of bus location and the distance to bus stop. Table 2 shows the result of *discriminant analysis*.

Variables	Estimated Parameters
Travel Speed	**-0.802**
Distance to bus stop	**-0.641**
Eigen value	**0.458**
Accumulated probability	**1.000**

Observed	Distinction by discriminant analysis		
Travel mode	% of distinguishing correctly	Running	Halting
Running	**95.8**	**1667**	**73**
Halting	**92.0**	**29**	**332**
Total	**95.1**	**1996**	**405**

Table 2: Result of Discriminant Analysis

It is found that around 95% of bus probe data can be classified properly in total, although the percentage of distinguishing halting of bus properly becomes only 92% due to the error of data of bus location obtained through GPS.

3.3.2 Way to Distinguish Acceleration / Deceleration

In order to correct travel speed of bus properly, it is necessary for us to adjust the speed during deceleration and acceleration due to halting at bus stop. Accordingly this study also proposes a rule to distinguish deceleration and acceleration modes of bus from the other travel modes. The rule can be described as follows. "We focus on the bus probe data during twenty seconds before and after halting at bus stop. If more than 0.77m/sec^2 of change in speed of bus continue at least for three seconds, the travel mode of bus can be regarded as deceleration or acceleration mode." Figure 3 indicates an example of applying the rule above to distinguish deceleration and acceleration modes using the bus probe data.

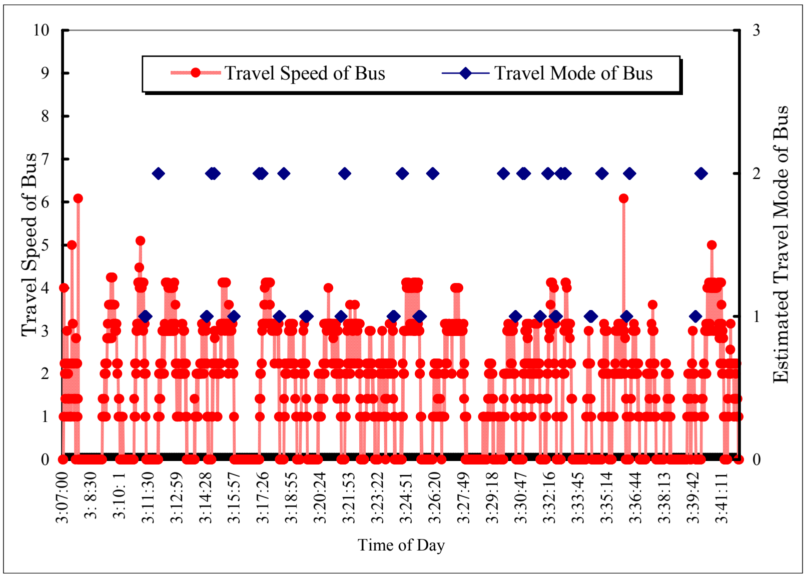

Figure 2: Example to Distinguish Deceleration and Acceleration Modes

The vertical axis of right hand side represents the estimated travel modes. "1" and "2" on the axis represents deceleration and acceleration respectively. If we compare the travel speed of bus estimated from the data of bus location given by GPS and the estimated travel modes, it can be said that the rule to distinguish deceleration and acceleration modes might work well.

3.3.3 Way to Adjust Travel Speed of Bus

Figure 3 indicates the diagram showing a concept to adjust travel speed of bus. At first, the bus probe data classified into halting at bus stop is assumed to be eliminated as shown in figure 3. In addition, the travel speed during deceleration is assumed to be replaced by the speed just before the bus starts to decelerate. The travel speed during acceleration after halting at bus stop is assumed to be replaced by the speed just after the bus finishes its acceleration.

Figure 4 shows an example of applying the second approach including *discriminant analysis* for adjusting the travel speed of bus. For simplicity's sake, we try to compare the travel time of passenger car and that of bus with / without adjustment. There is a possibility that the application of the second approach might adjust travel speed of bus and reduce the difference in travel time between the ordinary traffic and the bus probe.

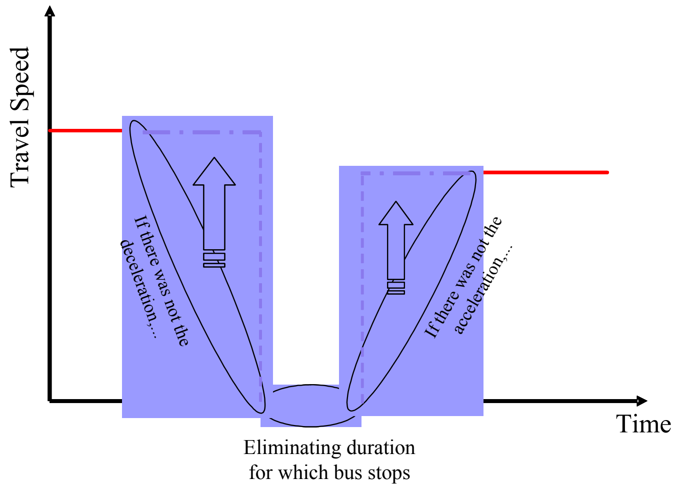

Figure 3: Conceptual Diagram for Adjusting Travel Speed of Bus

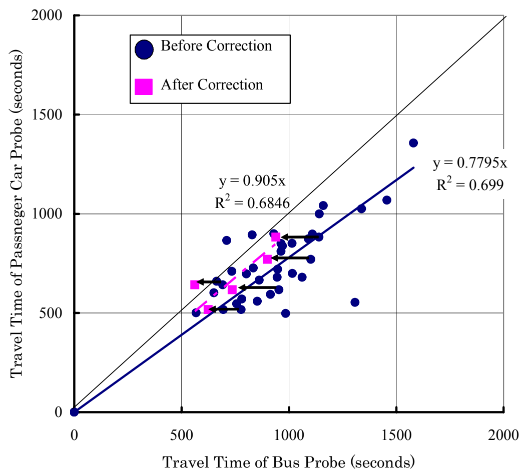

Figure 4: Relation of Travel Time between Passenger Car and Bus (2nd Approach)

4. CONCLUSIONS

This study applies some statistical approaches including *discriminant analysis* for making the model to detect stopping at bus stops and the model to distinguish deceleration and acceleration caused by halting at bus stops from the other traveling modes of bus. Through some cases of numerical experiments, it is found that the travel time corrected by the methodology above might be the better approximation of travel time experienced by the ordinary drivers using passenger or commercial vehicles. It is possible for us to utilize the database including the accumulated data of *Bus Probe Survey* corrected by the methodology proposed in this study for evaluating any arbitrary road section along the bus route from the viewpoints of travel time reliability.

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PRACTICAL INFORMATION PROVISION METHOD ON URBAN NETWORK WITH EMERGENCY CONDITIONS

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1. INTRODUCTION

The information provision should be an important technique of traffic management to produce the efficient traffic flow on the network. In particular, it is quite difficult to assume that drivers may have perfect information on the network in case of emergency. The study aims at proposing the practical information provision method on the network for efficient traffic management in emergency conditions. Basically, the drivers with particular information on the traffic condition with traffic accidents may change the routes easily to maintain the smooth traffic. On the other hand, the drivers without any information tend to remain the daily travel route. Since the conflict on the network occurs, the efficient traffic management should be required. It is assumed that the information is provided through the road side information boards on the network. A few incidents might be observed on the network simultaneously. Therefore, the allocation of traffic information should be analyzed with regarding to the impact to traffic flow. The effective information provision for the drivers would promote the detour traffic to reduce the social travel cost as total travel time on the network. Therefore, the traffic flow pattern produced by the information provision should be evaluated. The stochastic traffic assignment can be applied to estimate the detour traffic as an impact of information provision. The most effective allocation of the traffic information in emergency conditions should be provided as a solution of combinatorial optimization problems. The effective patterns of information provision would be proposed empirically with fuzzy reasoning formulation from the case studies for the urban network of Gifu city.

2. PRACTICAL INFORMATION PROVISION

It is assumed in the study that the information boards are distributed on the urban network to provide the traffic information to road users. The character information board should be a sort of fundamental equipment in information provision. It corresponds to the recent condition of information provision on urban network. The traffic information is provided according to the emergency condition on the network such as traffic accident, breakdown and so on. The information provision would be evaluated by a primitive method. Essential point of evaluation is to classify the road users into two groups to describe the traffic flow with information provision. The users with traffic information can make decision for diversion according to the traffic condition of the

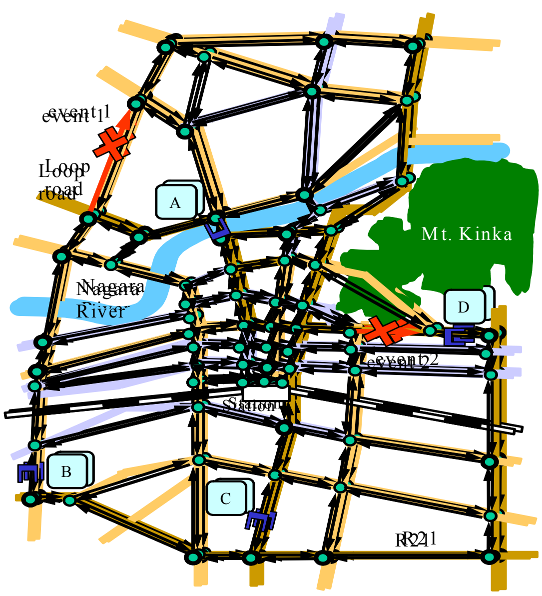

Figure 1: Urban Network in Gifu

network. On the contrary, the users without traffic information are travelling on the same route as usual according to the normal traffic condition on the network. The practical method of information provision for real scale network should be discussed in the study. **Figure 1** illustrates the urban network in Gifu. The railway station locates in the middle of the network. The north of the station corresponds to the central business district. The loop road and the national trunk road as route 21 consist of the surrounding ends of the city. There is the river Nagara which separates between the central area and suburban area. Therefore, the daily traffic congestion can be observed for crossing the river at peak hour. The objective network in Figure 2 consists of 256 links, 79 nodes and 33 zones. It is also assumed that four information boards are installed independently in each direction. According to the database of trip survey, the OD traffic demand can be estimated corresponding to the average day traffic in 2001. The peak rate for hourly traffic is assumed to be 10 % in estimation.

3. TRAFFIC FLOW ESTIMATION WITH INFORMATION PROVISION

The basic idea of evaluation to compare traffic flow patterns on the network with and without traffic information provision. This reflects on the route choice behaviour of the driver who obtains the proper information. The practical evaluation steps are proposed as shown in **Figure 2** estimating the traffic flow with/without information provision as follows (Akiyama & Iwata, 2000):

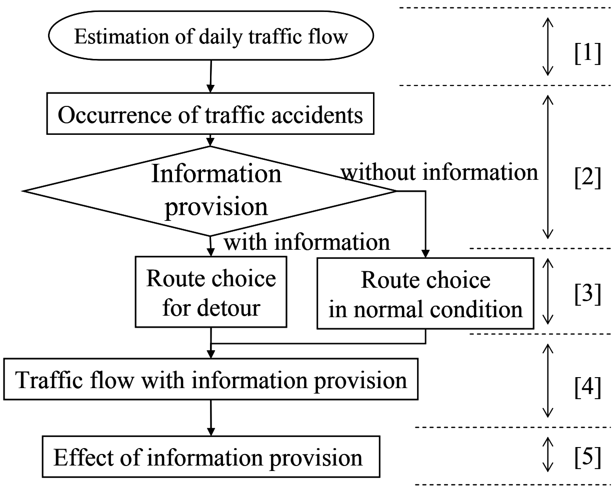

Figure 2: Evaluation process of information provision

[Step 1]: The traffic flow on the network can be estimated under the normal condition without any event. This corresponds to SUE traffic flows for daily average traffic. Therefore, the path flows are estimated by SUE algorithm as MSA involving the Dial approach. It must be quite common approach. The traffic flow on the network can be estimated reflecting that all drivers are travelling on the daily route according to the experience without particular event.

[Step 2]: The physical conditions for related links are changed according to the observed events such as accident, breakdown etc. on the networks. Calculate the total travel time assuming that all drivers use the route as before because they do not recognize the change of road conditions without traffic information. As a result, the total travel time should be greater than that of Step 2.

[Step 3]: Determine the paths via the link installed the information equipment and the link located the events. The path flows are removed from the loaded traffic on the network. The flows should be loaded on the network again. Assume the drivers on the related paths mentioned above may change the route according to the provided information. At the same time, the other drivers do not change the route to maintain the same paths.

[Step 4]: The removed path flows are assigned on the network under the physical road conditions with events. Calculate the total travel time from the link flows loaded. It corresponds to the social costs.

[Step 5]: Evaluation. The reduction of total travel time on the network is calculated from the results in step 3 and step 4. The reduction indicates the benefit of traffic information provision in terms of social cost.

4. EVALUATION OF INFORMATION PROVISION

It is often observed that some events such as traffic accidents happen on the network simultaneously. The information boards may display different events. Therefore, the combination of provided information would be investigated to produce the efficient traffic on the network. The reduction of total travel time is introduced to evaluate the efficiency of information provision.

Let us assume that two accidents happen simultaneously on the network illustrating in **Figure 1**. Both accidents are equivalent to the 50 % capacity reduction of the links. The display alternatives of information provision should be "event 1", "event 2" and "none" for each information board. Therefore, the patterns of information can be counted as 3^4=81. As the number of cases is limited in the example, the value of effect as ΔTC is calculated for all patterns. **Table 1** summarizes 20 effective patterns of information provision in order of the value of ΔTC. The maximum value of ΔTC should be 812.09 min□veh (ΔTC_{max}) with the information boards as (A, B, C, D) displaying (event 2, event 1, event 2, event 1) respectively. It is observed as well that the pattern such as event 2 on information board A and event 2 on information board B tends to provide higher efficiency for the example.

Information Contents				Δ TC
Information board A	Information board B	Information board C	Information board D	[min*veh]
Event2	Event1	Event2	Event1	812.09
Event2	Event1	Event1	Event1	806.37
Event2	Event1	-	Event1	806.37
Event2	Event1	Event2	Event2	630.72
Event2	Event1	Event2	-	630.72
Event2	Event1	Event1	Event2	624.99
Event2	Event1	-	Event2	624.99
Event2	Event1	Event1	-	624.99
Event2	Event1	-	-	624.99
Event2	Event2	Event2	Event1	621.03
Event2	Event2	Event1	Event1	615.99
Event2	Event2	-	Event1	615.99
Event1	Event1	Event2	Event1	524.72
-	Event1	Event2	Event1	524.72
Event1	Event1	Event1	Event1	517.66
Event1	Event1	-	Event1	517.66
-	Event1	Event1	Event1	517.66
-	Event1	-	Event1	517.66
Event2	-	Event2	Event1	516.57
Event2	-	Event1	Event1	510.84

Table 1: The Effects of Information Provision

5. METHOD OF INFORMATION PROVISION

The effective patterns of information provision have been discussed in the previous chapter. Even though the optimal pattern of information provision can be estimated with exhaustive comparison, the method may not be applicable to real scale problem with several information sites and events on the urban network. If the pattern of information provision can be determined corresponding to some measurable factors, the method might be helpful for practical application. Therefore, the following indices are proposed reflecting the efficiency of information provision.

1) Index of Reasonable Path :IRP

The effect of information provision becomes larger in proportion to the number of drivers obtaining the information as well as going through the link on which the event happens. The definition of reasonable path is proposed to determine the connection between the information site and event location. The single path algorithm can be applied to identify the reasonable path as follows:

$$\begin{cases} IRP = 1, & r(i) \le r(j) \\ IRP = 0, & r(i) > r(j) \end{cases} \qquad (1)$$

2) Degree of Significant Information: DSI

The drivers who obtain the traffic information at the site of information board can easily avoid coming through the link with obstacle. The number of junction as node, N is measured between information board site and the event site. The driver has many opportunities to change routes as N is large.

$$DSI = 1 - \alpha \cdot N \qquad (2)$$

The parameter α indicates the magnitude of information according to the avoidable traffic to the event. The value of α is determined as 0.04 considering the network structure.

3) Preference of Detour Route: PDR

The influence of the event differs corresponding to the traffic volume and the capacity of the link. Therefore, the detour route would be preferred if the large influence of event is measured.

$$PDR = V_a / Q_a \qquad (3)$$

where V_a is average traffic on the link and Q_a is capacity of the link with the event.

The display on the information board can be determined in the next stage of evaluation. The information of each event can be located on each information board according to the value of evaluation. According to the definitions of indices, the reasonable paths are selected (*IRP=1*) at first. Otherwise, the indices *PDR* and *DSI* cannot make sense. The value of evaluation is calculated as follows:

$$EVL \begin{cases} PDR \times DSI, & IRP = 1 \\ 0, & IRP = 0 \end{cases} \qquad (4)$$

The event with the highest value of *EVL* is determined to display on the individual information board. If the displayed events are selected on all information boards according to the procedure, the pattern of information provision is determined.

6. PERFORMANCE OF INFORMATION PROVISION

As mentioned previously, the optimal pattern of information provision has been determined as a result of comparison for all feasible combinations. Therefore, the performance of proposed *EVL* method can be measured comparing to the optimal pattern as follows:

$$R = \Delta TC_{\inf} / \Delta TC_{\max} \qquad (5)$$

where $\Delta TC_{\inf}$ is reduction of total travel time in proposed method and $\Delta TC_{\max}$ is that in optimal pattern of information provision. Assuming two events happen on any places of networks as 30 links, the results for 435 cases ($= {}_{30}C_2$) can be summarized. The performance of the information provision can be indicated by the percentage to the maximum reduction of total travel

ΔTC_{info} [min*veh]	724.8
ΔTC_{max} [min*veh]	799.1
$\frac{C_{info}}{C_{max}} \times 100$ (%)	90.7

Figure 3: Performance of Information Provision

time in **Figure 3**.

If the proposed method provides the same pattern as the optimal, $\Delta TC_{\inf}$ should be equivalent to $\Delta TC_{\max}$. Therefore, the performance level is indicated as 100% in the figure. This condition is realized over 65% for all cases (=285/435). On the contrary, total travel time is increased by improper pattern in some cases. Moreover, the average reduction of total travel time is counted as 724.8 $veh \cdot \min$. Therefore, the information provision is performed at the level of over 90 % for optimal pattern as 799.1 $veh \cdot \min$ in average even though a few differences can be seen in the contents of display on the information boards.

7. FUZZY REASONING APPLICATION

The primitive evaluation method for information provision has been proposed. Even though the key factors to evaluate the information provision can be summarized, the general formulation would be required particularly to modify the information provision procedure. Fuzzy reasoning is one of the practical approaches to formulate the information provision having the advantages. The rule base knowledge with linguistic variables may help describing the essential decision in information provision quite obviously. At the same time, the importance of information can be evaluated though the highly non-linear relationship among the factors. **Table 2** summarizes the inference rules for evaluation of information.

DSI \ ***PDR***	very large	large	medium	small	very small
very large	large	large	large	medium	medium
large	large	large	large	medium	medium
medium	large	large	medium	medium	small
small	large	medium	small	small	small
very small	medium	small	small	small	small

Table 2: Inference Rules for Evaluation of Information

The evaluation would be provided through fuzzy reasoning with the value of PDR and DSI instead of mathematical formulation. For example, the rule "If PDR is very large and DSI is very large then the evaluation is large" is indicated the top left corner element of the matrix as "large". All linguistic variables for PDR and DSI are described by membership functions.

The singleton fuzzy reasoning is introduced as a practical method with single number in concluding part of inference formulation. This method is often used in the practical applications of fuzzy reasoning.

Figure 4 summarizes the performance of fuzzy reasoning information provision with percentage to the optimal pattern similarly to the previous method. The level of performance for overall cases distributes similarly to the previous even though only the essential knowledge is described by inference rules. The number of optimal information patterns (100%) is slightly reduced from 285 to 281. On the other hand, the number of cases with second higher performance (80-100%) is

ΔTC_{info} [min*veh]	726.0
ΔTC_{max} [min*veh]	799.1
$\frac{\Delta TC_{info}}{\Delta TC_{max}} \times 100$ (%)	90.9

Figure 4: Performance of Information Provision with Fuzzy Reasoning

increased from 75 to 82. It is observed as well that the average level of performance becomes slightly higher than the previous method.

This result is given from simple translation of the previous method to fuzzy reasoning description. In terms of application, fuzzy reasoning model easily allows to change the different structure of inference with modified rules as well as proper definition of membership functions. Therefore, it can be mentioned that fuzzy reasoning formulation may have some advantages for further modification of the method of information provision. The applicability of fuzzy reasoning system would be discussed as well. The proposed method is applied in different traffic condition. The performance of information provision in different traffic demand is summarized in **Figure 5**. The method provides the certain level of performance even though the traffic demand changes gradually. The fact shows the robustness of information provision on the network. Furthermore, it can be known that the displayed information with fuzzy reasoning is similar to optimal patterns as the traffic demand becomes large. Therefore, the proposed method seems to be more efficient in congested networks.

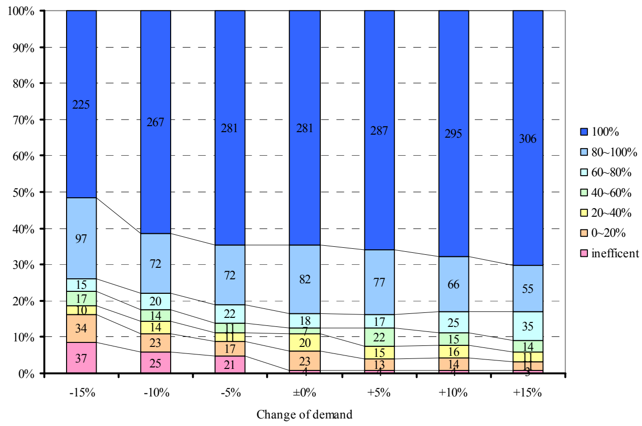

Figure 5: Applicability in Traffic Demand Change

8. CONCLUDING REMARKS

It would be concluded that practical information provision method in emergency conditions can be formulated as fuzzy reasoning system to restore the traffic flow on the network. The effectiveness of the proposed method would be practically applicable comparing to the theoretical result of optimized allocation of information. The robustness of the method can be confirmed as well with empirical examples.

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TRAVEL TIME RELIABILITY IN VEHICLE ROUTING AND SCHEDULING WITH TIME WINDOWS

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1. PROBABILISTIC VEHICLE ROUTING AND SCHEDULING MODEL

This study adopted Probabilistic Vehicle Routing and scheduling Problems with Time Windows (VRPTW-P) model. The VRPTW-P model is defined as follows. A depot and a number of customers are defined for each freight carrier. A fleet of identical vehicles collects goods from customers and deliver them to the depot or deliver goods to customers from the depot. For each customer a designated time window, specifying the desired time period to be visited is also specified. The VRPTW-P model minimises the total cost of distributing goods with truck capacity and designated time constraints. The total cost is composed of three components; (a) fixed cost of vehicles, (b) vehicle operating cost that is proportional to time travelled and spent waiting at customers, (c) delay penalty for designated pickup/delivery time at customers. The VRPTW-P model takes into account the uncertainty of link travel times on road network to identify the optimal solution. Taniguchi et al. (2001) presented formulation for VRPTW-P model.

2. CASE STUDIES IN SOUTH-OSAKA AREA

2.1. OVERVIEW

In order to show the effectiveness of VRPTW-P model in real delivery systems, we performed case studies in South Osaka area, Japan. These studies measured precise movements of a pickup-delivery truck using the measurement device with GPS (Global Positioning System). The truck visited about 10 customers for delivering electronic products per day in South Osaka area and the total distance travelled was about 30 km per day. It used wide range of roads including trunk roads and urban streets.

The best approach to show the effectiveness of VRPTW-P is to compare total costs of the optimal solution of VRPTW-P with those of real operation. However, because of lack of link travel time information except links where a probe vehicle runs, it is difficult to identify total costs and CO_2, NOx and SPM (Suspended Particle Materials) emissions of optimal solution of VRPTW-P. Therefore, we will use historical data of travel times given by VICS (Vehicle Information Communication Systems) as well as probe vehicle data.

2.2. ESTIMATING TRAVEL TIME DISTRIBUTION USING PROBE VEHICLE DATA

The measurement system was installed in a small pickup-delivery truck (load capacity = 2 ton) which delivers electronic products to retail shops in South Osaka area. The measurement device can record the current position of a vehicle at the interval of 1 second receiving GPS signals from satellites. Data were recorded in a memory card and collected every day via Internet during 3 months (13th March 2004 – 2nd June 2004). This study used a single pickup-delivery truck and the data were taken for 66 days.

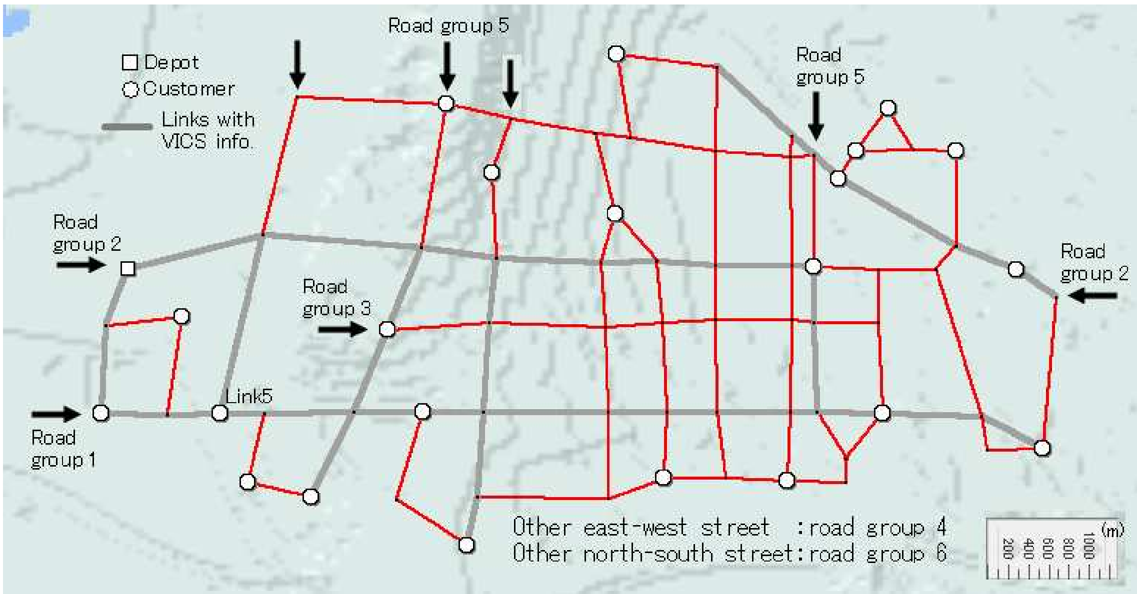

Figure 1: South Osaka road network

We formed a road network for the analysis of vehicle routing and scheduling based on the actual running path of probe vehicle. FIGURE 1 indicates the road network in South Osaka area. The road network only represents trunk roads and urban streets which are associated with visiting customers in this area. This road network contains 218 links and 69 nodes, where one depot and 22 customer nodes are located. A pickup-delivery truck leaves the depot to deliver goods to some of 22 customers and returns to the same depot.

The road network contains trunk roads of National Highways as well as urban streets with lower traffic capacity. These roads within the network were classified into 6 groups based on the class of roads and area. The historical data of link travel times have been accumulated at each road group to analyse the distribution.

Since the VRPTW-P model requires the distribution of travel times, we collected travel times by VICS for some of links which are shown by bold line in FIGURE 1. Travel times data we used were recorded by VICS during 14 months (1st February 2001 – 31st March 2002). For the other links, where VICS data are not available, we analysed travel times data by the probe vehicle in each road group. FIGURE 2 shows an example of travel time distribution at link 5. We approximate the travel time distribution to a triangular shape.

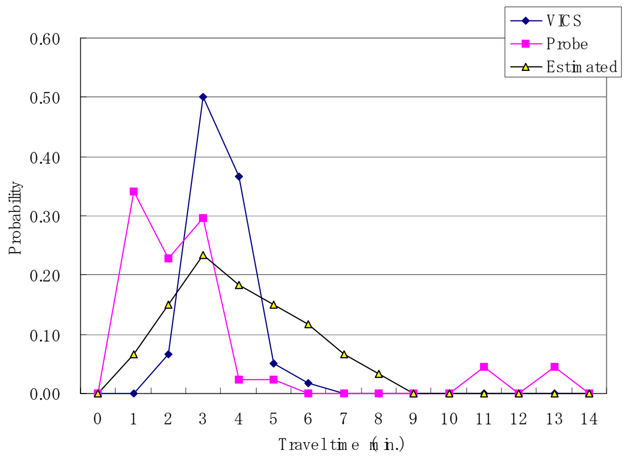

Figure 2: An example of travel time distribution (link 5 (see figure 1))

Analysing travel time data of each link gave the maximum, minimum and average value of travel times for each road group. FIGURE 3 shows the relationship of these values and the link distance for road group 2. A linear regression analysis was performed and the maximum, minimum and average travel speeds were identified from the inclination of the approximated line.

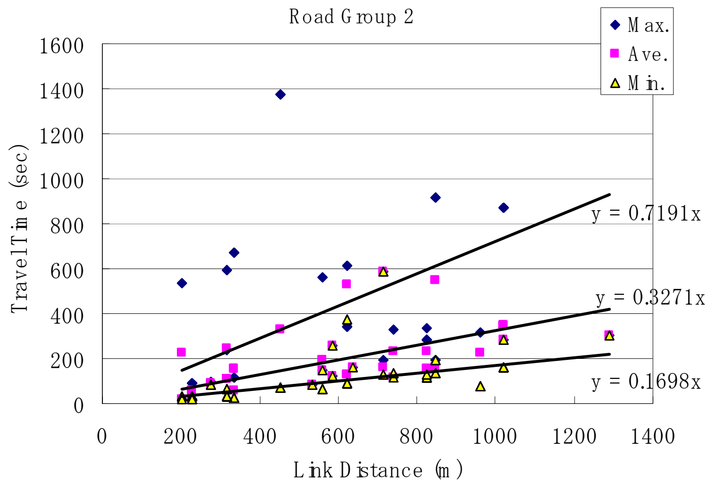

Figure 3: Travel time and link distance (road group 2)

Road Group	Travel Speeds(km/h)			Fluctuation
	Max. (a)	Ave. (b)	Min. (c)	((a)-(c))/(b)
1(E-W st.1)	18.0	6.9	3.1	2.17
2(E-W st.2)	21.2	11.0	5.0	1.47
3(E-W st.3)	20.1	9.0	3.1	1.89
4(E-W st.4)	11.3	6.8	4.6	0.99
5(N-S st.1)	17.4	6.5	2.3	2.32
6(N-S st.2)	21.3	10.7	4.1	1.62

Table 1: Maximum, minimum and average travel speeds and their fluctuation

A triangular shape distribution of travel times was used for VRPTW-P model. It can be produced as follows: (a) Determine the maximum, minimum and average travel times using the relationship of travel time and link distance as shown in FIGURE 3, (b) Form a triangular shape distribution to let the area of triangle be 1. FIGURE 2 shows an example of the estimated triangular shape distribution for link 5.

2.3 DELIVERY

The case studies evaluate delivery activities on two days of 7th and 10th April 2004. The pickup-delivery truck visited 9 customers on 7th April and 11 customers on 10th April, 6 customers of which were same. A single two-ton truck started the depot at 8 a.m. and returned to the same depot after delivering goods to customers.

2.4 ASSUMPTIONS FOR VRPTW-P

There are some assumptions for calculating the optimal solution of VRPTW-P:

(a) A single two-ton truck is allowed to be used
(b) Each customer sets soft time window of 3 hours (1.5 hours before and after the actual arrival at customer)

(c) The configuration of link travel time distribution during delivery is same for a specific link.

2.5 IDENTIFYING THE OPTIMAL SOLUTION

7th April	Case (EA) (Yen)	Optimal solution (Yen)	Change (%)
Fixed cost	10,417	10,417	0.00
Operation cost	26,310	20,083	-0.24
Delay Penalty	16,662	17	-1.00
Early arrival penalty	89	538	5.04
Total cost	53,478	31,055	-0.42
10th April	Case (EA) (Yen)	Optimal solution (Yen)	Change (%)
Fixed cost	10,417	10,417	0.00
Operation cost	26,924	21,925	-0.19
Delay Penalty	5,018	2,661	-0.47
Early arrival penalty	923	923	0.00
Total cost	43,282	35,926	-0.17

Table 2：Comparison of costs

The VRPTW-P model identified the optimal visiting order of customers and departure time of depot for two days of 7th and 10th April. It also determined the shortest path between customers using the average travel times. Here we assume expected average case based on the real operation (Case (EA)): (a) A pickup-delivery truck follows the same roads of real operation, but (b) It runs at the estimated average travel time by the regression model as shown in FIGURE 3 and TABLE 1. Thus expected average costs for Case (EA) can be calculated.

Table 2 shows the comparison of costs for Case (EA) and optimal solution of VRPTW-P. The table indicates that the total costs of the optimal solution of VRPTW-P were reduced by 17-42% compared with that of Case (EA). In particular, the operation cost of the optimal solution of VRPTW-P was reduced by 19-24% compared with Case (EA). This is attributed to choosing better visiting order of customers and roads used. The delay penalty for the optimal solution of VRPTW-P was also decreased for both two days. The early arrival penalty was increased for the optimal solution of VRPTW-P on 7th April. The results represent the characteristics of VRPTW-P model that tends to arrive earlier avoiding any delay at customers considering the uncertainty of travel times. Therefore, VRPTW-P can contribute to provide better service to customers by decreasing an opportunity to arrive late at customers.

2.6 NEGATIVE ENVIRONMENTAL IMPACTS

It is important to look into the improvement of negative environmental impacts of VRPTW-P as well as cost reduction. FIGURE 4 compares travel times of pickup-delivery truck, CO_2, NOx and SPM (Suspended Particle Materials) emissions of the Case (EA) and the optimal solution of VRPTW-P. The figure indicates that travel times of pickup-delivery truck for the optimal solution of VRPTW-P compared with those of Case (EA). This reduction of travel times can contribute to alleviate traffic congestion. The emissions of CO_2, NOx and SPM for the optimal solution of VRPTW-P were also reduced by 10.1-16.5%, 6.1-13.2%, and 5.3-12.4%, respectively. Therefore, VRPTW-P can contribute not only to decrease total costs but also to decrease traffic congestion and negative environmental impacts.

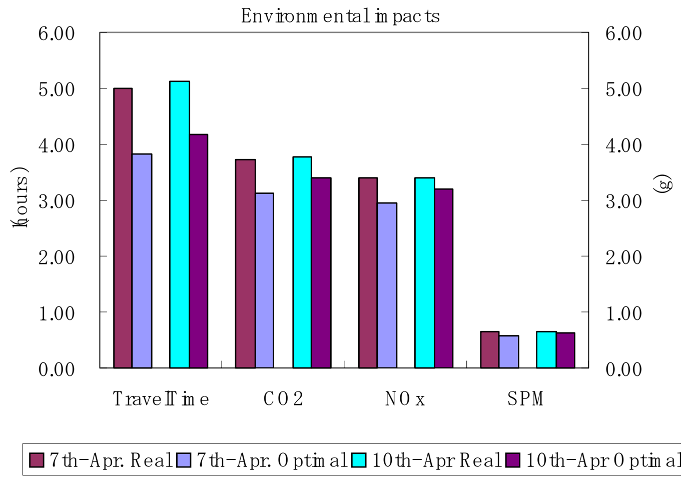

Figure 4: Environmental impacts

3. CONCLUSIONS

This study derived following findings.

(a) Total costs of the optimal solution of VRPTW-P were reduced by 17-42% compared with that of the expected average case based on the real operation of pickup-delivery truck. In particular the operation cost and the delay penalty were considerably decreased due to better routing.

(b) The VRPTW-P also resulted in reducing the travel times and CO_2, NOx and SPM emissions compared with those of the expected average case based on the real operation. Therefore, the VRPTW-P can contribute to decrease traffic congestion and negative environmental impacts.

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DATA FUSION OF VICS AND PROBE TO REDUCE UNCERTAINTY OF TRAVEL TIME INFORMATION

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1. INTRODUCTION

This research aims to present the effect of data fusion of probe and VICS travel time information. VICS, which came into operation from 1996, is so-called Advanced Travel Information System in Japan. VICS collects link travel time based on loop or ultra-sonic detector speed, and updates travel time information every 5 minutes via on-board navigation system.

However, a couple of shortcomings are pointed out to VICS. At first, it covers only highways and major arterial roads (VICS links) on which detectors are installed. As shown in Figure 1, VICS links sparsely cover the network, comparing with full links in Nagoya-city area. If someone starts his/her trip to destination, he/she will use not only major roads but also minor roads for access and egress, which sometimes may be in severe traffic conditions. A demand for the informative service including those minor roads seems to be large.

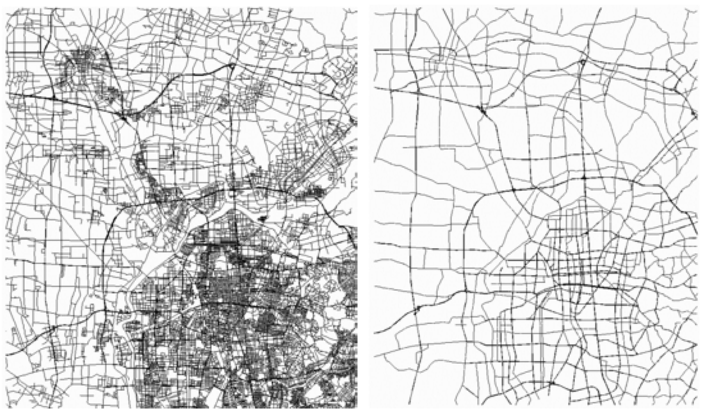

Figure 1: Full links (left) and the VICS links (right) in Nagoya-city area.

At second, it has to estimate link section travel time from detector speed at one point. Some models, such as simple queuing model, will be required for the estimation, but it is difficult and costly to calibrate those models well in long term. Moreover, detector speed can not distinguish vehicles' turning movements. Therefore, VICS only provides link travel time by assuming straight through direction.

Considering these shortcomings, we may regard even a driver using VICS is facing uncertainty of travel time information. It can be happen that VICS misleads a driver to worse situation than the driver without VICS information when the minor roads out of VICS links are severely congested, because most of on-board navigation system assume constant and moderate travel speed for those minor roads.

In order to provide much reliable travel time information, it is expect to merge prove information into VICS. Against to VICS, probe data can be collected on every roads that vehicles may run. It directly measures section travel time along the path of a probe vehicle by including the delay at left/right turn. Still we can not expect high frequency of updating travel time with probe at present, we may utilize stored probe data and extract statistical information among them.

In the following chapter, we will report the practical study for the data fusion of VICS and probe travel times. The concept and the methodology of data fusion will be explained at first. In the second part, the practice using real VICS and probe data collected in Nagoya-city will be presented to demonstrate the effect of data fusion.

2. CONCEPT OF DATA FUSION OF VICS AND PROBE DATA

The methodologies of data fusion proposed here take two ways, correction of VICS link travel times and spatial complement to VICS links with stored probe data. The concepts of these two methodologies are described in the subsequent sections.

2.1 CORRECTION OF VICS LINK TRAVEL TIMES WITH PROBE DATA

The popular way to estimate the travel time of a VICS link is so-called 'sandglass' method, which counts the number of vehicles at the upstream of the link as the traffic demand. By assuming the parameter of a reasonable flow rate at the downstream section of the link, the method calculates the average travel time with simple queuing theory.

It is obvious that the accuracy of the traffic counts and the flow rate will strongly affect on the reliability of the estimated travel times. In practice, however, it is the case that the assumed flow rate is different from the actual value or that the measured traffic counts include errors by some reasons from maintenance works. Since it will be very costly to seek the perfection to maintain the sensors and the parameter values, we may permit some errors in VICS travel time information whatever the magnitude of errors are not acceptable.

In order to correct the errors in VICS link travel time, VICS data is to be compared with stored probe data that is reasonably cleansed to measure link travel times (Sarvi, *et. al*, 2002), as shown in Figure 2. Each plot in the figure represents VICS link travel time at the same time when a probe vehicle passes through the subject VICS link.

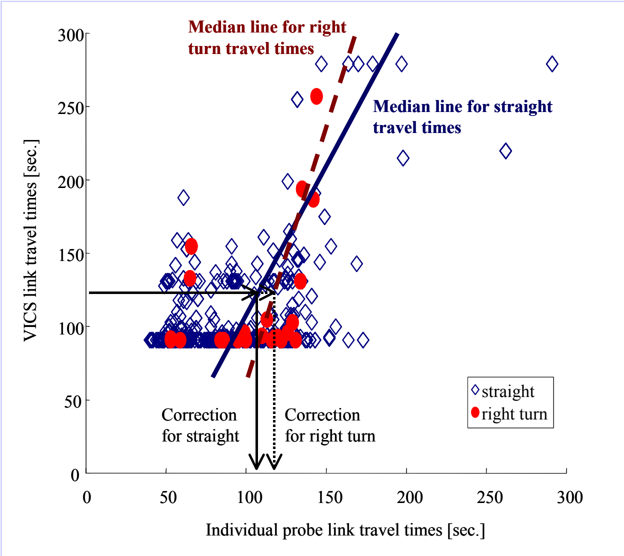

Figure 2: Correction of VICS link travel times with stored individual probe data.

Even though the variation of 'individual' probe travel times is larger than VICS travel times, we may derive some relationships from the comparison to be used for the correction of VICS data. In Figure 2, we derived two liner regression lines to the 'median' plots which provide median values of prove travel times for every 30 second range of VICS travel times. Since the turning movement at the downstream intersection is given to each probe travel time, we may obtain the correction line not only for straight but also right or left turn. When a certain value of link travel time is provided by VICS, different travel times will be provided according to the turning movement at the intersection by using this method.

2.2. SPATIAL COMPLEMENT TO VICS LINKS WITH PROBE DATA

As shown in the right picture of Figure 1, most of the minor roads are not designated as VICS links. However, considerable number of VICS links are not given travel time information because of the reason that they have no traffic detector on themselves and so on. Table 1 shows the total length of links in terms of information provision types in Nagoya-city. It is found that only 4% out of whole links are provided travel time information, and we have to estimate the travel times for the rest of 76% links by not using VICS.

Type	Description	Total length	%
1	VICS link with travel time information	400 km	4%
2	VICS link without travel time information	2,150 km	22%
3	Non-VICS link	7,000 km	74%

Table 1: Total length of links for each information provision type (Nagoya-city).

In this research, timetables of expected travel times are derived from the historical probe data for the links without VICS information. Figure 3 illustrates an example that contains the expected link travel times of certain non-VICS link for every 15 minutes. Even though the derived timetable is static and cannot consider the daily traffic condition, it still reveals that the profile of the travel time has two peaks in the morning and the evening. This timetable helps to make the travel time information be reliable, rather than by assuming constant speed.

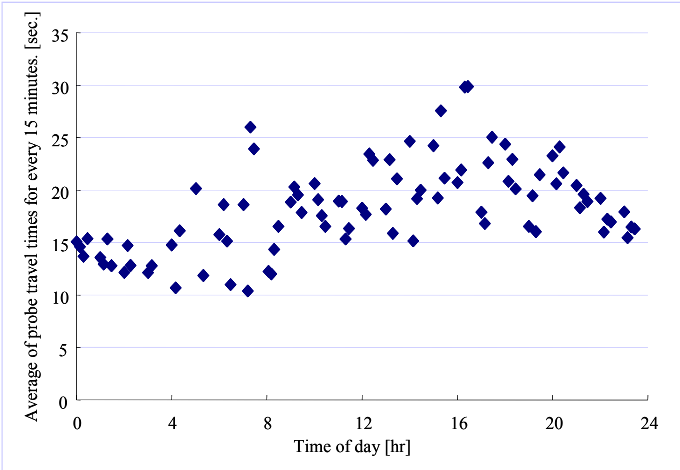

Figure 3: Timetable of expected travel times for a non-VICS link.

3. PRACTICE OF DATA FUSION USING REAL VICS AND PROBE DATA

In order to demonstrate the effect of data fusion, two sample path as shown in Figure 4, which start from Nagoya-city and goal to Ichinomiya-IC, is selected. The distance from start to goal is approximately 13 km. VICS link travel time is provided to the section of 2.4 km along Path-1, while no VICS link travel time is provided to Path-2.

Figure 4: Sample path to demonstrate the effect of data fusion.

Figure 5 compares the travel times of the two paths for every 15 minutes on a certain day. The left picture shows the travel times using only VICS information. As we assume constant travel times for non-VICS links and VICS links without information, the travel times of Path-2 are always the same. Although the change in the travel time of Path-1 is moderate, the graph says Path-1 always faster than Path-2.

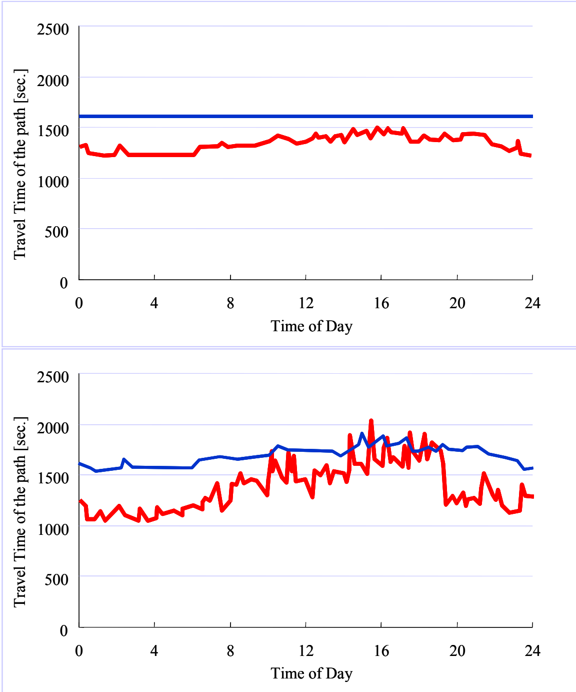

Figure 5: Comparison of path travel times (left: only VICS data, right: data fusion)

On the other hand, the right picture shows the travel times calculated by the data fusion method proposed in this paper. The changes in the travel times now become more conspicuous than the left picture. The difference of travel times between Path-1 and Path-2 gets larger during the off-peak, and are almost equal to each other at the peak period. The result of data fusion seems to be more realistic than the result with only VICS data.

4. CONCLUSION

In this paper, we described the concepts and the processes of data fusion with VICS and probe link travel time data. Imagine a driver who provided the path travel times based on the left graph in Figure 5 at peak period, he/she will tend to choose Path-1 that looks faster than Path-2. However, provided the data fusion travel times in the peak period, he/she may aware both Path-1 and Path-2 are congested as much as each other, and the result of path choice behavior will never be the same as the previous case. Indeed, let us conclude that the data fusion can reduce the uncertainty of travel times and increase the reliability of the network.

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DYNAMIC REVENUE MANAGEMENT OF TOLL ROAD PROJECTS UNDER TRANSPORTATION DEMAND UNCERTAINTY

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1. INTRODUCTION

In the present study, we propose a prototype framework for quantitative analyses of dynamic revenue management of toll road projects, taking into account the stochastic dynamics of transportation demand. In our framework, the toll is switched between several discrete levels depending on the observed transportation demand at each moment. More precisely, the toll is increased when the transportation demand exceeds a certain threshold and is decreased when the demand falls below another threshold. With this feedback fare control, the manager of the toll road is able to maximize the expected net present value of the revenues from the project. Thus far, few studies have examined the development of a quantitative method for such dynamic revenue management, despite its importance with respect to the financial reliability of transportation network systems.

The present paper is organized as follows: In Section 2, we first formulate the dynamic revenue management problem as a stochastic impulse control problem. We then decompose the problem into a series of *generalized linear complementarity problems* (GLCP). In Section 3, we reveal that the GLCP reduces to a standard LCP by using certain function transformation techniques. This enables us to develop an efficient algorithm for solving the problem in a successive manner, exploiting the recent advances in linear complementarity theory. Finally, in Section 4, several numerical examples are shown.

2. MODEL

2.1. FORMULATION

In the present study, we consider a manager who operates a toll road project for a certain period [0, *T*]. At each moment of time *t*, the manager is assumed to select the toll mode *m(t)* from two alternatives, either a higher toll mode *m(t)=H* or a lower toll mode *m(t)=L*. The toll at *t* is $E(t)= E_H$ when the higher toll mode is chosen and $E(t)= E_L$ when the lower toll mode is chosen. Here, *E(t)* and E_L (E_H>E_L) are assumed to be given constants. In addition, we assume that the fixed cost I_L is required when switching from the higher toll to the lower toll, and the fixed cost I_H is required when switching from the lower toll to the higher toll.

The transportation demand (number of vehicles per unit of time) $q(t)$ is assumed to vary stochastically over time. The dynamics of the transportation demand are

$$dq(t) = \alpha(q, E(t))dt + \sigma(q)dW(t), \quad q(0) = q_0, \tag{1.}$$

where $dW(t)$ is the increment of a Wiener process and $\alpha : R_+ \times R_+ \to R$ and $\sigma : R_+ \to R_+$ are given functions. The first term on the right-hand side of (1.) represents the expected transportation demand growth, and the second term is its stochastic perturbation. We assume that $\partial\alpha/\partial E < 0$, that is, the expected demand growth rate per unit of time is a decreasing function of the toll. We denote this as $\alpha_m(q) \equiv \alpha(q, E_m)$ for simplicity. In addition, we assume $\alpha(0, E) \geq 0$ and $\sigma(0) = 0$, reflecting the fact that the transportation demand cannot be negative.

The manager decides the toll mode strategy $\{m(t) \mid t \in [0, T]\}$ so as to maximize the expected net present value of total revenues during the operation period $[0, T]$. The total revenues consist of the instantaneous profits $\{\pi(t) \mid t \in [0, T]\}$ and the switch costs $\{I_K \mid k \in K(0)\}$. The toll switches are indexed by $k = 1, 2, \cdots K$. We denote the time and cost of the kth toll switch by τ_k and I_k (which takes the value of I_H or I_L), respectively. This is formulated as the following stochastic impulse control problem.

$$\textbf{[P]} \qquad \max_{\{m(t)|t\in[0,T]\}} E\left[\int_0^T e^{-\rho t} \pi_{m(t)}\big(q(t)\big) dt - \sum_k e^{-\rho \tau_k} I_k \,\middle|\, q(0) = q_0, m(t) = m_0 \right],$$

where ρ is a discount rate (given constant).

2.2 OPTIMALITY CONDITION

We shall derive the optimality condition of the dynamic revenue management problem [P] using the dynamic programming principle. First, when the transportation demand $q(t) = q$ is observed and the toll mode $m(t) = m$ is chosen at time t, we define the value function of the problem [P] as follows:

$$V(t, q, m) \equiv \max_{\{m(s)|s\in[t,T]\}} E\left[\int_t^T e^{-\rho(s-t)} \pi_{m(s)}\big(q(s)\big) ds - \sum_k e^{-\rho(\tau_k - t)} I_k \,\middle|\, q(t) = q, m(t) = m \right] \quad (2.)$$

The value function represents the expected net present value (evaluated at time t) of total revenues during a period $[t, T]$ under the optimal strategy $\{m(s) \mid s \in [t, T]\}$. For simplicity, we use the notation $V_m(t, P) \equiv V(t, P, m)$.

Suppose that the transportation demand $q(t) = q$ is observed and the higher toll mode H is chosen at time t. In this situation, the manager can either continue to use the current higher toll for at least an infinitesimal time or switch to the lower toll mode L. If the higher toll mode is kept until time Δ, the value function must satisfy the following:

$$\begin{aligned} V_H(t, q) \geq \mathrm{E}\Bigg[\int_t^\Delta e^{-\rho(s-t)} \pi_H\big(P(s)\big) ds + e^{-\rho(\Delta - t)} \max_{\{\mathrm{m(s)|s\in[\Delta,T]}\}} E\bigg[\int_\Delta^T e^{-\rho(s-\Delta)} \pi_{m(s)}\big(q(s)\big) ds \\ - \sum_k e^{-\rho(\tau_k - \Delta)} I_k \,\bigg|\, q(\Delta) = q + dq(t), m(\Delta) = H \bigg] \,\Bigg|\, q(t) = q, m(t) = H \Bigg] \end{aligned} \quad . \quad (3.)$$

The first term on the right-hand side of the inequality is the profit obtained by maintaining the current toll mode for $[t, \Delta]$, whereas the second term is the expected total revenues from Δ to T, in which the strategy $\{m(s)\}$ is optimal for the problem starting from Δ. From the definition of the value function, equation (3.) reduces to the following recursive inequality.

$$V_H(t,q) \geq \mathrm{E}\left[\int_t^{\Delta} e^{-\rho(s-t)} \pi_H\big(q(s)\big) ds + e^{-\rho(\Delta - t)} \left\{ V_H(t,q) + dV_H(t) \right\} \middle| q(t) = q, m(t) = H \right]. \quad (4.)$$

Taking $\Delta \to t$ and using Ito's lemma, we obtain the following equation:

$$F_H\big(\mathbf{V}(t,q)\big) \equiv -\pi_H(q) - L_H V_H(t,q) \geq 0\,, \quad (5.)$$

where $\mathbf{V}(t,q) \equiv \{V_H(t,q), V_L(t,q)\}$ and L_m is a partial differential operator defined by

$$L_m V_m(t,q) \equiv \frac{\partial V_m(t,q)}{\partial t} + \alpha_m(q)\frac{\partial V_m(t,q)}{\partial q} + \frac{1}{2}\sigma(q)^2 \frac{\partial^2 V_m(t,q)}{\partial q^2} - \rho V_m(t,q),\ m = H, L. \quad (6.)$$

When switching to the lower toll, $V_H(t,q) \geq V_L(t,q) - I_L$ holds, or equivalently,

$$G_H\big(\mathbf{V}(t,q)\big) \equiv V_H(t,q) - V_L(t,q) + I_L \geq 0\,. \quad (7.)$$

Since only one of the two actions should be optimal, either equation (5.) or equation (7.) holds, and we have

$$F_H\big(\mathbf{V}(t,q)\big)\cdot G_H\big(\mathbf{V}(t,q)\big) = 0,\quad F_H\big(\mathbf{V}(t,q)\big) \geq 0,\ G_H\big(\mathbf{V}(t,q)\big) \geq 0\,. \quad (8.)$$

Similarly, the optimality condition for switching from the lower toll to the higher toll is

$$F_L\big(\mathbf{V}(t,q)\big)\cdot G_L\big(\mathbf{V}(t,q)\big) = 0,\quad F_L\big(\mathbf{V}(t,q)\big) \geq 0,\ G_L\big(\mathbf{V}(t,q)\big) \geq 0\,. \quad (9.)$$

At each point in time t, the conditions in equations (8.) and (9.) should be satisfied simultaneously for any $q(t) \in R_+$. We see that the optimality condition for t reduces to the following infinite-dimensional GLCP.

[GLCP(t)] Find $\{\mathbf{V}(t,q) \mid q \in R_+\}$ such that

$$\begin{cases} F_H\big(\mathbf{V}(t,q)\big)\cdot G_H\big(\mathbf{V}(t,q)\big) = 0, & F_H\big(\mathbf{V}(t,q)\big) \geq 0,\ G_H\big(\mathbf{V}(t,q)\big) \geq 0 \\ F_L\big(\mathbf{V}(t,q)\big)\cdot G_L\big(\mathbf{V}(t,q)\big) = 0, & F_L\big(\mathbf{V}(t,q)\big) \geq 0,\ G_L\big(\mathbf{V}(t,q)\big) \geq 0 \end{cases} \quad \forall q \in R_+,$$

with the following terminal conditions at T,

$$V_H\big(T, q(T)\big) = V_L\big(T, q(T)\big) = 0, \forall q(T) \in R_+\,. \quad (10.)$$

3. REDUCTION TO A LINEAR COMPLEMENTARITY PROBLEM

3.1. DISCRETIZATION

Since [GLCP(t)] cannot be solved analytically, the solution of the dynamic revenue management problem [P] should be obtained numerically. Therefore, we first reformulate [GLCP(t)] in a discrete framework. First, we suppose a sufficiently large subspace $[q_{\min}, q_{\max}]$ in the state (transportation demand) space R_+. We then consider a discrete grid in the time-state space $[q_{\min}, q_{\max}] \times [0, T]$ with increments Δt and Δq. We denote each point of the grid by $(t^i, q^j) \equiv (i\Delta t, j\Delta q + q_{\min})$, where the indices $i = 0,1,\cdots I$ and $j = 0,1,\cdots,J,J+1$ characterize the locations of the point with respect to time and state, respectively. We also denote the value function $V_m(t,q)$ and the instantaneous profit $\pi_m(q)$ at a grid point (t^i, q^j) by $V_m^{i,j}$ and π_m^j, respectively.

In this framework, the differential operator L_m can be approximated by an appropriate finite-difference scheme (e.g. Crank-Nicholson) as follows:

$$L_m V_m(t^i, q) \approx \mathbf{L}_m \mathbf{V}_m^i + \mathbf{M}_m \mathbf{V}_m^{i+1},$$

where $\mathbf{V}_m^i \equiv [V_m^{i,1} \cdots V_m^{i,J}]^{\mathrm{T}}$ is a J-dimensional column vector of which the elements are the values of toll m at time t^i, and $\mathbf{L}_m$ and $\mathbf{M}_m$ are $J \times J$ square matrixes determined by the transportation demand process (1.). Then, the subproblem [GLCP(t^i)] can be given as

[GLCP^i] Find $\mathbf{V}^i \equiv \{\mathbf{V}_H^i, \mathbf{V}_L^i\}$ such that

$$\mathbf{F}(\mathbf{V}^i) \cdot \mathbf{G}(\mathbf{V}^i) = 0, \qquad \mathbf{F}(\mathbf{V}^i) \geq \mathbf{0},\ \mathbf{G}(\mathbf{V}^i) \geq \mathbf{0}$$

where $\mathbf{F}$ and $\mathbf{G}$ are linear functions of $\mathbf{V}^i$ defined by

$$\mathbf{F}(\mathbf{V}^i) \equiv \begin{bmatrix} -\mathbf{L}_H \mathbf{V}_H^i - \mathbf{M}_H \mathbf{V}_H^{i+1} - \boldsymbol{\pi}_H \\ -\mathbf{L}_L \mathbf{V}_L^i - \mathbf{M}_L \mathbf{V}_L^{i+1} - \boldsymbol{\pi}_L \end{bmatrix}, \ \mathbf{G}(\mathbf{V}^i) \equiv \begin{bmatrix} \mathbf{V}_H^i - \mathbf{V}_L^i + \mathbf{1} I_L \\ \mathbf{V}_L^i - \mathbf{V}_H^i + \mathbf{1} I_H \end{bmatrix}.$$

Here, $\mathbf{1}$ is a J-dimensional column vector of ones. Similarly, we can rewrite the terminal condition given by equation (10.) at time $t^I = T$ as

$$\mathbf{V}_L^I = \mathbf{V}_M^I = \mathbf{0}. \tag{11.}$$

Note that the subproblem [GLCP^i] is independent from other subproblems [GLCP^j] $(\forall j \neq i)$ when $\mathbf{V}^{i+1} \equiv \{\mathbf{V}_H^{i+1}, \mathbf{V}_L^{i+1}\}$ is known. This characteristic reveals that the series of subproblems $\{[\mathrm{GLCP}^i] \mid i = 0,1,\cdots I\}$ can be solved in a successive manner as follows: i) using the terminal condition $\mathbf{V}_H^I = \mathbf{V}_M^I = \mathbf{0}$, solve the subproblem [GLCP^{I-1}] and obtain the solution $\mathbf{V}^{I-1}$; ii) using $\mathbf{V}^{I-1}$ as a given constant solve the subproblem [GLCP^{I-2}] and obtain $\mathbf{V}^{I-2}$; and iii) repeating the procedure recursively, obtain the total value function $\{\mathbf{V}^i \mid i = 0,1,\cdots,I\}$. Thus, we should focus on methods by which to solve each subproblem [GLCP^i] individually, rather than all at once.

3.2. REDUCTION TO STANDARD LINEAR COMPLEMENTARITY PROBLEM

The subproblem [GLCP^i] is still difficult to solve, even numerically, because the problem is not in standard form. Therefore, this section shows that the subproblem [GLCP^i] reduces to a standard LCP by using certain variable transformation techniques.

Suppose that the value functions $\mathbf{V}_H^{i+1}$ and $\mathbf{V}_L^{i+1}$ are known when we solve [GLCP^i], and consider the following variable transformation.

$$\mathbf{X}_m^i \equiv -\mathbf{L}_m \mathbf{V}_m^i - \mathbf{g}_m^i, \qquad \forall m \in \{H, L\},\ \forall i \in \{0,1,\cdots I-1\}, \tag{12.}$$

where $\mathbf{g}_m^i \equiv \mathbf{M}_m \mathbf{V}_m^{i+1} + \boldsymbol{\pi}_m$ is a given constant. Assuming the matrix $\mathbf{L}_m$ is nondegenerated, we can represent the value function $\mathbf{V}_m^i$ as a linear function of $\mathbf{X}_m^i$, that is,

$$\mathbf{V}_m^i = \mathbf{V}_m^i(\mathbf{X}_m^i) \equiv -\mathbf{L}_m^{-1} \mathbf{X}_m^i - \mathbf{h}_m^i, \qquad \forall m \in \{H, L\},\ \forall i \in \{0,1,\cdots,I-1\}, \tag{13.}$$

where $\mathbf{h}_m^i \equiv -\mathbf{L}_m^{-1}\mathbf{g}_m^i$ is a given constant.

Substituting equations (12.) and (13.) into [GLCP^i], we obtain the following standard LCP, the only unknown variables of which are $\mathbf{X}_H^i$ and $\mathbf{X}_L^i$.

[LCP^i] Find $\mathbf{X}^i$ such that

$$\mathbf{X}^i \cdot \mathbf{H}^i(\mathbf{X}^i) \equiv 0, \qquad \mathbf{X}^i \geq \mathbf{0},\ \mathbf{G}^i(\mathbf{X}^i) \geq \mathbf{0},$$

where $\mathbf{X}^i \equiv \begin{bmatrix} \mathbf{X}_H^i \\ \mathbf{X}_L^i \end{bmatrix}$, $\mathbf{H}^i(\mathbf{X}^i) \equiv \begin{bmatrix} -\mathbf{L}_H^{-1} & \mathbf{L}_L^{-1} \\ \mathbf{L}_H^{-1} & -\mathbf{L}_L^{-1} \end{bmatrix}\begin{bmatrix} \mathbf{X}_H^i \\ \mathbf{X}_L^i \end{bmatrix} + \begin{bmatrix} -\mathbf{h}_H^i + \mathbf{h}_L^i + \mathbf{1}I_L \\ -\mathbf{h}_L^i + \mathbf{h}_H^i + \mathbf{1}I_H \end{bmatrix}$.

Since [LCP^i] is in standard form, we can develop an efficient algorithm for solving the problem exploiting the recent advances in the linear complementarity theory (see Ferris and Pang (1997)). If the solution of [LCP^i], $\mathbf{X}^i$, is obtained, we can easily calculate the original unknown variable (i.e. the solution of the subproblem [GLCP^i]), $\mathbf{V}^i$, via reverse variable transformation, as shown in equation (13.). We can now summarize the algorithm for solving dynamic revenue management [P] as follows:

Step 0 Set $\mathbf{V}_H^I = \mathbf{V}_L^I = \mathbf{0}$ and $i := I - 1$.

Step 1 If $i < 0$, then STOP.

Step 2 Obtain $\mathbf{X}^i$ as the solution of [LCP^i] by regarding $\mathbf{V}^{i+1}$ as a given constant.

Step 3 Calculate $\mathbf{V}^i$ via reverse variable transformation (equation (13.)).

Step 4 Set $i := i - 1$ and return to **Step 1**.

4. NUMERICAL SOLUTION

In this section, we report numerical results as illustrative examples. We first specify the transportation demand process as a mean-reverting process as

$$dq(t) = \mu\{\overline{q}_m - q(t)\}dt + \sigma q(t)dW(t), m = H, L$$

The first term on the right-hand side of the equation indicates that the transportation demand reverts to certain long-term mean levels $\overline{q}_H$ and $\overline{q}_L$ corresponding to the toll modes *H* and *L*, respectively. The second term represents the random fluctuations of the demand. The parameters, the speed of the reversion μ, the long-term mean demands $\overline{q}_H$ and $\overline{q}_L$, and the volatility of the transportation demand σ are given.

The parameters are set as T=20, μ=0.2, σ=20%, ρ=10% and $\overline{q}_H$=0, $\overline{q}_L$=1, E_H=1.5, E_L=1, I_H=1 and I_L=2, the dynamic revenue management problem [P] is then solved. Figure 1 plots the value functions for each toll mode V_L and V_H at time $t=0$ as functions of the initial transportation demand q_0. In this figure, $\hat{\overline{q}}_H(t)$ and $\hat{\overline{q}}_L(t)$ are the critical transportation demands for switching the toll mode. More precisely, when the higher toll mode $m(t)=H$ is chosen and the transportation demand $q(t)$ falls below $\hat{\overline{q}}_L(t)$, the toll mode is switched to the lower toll mode. In contrast, if the lower toll mode $m(t)=L$ is chosen and $q(t)$ exceeds $\hat{\overline{q}}_L(t)$, then the toll mode shall be switched to the higher toll mode. Note that when $q(t)$ remains between these thresholds (i.e. $q(t) \in (\hat{\overline{q}}_H, \hat{\overline{q}}_L)$), the current mode is maintained.

The evolution of the two thresholds $\hat{\hat{q}}_H$ and $\hat{\hat{q}}_L$ is shown in Figure 2. Observe that both thresholds decrease with time because, as time passes, the manager prefers to yield instantaneous profits by choosing the higher toll mode, rather than to growth the transportation demand by choosing the lower toll mode. This is due to a time lag between mode changes and their effect on transportation demand.

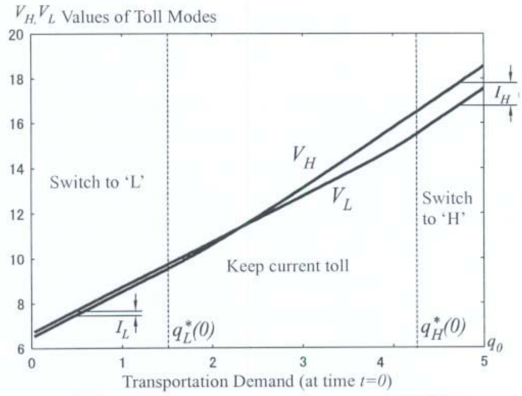

FIGURE 1. VALUE FUNCTION

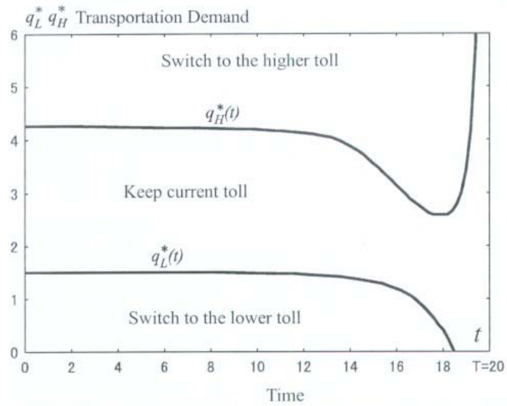

FIGURE 2. OPTIMAL SWITCHING RULE

5. CONCLUSION

We proposed a prototype framework for quantitative analysis of dynamic revenue management of a toll road project involving transportation demand risk. We first formulated a dynamic revenue management problem as a stochastic impulse control problem, the optimality condition of which is written as a generalized linear complementarity problem (GLCP). Further analysis revealed that the GLCP reduces to a standard LCP via certain variable transformation techniques in a discrete framework. Finally, we developed an efficient algorithm, exploiting recent advances in linear complementarity theory.

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INTRODUCTION OF DIVERSION SYSTEM TO TRAFFIC MANAGEMENT FOR ACCIDENTS ON URBAN EXPRESSWAY

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1. INTRODUCTION

The serious traffic congestion is often caused by the accident on urban expressway. The incidence time and place of traffic accident can not be expected. Therefore, the traffic management would be required to restore the smooth traffic as soon as possible.
The outflow control as traffic management on urban expressway is adopted for the recovery of traffic condition. However, the double entering fares are charged according to the uniform toll system. It would be recommended that this situation is avoided in terms of rationality for user spending cost. If the detour routes can be provided for the users driving through the congested links caused by traffic accident, traffic condition can be improved.

The diversion system can be defined as a discount charge management to produce the detour traffic on uniform toll expressways. The exceptional treatment for this inevitable double charge has been regulated to be the same as a single charge in urban expressway. The study aims at proposing the application of diversion system to be a sort of emergency traffic management with particular information provision.

The term of the application of diversion system on the traffic management in emergency should be very shortest periods. The rapid change of traffic condition would be observed in emergency. Therefore, it is necessary to develop the traffic simulator for estimation of change of traffic flow with diversion system implement.

In the study, the effects of the diversion system implementation for accident can be evaluated with the traffic simulator. The calculation process with the traffic simulator is proposed for the estimation of traffic flow with diversion system implementation. The estimation step of diversion traffic volume with the hourly traffic assignment is introduced to the traffic simulation system. The traffic condition on urban expressway is estimated in detail with traffic flow simulator. The traffic condition on street is estimated with hourly traffic assignment. Interaction of traffic flow simulator and traffic assignment is coordinated with the route choice model for individual vehicles. In particular, the route choice behaviour with the impact of information provision in emergency is described and is included to the traffic estimation process.

2. DIVERSION SYSTEM FOR ACCIDENT ON URBAN EXPRESWAY

2.1. TRAFFIC ACCIDENTS ON URBAN EXPRESSWAY

The number of traffic accidents on urban expressway is counted as about 4,907 events per year. Percentage of congestion occuerence caused by accident is 8.9% on the whole. The number of accident on the loop road is quator of the whole and higher than on any other route.

Over than 100 accidents occuer on the three sections in figure 1. These sections are located between junctions. Many number of lane changes by vehicle can be observed in these sections. The highest number of accidents in a section on the loop road is 146 accidents of the section 1. On the other hand, the hourly distribution of accident occurrence is corelated with the distribution of traffic volume. In particular, the number of accident is high at the peak hour in the morning and evening. Accident occuerence on the weaving section at the peak time is analized mainly in this study.

2.2. TRAFFIC MANAGEMENT FOR ACCIDENTS ON URBAN EXPRESSWAY

Traffic management support to respond rapidly to accidents and breakdowns and restore normal traffic flow. when an accident or vehicle breakdown occurs, the nearest patrol car can rush to the site and some lanes are restricted by traffic control center. 598 restrictions are implemented as traffic management for accident. One lane restriction is counted as 96.2% on the whole of restriction. Multi lane restriction is implemented rarely. Restriction time for 86.1% of accident is observed less than one hour. Most of restriction can be finished within less than two hour. Average of restriction time is 40 minutes. One lane restriction for accident within less than one hour is analized mainly in this study.

2.3. DIVERSION SYSTEM FOR TRAFFIC ACCIDENTS

The double entering fares are charged according to the uniform toll system. It would be recommended that this situation is avoided in terms of fairness for user spending cost. In the real system such as Hanshin expressway, the exceptional treatment for this inevitable double charge has been regulated to be the same as a single charge. The expressway network represents the loop road and some other radius routes as a part of Urban Expressway networks in Figure 1. There are 60 on-ramps and 58 off-ramps indicated as connected links between streets and expressway.

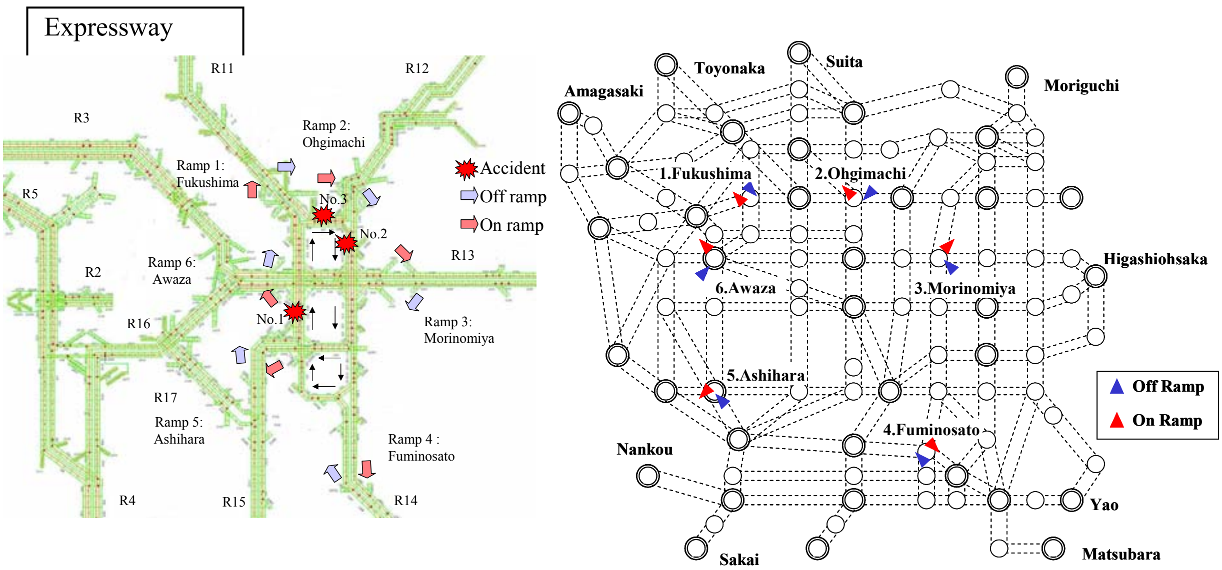

Figure 1: Urban Network

On the other hand, the sufface roads network might cover the OD traffic generated at 27 zones in central Osaka and 9 zones in surrounding area. The descriptive network consists of 99 nodes and 354 links for the streets. All on-ramps and off-ramps are corresponding to the node on the street.

The diversion system proposed here would encourage the users on the expressway change routes, so as to reduce the traffic volume on the congested sections. Many possible routes can be found for implementation of the diversion system. 6 off-ramps and 6 on-ramps near the loop road are set up as the implementation of the diversion system. These ramps are indecated in figure 1. 30 ramp pairs can be implementated with combination of these ramps. When the accident is happned on the loop road, 6 on-ramps are simultaneously implementated for 2 hours since the accident occarence as the ramp for the diversion system.

3. TRAFFIC FLOW ESTIMATION WITH DIVERSION SYSTEM IMPLEMENTATION

3.1. STRUCTURE OF ESTIMATION SYSTEM

The calculation process with the traffic simulator is proposed for the estimation of traffic flow with diversion system implementation. The estimation step of diversion traffic volume with the hourly traffic assignment is introduced to the traffic simulation system. The interaction between traffic assignment and traffic simulator should be mentioned in the estimation process of Figure 2.

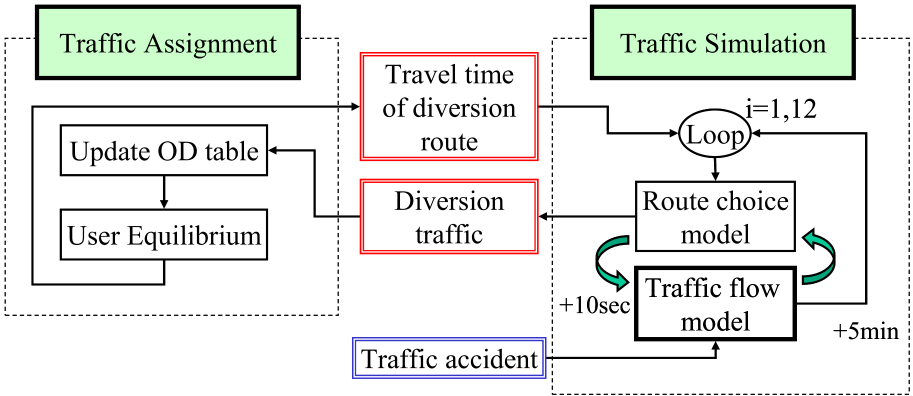

Figure 2: Outline of Diversion Traffic Estimation System

3.2. HOURLY TRAFFIC ASSINMENT

The inflow traffic volume and the diversion traffic volume are determined with hourly traffic assignment. The probability of diversion route choice for traffic simulator is determined with the diversion traffic volume at the each pair of off and on ramp. On the other hand, the traffic congestion of the each section can be summarized with traffic simulator by every five minutes. The travel time of the route on urban expressway between pairs of on and off ramp is estimated simultaneously. Remain traffic volume to the next time band is updated by OD travel time. Estimation process of traffic flow is descried with interface between traffic simulation and hourly traffic assignment.

3.3. TRAFFIC SIMULATION

The base model of traffic simulator is constructed in the related studies. The traffic flow theory is applied in the model to estimate traffic flow with microscopic point of view. Each route of the expressway is formulated as a sequence of the 250m sections. The traffic condition for each section is estimated with the traffic density by every 10 seconds. The traffic flow can be estimated from the upstream to downstream by section.

Traffic congestion on expressway can be estimated with the traffic simulator. The evaluation of the diversion system can be performed though the iteration between traffic assignment and traffic simulation.

3.4. ROUTE CHOICE MODEL

The decision process of choice with the original route on expressway and the diversion route on the street should be mentioned. The route choice process of individual vehicles is descried in Figure 3.

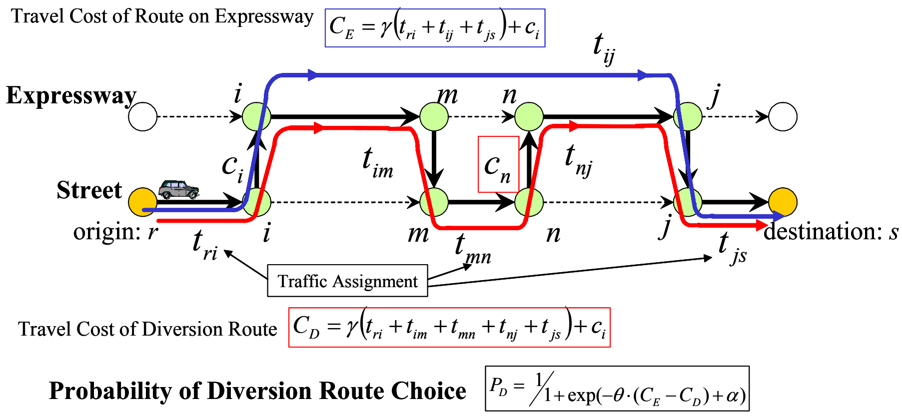

Figure 3: Route Choice Process of Individual Vehicles

Two indicator values C_E, C_D as travel cost of route are defined for compare of routes. One part of travel time is estimated with traffic simulator and another part of travel time is estimated with traffic assignment. The probability P_D in choice of diversion route is formulated. The diversion traffic volume is estimated as the result of decision of individual vehicles. The concrete diversion routes are determined with the traffic assignment.

4. EFFECT ANALISYS OF THE DIVERSION SYSTEM IMPLEMENTATION WITH USING TRAFFIC SIMULATOR

4.1 ALLOCATION OF THE DIVERSION SYSTEM IMPLEMENTATION FOR TRAFFIC ACCIDENT

The traffic flow change has been estimated for each individual diversion between off-ramp and on-ramp previously. In terms of influence to overall network, the change of total travel time should be measured as an effect of diversion system implementation. Table 1 summarizes the increment of total travel time with implement of diversion system for each ramp pair.

No.		Diversion Traffic (veh)	Probability of Diversion	Increment of Total Travel Time (A) Expressway	(B) Street	(A)+(B)
	Without Diversion System	0	0%	4,488	47,373	51,861
	Off Ramp					
1	R11 Fukushima	4,538	46%	△ 399	96	△ 303
2	R12 Ohgimachi	4,006	28%	△ 84	105	21
3	R13 Morinomiya	4,493	26%	△ 250	126	△ 124
4	R14 Fuminosato	3,077	21%	△ 133	147	14
5	R15 Ashihara	2,873	22%	△ 385	72	△ 312

Table 1: Total Travel Time with Diversion System Implementation in Emergence

The most effective implementation can be pointed out from Table 1 as the off ramp of R15 Ashihara. Even though the total travel time for streets increases a little, the reduction of total travel time for the expressway is quite large. It seems to reflect on the reduction of congestion on the loop road.

It means that the diversion system is effective for the user of expressway. However, the diversion system implementation cannot always produce the smooth traffic on the expressway as well as street. Similarly, the total travel time for the overall network is not reduced in some cases. It may be true that the diversion system provides on efficient way to manage the traffic on the urban networks in the sense of social travel cost with proper selection of off-ramp and on-ramp.

The cases as limitation of on-ramp for diversion is estimated for compairing with 6 on-ramps combnation cases. Total travel time with limitation of on-ramp for the diversion system implementation is shown in Table 2.

No.	Off Ramp	On Ramp	Diversion Traffic (veh)	Probability of Diversion	Increment of Total Travel Time (A) Expressway	(B) Street	(A)+(B)
	Without Diversion System		0	0%	4,488	47,373	51,861
1	R11 Fukushima	R16 Awaza	1,246	58%	△ 370	11	△ 359
2	R12 Ohgimachi	R11 Fukushima	0	0%	0	0	0
3	R13 Morinomiya	R11 Fukushima	760	50%	△ 278	16	△ 262
4	R14 Fuminosato	R11 Fukushima	1,194	55%	△ 344	49	△ 295
5	R15 Ashihara	R11 Fukushima	1,664	54%	△ 2	26	24

Table 2: Total Travel Time with Limitation of on-ramp for Diversion

The diversion system may more efficiently work with carefully select of ramp pair to responding for the location of accident occurrence.

4.2. INFLUENCE OF THE DIVERSION SYSTEM IMPLEMENTATION

The effect of diversion system implementation would be observed in the comparison of traffic congestion shown in Figure 5. The congested sections are clearly reduced relating with the diversion route between R15 Ashihara and 6 on-ramps. Since the heavy congestion is observed originally, the reduction might be measured by large scale particularly on the loop road.

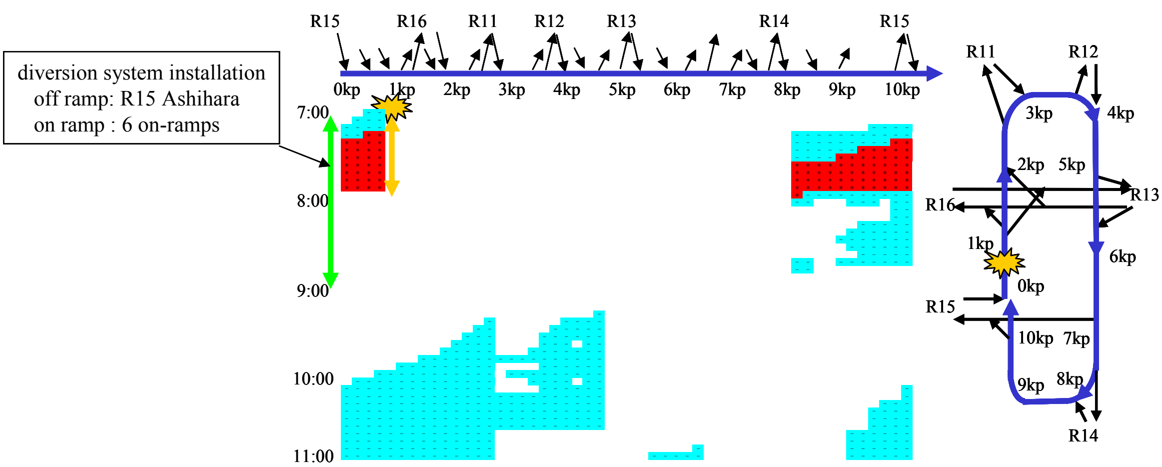

Figure 4: States of Traffic Condition between 7:00 and 11:00

It is known from the observation that the diversion system may provide the reduction of congestion for the loop road as traffic concentrated area. The travel time on street between pair of ramps with diversion system implementation can be discussed. The average of travel time of vehicles is compared with the case of no diversion system and the case of implementation from R15 Ashihara off-ramp to R11 Fukushima on-ramp in Figure 5.

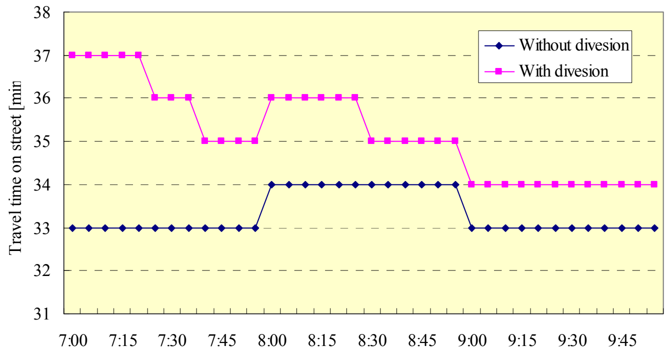

Figure 5: Change of Travel Time on Diversion Route between 7:00 and 10:00

It can be mentioned that the diverson system works efficiently. The influence to travel time on street is not so much as about within 5 minutes of late arrival.

5. CONCLUDING REMARKS

It would be concluded that the implementation of the diversion system to traffic management for accident can provide the efficient traffic as a practical traffic management method in emergency. The efficient traffic is provided with the diversion system implementation to the ramp pairs as detour route for avoid of passing through the congested sections caused by traffic accident. Otherwise, the information provision for route guidance relating with diversion traffic would be considered in terms of practical installation of the system. The earlier recover of traffic condition is provided with the information about the travel time of the detour route on the street. The reliability of the urban road network would be improved with diversion system implementation in emergency condition.

ACKNOWLEDGMENTS

The authors record here warmest acknowledgment to members of the investigation committee of traffic congestion in Hanshin Expressway for discussing the practical problems of the diversion system as advanced traffic management in the real networks.

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REGIONAL ACCESSIBILITY ANALYSIS FROM A VULNERABILITY PERSPECTIVE

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1. INTRODUCTION

1.1. BACKGROUND

In the Swedish national transport policy, accessibility is one of six goals that need to be reached in order to obtain a long term sustainable transport system. Accessibility is continually monitored by the Swedish National Road Administration (SNRA) through a number of indicators, for instance travel time by car to four different regional functions/services: commercial center, airport, railway station and emergency hospital. Another function to be fulfilled by the transport system is to ensure that people kan get to work, which can be expressed as the number of job opportunities that can be reached within eg 45 minutes by car. These overall measures give a reasonably good picture of the situation during normal conditions, but actually say nothing of the efficiency of the system in case something unexpected should occur. Also, a long term sustainable transport system should not be based on the car as the main mode for transport. Instead, public transport should be emphasised and developed in a direction that makes it a satisfactory alternative also in travel relations that are today executed mainly by car. Furthermore, it is desirable to develop new/other relevant indicators in order to be able to describe and follow up accessibility from the perspectives of both citizens' and the commercial/business sector.

1.2 AIM

The present summary paper describes the scope and approach of a recently started research project in which the aim is twofold. First, the project will extend the accessibility monitoring so that public transport, as well as the car, alternatives are highlighted – for the private as well as public/business sectors. Second, it will develop a network based analysis method for systematically studying accessibility from a vulnerability perspective, i.e. how the accessibility is affected when especially part of the road network for some reason becomes completely/partly impossible to use. The analysis is performed by means of the Swedish national transport forecast model SAMPERS and a case study will be carried out for a selected road administration region.

The main parts of the project can be described in four steps:

- identifying relevant accessibility indicators
- investigating accessibility during normal conditions
- identifying links critical for the transport system function
- investigating accessibility in a number of "problem scenarios"

In the following, mainly the first point above is developed further by introducing a "new" accessibility measure. Also, the third point is discussed briefly in outlining an approach for identifying critical links and the subsequent analysis of effects on accessibility.

2. METHODS AND MODELS

Despite the fact that risk and vulnerability are important issues, they have not until fairly recently been the subject for more systematic research. Especially, reliability and vulnerability are so far not included in the cost-benefit analyses commonly used in e.g. investment planning processes. Uncertainty and unreliability has been put on the agenda lately (see e.g. Cohen & Southworth, 1999; Wardman, 2001; Noland & Polak, 2002; Eliasson, 2002) but the need for more knowledge is still great at all levels. One reason for this is that vulnerability is a complex issue, involving both theory and practice, cause and effect, producers as well as consumers of transport services – aspects that are difficult to tackle simultaneously! A recent PhD thesis therefore proposes that vulnerability can be regarded as an attitude – a way of thinking – rather than a quantitative measure in itself (Berdica, 2002).

This project aims at supplementing our knowledge with a more focused analysis of how vulnerability in the transport system affects the possibility for citizens as well as industry to reach vital regional community functions with different modes of transport. Planning for a long term sustainable transport system also means that accessibility to various services/activities should be satisfied by means of public transport. Hillman & Pool (1997) describe e.g. how accessibility to a sports field on the outskirts of London can be calculated using a GIS. Lovett et al. (2002) have in a similar manner concentrated on general practitioners services, while Carson et al. (1999) have used an emme/2-based public transport model to describe accessibility in Wycomb District, England. O'Sullivan et al. (2000) illustrate the same thing through travel time isochrones in a GIS environment.

The method proposed in this project is built on the latter, however with the extension of taking vulnerability aspects into account. The tool used is the emme/2-based forecast model SAMPERS, containing a lot of data on networks for different modes (car, bus, train), land use information (inhabitants, work places) etc., on a fine-meshed geographical level. This enables an analysis and description of accessibility to various regional functions in detail. It should be noted that the SAMPERS system, like most other existing forecast tools, assumes "perfect conditions", hence excluding vulnerability aspects. The latter should eventually be incorporated in the system specification/design. However, as a step on the way, the present project provides a method for sensitivity analyses within the existing framework.

3. MEASURING ACCESSIBILITY

3.1. COMMON ACCESSIBILITY MEASURES

The maybe most common type of accessibility measure is the one expressing so called *reachability*, e.g. "number of work places reachable by some mode within some timeframe". Measures of this type are burdened with a number of disadvantages:

1. It is sensitive to the timeframe so results may differ greatly depending on which interval is chosen.
2. It is insensitive to travel cost, as only travel time is included. If travel time is translated into generalised cost, the measure's advantage of "easy to explain" disappears.
3. It cannot be aggregated over neighbouring areas.

4. It has no unit or interpretation that makes it possible to translate into effects on e.g. housing market or productivity.
5. It is difficult, not to say impossible, to aggregate over modes. Either accessibility is described by "fastest"/best mode (almost always car!) or it is restricted to concerning only public transport.

Especially points 1 and 2 are serious drawbacks that may well make the measure downright misleading.

An accessibility measure often suggested from the direction of transport modelling is the *logsum*. It can be described as the weighted average value of the generalised cost for all modes to all destinations, where modes and destinations are weighted according to how attractive they are. The logsum is in many ways the perfect accessibility measure, its only actual drawback being that it is difficult to interpret. However, as it so happens, the accessibility measure proposed below in fact coincides exactly with the logsum – provided that the accessibility changes are not too large – as it is its first order Taylor approximation.

3.2. A "NEW" MEASURE FOR ACCESSIBILITY

How then should accessibility be measured? A sensible accessibility measures should mirror the time and money spent on travel when living in a certain area. However, this is often found to be insufficient. People in areas with high accessibility may well experience relatively speaking long travel times and high travel costs, simply because there is such a great supply to take part in! Travel becomes more "worth its price", so to speak, resulting in an increased "consumption" of travel.

This means that a reasonable measure should consist of a sum of three components:

- average travel time for an inhabitant in the area,
- average travel cost for an inhabitant in the area, and
- the worth of suppressed travel compared to a reference area.

Hence, let accessibility for area i consist of the above, namely average travel time $\bar{t}_i$, average travel cost $\bar{c}_i$, and suppressed travel $\bar{T}_i$ compared to a reference area (assumed to be indexed 1). The accessibility of area i, Ω_i, is then the sum of these, expressed as:

$$\Omega_i = \theta \bar{t}_i^0 + \bar{c}_i^0 + \bar{T}_i^0 \qquad \text{(Eq.1)}$$

where

$$\bar{t}_i^0 = \frac{\sum_{jm} T_{ijm}^0 t_{ijm}^0}{\sum_{jm} T_{ijm}^0} \qquad \text{(Eq.2)}$$

$$\bar{c}_i^0 = \frac{\sum_{jm} T_{ijm}^0 c_{ijm}^0}{\sum_{jm} T_{ijm}^0} \qquad \text{(Eq.3)}$$

$$\overline{T}_i^0 = \frac{1}{2}\sum_{jm}\left(\frac{T_{1jm}^0}{\sum_{jm} T_{1jm}^0} - \frac{T_{ijm}^0}{\sum_{jm} T_{ijm}^0}\right)\left(c_{ijm}^0 + c_{1jm}^0 + \theta t_{ijm}^0 + \theta t_{1jm}^0\right) \qquad \text{(Eq.4)}$$

using the following notation:

T^0_{ijm}	no of trips $i \rightarrow j$ with mode *m* (in scenario 0).
t^0_{ijm}	travel time $i \rightarrow j$ with mode *m* (in scenario 0)
c^0_{ijm}	travel cost $i \rightarrow j$ with mode *m* (in scenario 0)
θ	value of time

Accessibility to an area is hence larger, the lower the sum of these three components is. It should be noted that the worth of "more" or "less" travel must be calculated in relation to some reference. Also, the value of time is assumed to be constant for all types of trips in these formulas. If this is not the case, the measure should be calculated for each value of time category and then aggregated.

Some characteristics of this measure are listed below:

1. It is *quantitative* and expressed in precise (usually monetary but we could also use time) units that are easy to understand and possible to interpret.
2. It can be *summarised* over a number of areas, thus yielding average accessibility for a municipality or a region.
3. It is built on people's *actual travel behaviour*, which means that good data is needed from surveys or models. This also means that it is influenced by socioeconomic properties (for better or for worse!), mainly car ownership.
4. It can be calculated separately for *different modes*, and then summarised to yield total accessibility.
5. It describes "what is to be reached" starting from *type of errand* rather than type of destination, which enables us to give different types of e.g. shops different weights.

The calculation is based on the well-known welfare measure "rule-of-a-half", with the innovative element of introducing a reference area in order to make it possible to use the welfare measure to describe accessibility. It deserves mentioning that the measure is not chosen arbitrarily, but can be said to be the "correct" way of evaluating accessibility increase – albeit under the assumption that the demand curves for different travel relations and modes can be regarded as linear in the area studied.

If the question of interest is how accessibility *changes* due to some measure or alteration in circumstances, there is no longer any need for the so called reference. For calculating change in accessibility the formula must be altered a little, since the comparison is made to the same area in an original state instead:

Define

$$\overline{T}_i^1 = \frac{1}{2}\sum_{jm}\left(\frac{T_{ijm}^0}{\sum_{jm} T_{ijm}^0} - \frac{T_{ijm}^1}{\sum_{jm} T_{ijm}^1}\right)\left(c_{ijm}^1 + c_{ijm}^0 + \theta t_{ijm}^1 + \theta t_{ijm}^0\right) \qquad \text{(Eq.5)}$$

which gives the change in accessibility for area *i*, $\Delta\Omega_i$, between scenarios 1 and 0

$$\Delta\Omega_i = \theta\left(\bar{t}_i^0 - \bar{t}_i^1\right) + \left(\bar{c}_i^0 - \bar{c}_i^1\right) - \bar{T}_i^1 \qquad \text{(Eq.6)}$$

Using this definition, a positive number for $\Delta\Omega_i$ means an improvement (increase) in accessibility.

4. ACCESSIBILITY AND VULNERABILITY – FURTHER WORK

The overall hypothesis is that there are certain functions/services that citizens and industry need to and should be able to reach in a satisfactory manner regardless of the state of the transport system. In addition to commercial center, airport, railway station and emergency hospital that were mentioned earlier it could be of interest to include also schools, industrial plants, multimodal freight terminals etc. Accessibility is calculated during normal circumstances and the distribution of trips and/or volumes in the network give some idea of which links are the most "popular" and consequently central to travelling in the region. The next step is to use the so called "select link" function to see the origin/route/destination for the trips using each specific link, giving an idea of how "wide" an area would be "affected" if the link in question was not available. The connection to vulnerability at this stage is hence more concerned with the consequences part of the embedded risk concept, than with the probability for parts of the network to malfunction, although some such aspects will be taken into account when choosing which links to sever in the upcoming "reduced accessibility"-scenarios to be studied.

5. ENDNOTE

The measures presently used by the SNRA to describe and follow up on accessibility are indeed often of the less suitable "reachability" kind mentioned above. The "new" measure proposed is better from the perspective of being more readily applicable on various levels of aggregation, as well as being easier to use for interpretation of different effects. As the project as a whole is expected to result in more in depth knowledge of how interruptions in different parts of the transport system affect accessibility of both people and merchandise, using both private and public modes of transport, the exploration of using this "new" accessibility measure is an important step on the way. It is also compatible with a systematic method for analysis which can help in identifying where possible problems are likely to occur, and what the possibilities are for efficiently mitigating these effects.

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CRITICAL INFRASTRUCTURE AND TRANSPORT NETWORK VULNERABILITY: DEVELOPING A METHOD FOR DIAGNOSIS AND ASSESSMENT

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1. INTRODUCTION

Considerations of critical infrastructure are now a major concern in Australia as in many other countries. The concern stems from a variety of causes, including the state of development, condition and level of use of existing transport infrastructure; difficulties in public sector provision of new infrastructure; public-private partnership arrangement for infrastructure provision; and perceptions of risks and threats to infrastructure through malevolence such as acts of sabotage, war or terrorism. There are in fact many possible sources of degraded network performance, including natural events (e.g. floods, fires, earthquakes and blizzards); incidents (e.g. traffic crashes, special events, construction works and civil emergencies); malevolence; industrial disputes; day-to-day congestion; and interruptions to passenger and freight transport services due to breakdowns or commercial failure. These disruptions cause delays and detours with potentially severe social, economic and environmental consequences. Thus there is a need to develop methods to assess risk and vulnerability in transport networks. Decision support tools are needed that allow planners to make rational assessments of threats to facilities and infrastructure; the consequences of network degradation and failure at various locations and under different circumstances; and what to do about it. These concerns have led to research interest in *network vulnerability* (e.g. Berdica 2002, 2003, D'Este and Taylor 2001, 2003, Feng and Wang 2003, Feng and Wen 2003, Nicholson and Dalziell 2003, Taylor and D'Este 2003, 2004).

2. NETWORK VULNERABILITY

Whilst there is recognition of the need for vulnerability analysis of transport systems, there has been very little research explicitly directed at vulnerability. For a start, there is still no standard definition of vulnerability nor a theoretical basis on which to build. D'Este and Taylor (2003) suggested that the best starting point is probably the existing body of research into network reliability and risk assessment, and have offered working definitions of vulnerability (in terms of either network connectivity or accessibility to services and facilities). There are many important research issues: diagnosing transport system weaknesses, targeting detailed risk assessments, and formulating the best response (such as reducing the potential for network degradation from a given incident, reducing its likelihood, or reducing the consequences should the incident occur).

Our current working definition of vulnerability is to consider the connection between a particular origin and destination; or to access from a particular location to other parts of the network; or to the network as a whole. The following definition provides a starting point for applying the concept to network analysis and diagnosis: *a network node is vulnerable if loss (or substantial degradation) of a small number of links significantly diminishes the accessibility of the node, as measured by a standard index of* *accessibility.* Therefore vulnerability can be defined in terms of the overall quality of access from a given node to other parts of the network. In our earlier work (D'Este and Taylor 2001, 2003) a second definition, in terms of network connectivity and generalised cost of travel, was also proposed. The above definition encompasses the earlier one, as generalised cost may be used as a measure of the difficulty of access.

Berdica, Bergh and Carlsson (2003) provided a conceptual model for vulnerability studies relating to the road safety performance of rural highways. This model provides a useful basis for an overall systems approach to vulnerability analysis for transport networks. Figure 1 is a generalised version of the Berdica-Bergh-Carlsson model.

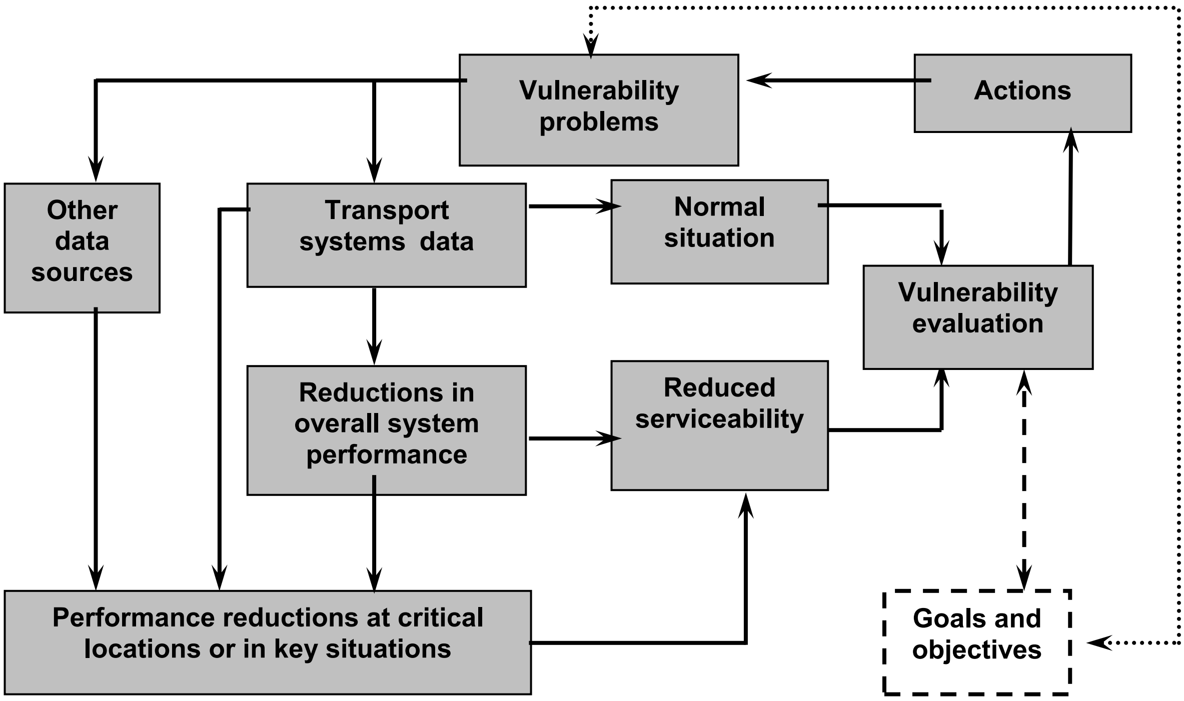
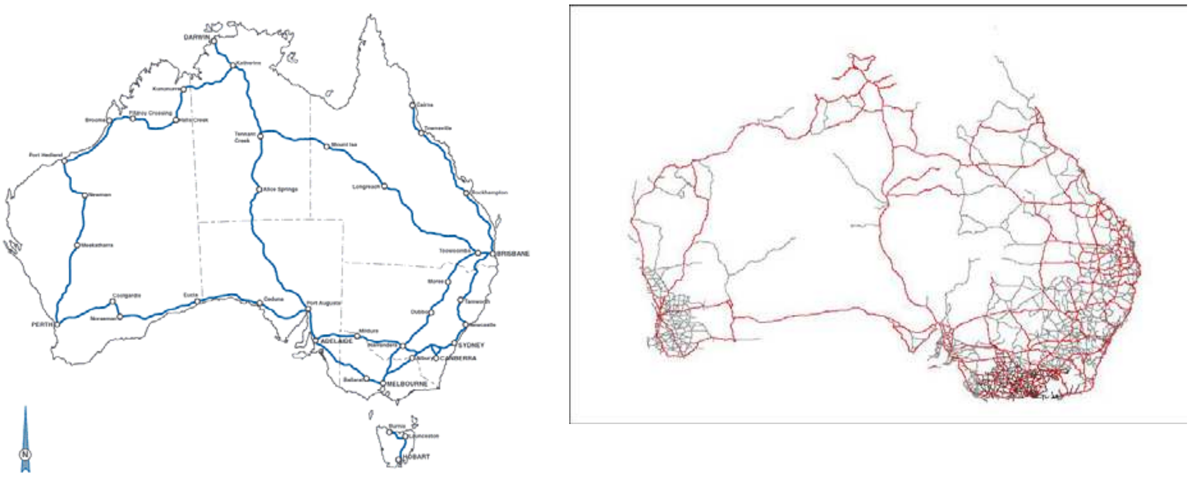


Figure 1: Conceptual model for vulnerability studies in transport networks (derived from that proposed by Berdica, Bergh and Carlsson (2003))

Thus states of vulnerability should be identified and assessed on the basis of variations in the performance of system components that fall outside the expected range of normal operations. Any (transport) system can experience variations in its performance under different travel demand and environmental conditions. The issue is when do those variations indicate performance outside an acceptable state and what are the risks associated with the unacceptable state. This approach may be applied at a variety of planning levels, including the strategic level that is the focus of our analytical work. Our current research seeks methods based on this systems approach, including analytical, interpretive and visualisation tools that will assist in identifying critical components of transport infrastructure and developing contingency plans to reduce risk and deal with the consequences of infrastructure degradation or failure. The method considers vulnerability assessment as in terms of a systems planning process in which the performance of network components is tested against established performance criteria. The risks and consequences associated with failures at different locations need to be accounted for. Suitable metrics to help interpret the extent and consequence of network failure or degradation are needed.

The Australian strategic road network is being used as the database for our current research. This network includes three levels of roads: (1) the designated National Highway System (NHS), (2) state highways and main roads, and (3) other main roads. The levels are distinguished on jurisdictional and administrative grounds – the NHS is the concern of the federal government, the other levels are the concern of state (and local) government. The NHS provides the basic skeleton of the national road transport system. Figure 2 provides maps showing the strategic road network and the NHS. The NHS is a subset of the full strategic network and apart from the more remote areas there are alternative paths through the rest of the road network for many trips.



(a) National Highway System (NHS) network

(b) Main roads and highways network (including NHS)

Figure 2: The Australian strategic road network, identifying the National Highway System (NHS) network

3. ANALYTICAL APPROACH

D'Este and Taylor (2003) and Taylor and D'Este (2004) discuss a method for vulnerability assessment based on probabilistic route choice models, while Taylor and D'Este (2003) presents an initial application of that method to the NHS. A more general approach may also be appropriate.

Consider a measure of vulnerability that is the change in generalised cost of travel between two locations if a given link fails, where the generalised cost is an appropriate measure of disutility of travel such as distance, time, money, etc. In other words, the loss of amenity from link failure. Let v_{ijrs} denote the change in generalised cost of travel from i to j if link e_{rs} fails. Then the loss of community amenity is $d_{ij} \,.\, v_{ijrs}$ where d_{ij} is the demand for movement from i to j and demand is a measure of the quantity of movement from i to j. It follows that the total loss of amenity from the failure of e_{rs} is

$$V_{rs} = \sum_i \sum_j d_{ij} . v_{ijrs}$$

The two measures, v_{ijrs} and V_{rs} provide local and global measures of the consequences of failure of link e_{rs}. Hence they are direct measures of the extent to which the operation of the transport system is vulnerability to failure of specific links. Note that similar definitions could be developed for node failures.

In more formal terms, the problem can be stated as follows. Consider a network $G(N,E)$ where N is a set of n nodes and E is a set of m directed links. Associated with each link is a non-negative attribute that measures the utility of the link according to a particular link characteristic, such as distance, time, money cost, reliability, or generalised cost. Let s[ij, $G(V,E)$] be the 'cost' of the least cost path from i to j then

$$v_{ijrs} = s[ij, G(N,E)] - s[ij, G(N,E- e_{rs})]$$

That is, the difference between the least cost path with the network intact and the least cost path without the link from r to s, e_{rs}. The task of calculating v_{ijrs} and V_{rs} can be readily achieved by 'brute force'. Consider the following approach.

STEP 0 Initialise the matrix of global vulnerability measures V_{rs} and construct the demand matrix d_{ij}

STEP 1 Use the Floyd-Warshall shortest path algorithm (Floyd 1962, Warshall 1962) to calculate a matrix of least costs $\boldsymbol{S}$. [Use the Floyd algorithm because it calculates least costs for all origin-destination pairs at once, but any other method would do.]

STEP 2 Break the link e_{rs} (set its cost to be infinite) then reapply the Floyd (or other) algorithm to give $\boldsymbol{S'}$, the matrix of costs for the degraded network

STEP 3 Calculate the loss of amenity $\boldsymbol{d}.(\boldsymbol{S} - \boldsymbol{S'})$ for all origin-destination pairs (v_{ijrs}) and then calculate V_{rs} by summing over i and j

STEP 4 Repeat from Step 2 for all other links.

The output is a matrix showing the loss of community amenity that would result from failure of any single specific link in the network. The method could also be adapted to looking at the effect of correlated failure of multiple links. It could provide a reasonably efficient way of calculating the local and global vulnerability measures. It requires applying the Floyd-Warshall algorithm (m+1) times and therefore it has time complexity something like $O(m\ n^3)$. For small/medium networks this approach should be satisfactory since the calculations are straightforward and quick on a fast computer. The approach would also lend itself to parallel processing because the effect of breaking different links can be calculated independently. However it should also be possible to exploit the inherent properties of the problem to devise more efficient algorithms. For a start, the global measure is easy to calculate given the OD-specific measure. Therefore the issue is to find an efficient way of calculating v_{ijrs}. Assume that under normal conditions all travel uses the 'shortest' path, which is a reasonable assumption for strategic non-urban networks. Since all trips from i to j use shortest paths, the effect of failure of any link that is not on a shortest path is zero. Therefore it is only necessary to consider failure of links on the shortest path. Consider the following approach to calculating v_{ijrs} for a given origin and destination:

STEP 0 Initialise the matrix of local vulnerability measures v_{ijrs}

STEP 1 Find the shortest path from i to j using an efficient algorithm. Record the least 'cost' S and the set of links that make up the shortest path

STEP 2 Break the first link of the absolute shortest path e_{rs} and calculate the degraded shortest path length S'. This will probably require recalculating the path from scratch, see comments below

STEP 3 Calculate the loss of amenity $(S - S')$ from breaking link e_{rs} and record the value in v_{ijrs}

STEP 4 Repeat from Step 2 for all other links of the shortest path.

Note that link e_{rs} of the shortest path may also be part of the second-best path, and also part of the third-best path, and so on. Indeed this is likely since the second-best path is a first order deviation from the shortest path, and so on (D'Este 1997). Therefore a direct 'second-best path' approach is not valid. In fact it is necessary to find the 'second best' path across a network cut that includes e_{rs}. However, algorithms for constructing network cuts tend to be inefficient so the use of network cuts, although theoretically appealing, may not be effective. Repeated calculation of shortest paths for a specific O-D pair is reasonably efficient for calculating the extent of effects of network degradation and hence the links for which travel is most vulnerable. For a given O-D pair, it involves applying a shortest path algorithm once plus the number of links in the shortest path. Therefore worst case complexity is something like $O(m^2 \log n)$.

Having identified where the network is vulnerable, the next step is to do something about it. Broadly there are three approaches to be considered:

- reduce the probability that the exposed link will fail, i.e. protect link from failure using engineering or management methods
- reduce the cost of an alternative path (link) to make it a better alternative, i.e. upgrade an alternative path
- introduce a new link into the network to provide a good alternative, i.e. make new alternatives

The first option, protection of links from failure, is an interesting engineering or management problem but inherently requires a case-by-case approach. Possible measures to reduce the risk of failure will be different in urban and non-urban areas, and may include:

- incident management plans and counter-measures
- increased traffic capacity
- protection from flood, storm surge, etc
- relocation to less vulnerable alignment
- better drainage

Interestingly enough, our research has found evidence of similar approaches being applied to transport networks in earlier times. For instance Lee (1946) discussed engineering and management methods used to reduce the vulnerability of the UK national railway network during the Second World War.

4. FURTHER RESEARCH

This summary paper discusses the formulation of techniques for identify specific 'weak spots' – critical infrastructure – in a network, where failure of some part of the transport infrastructure would have the most serious effects on access to specific locations and overall system performance. The Australian national road network is being used as a case study, but the concepts and techniques can have much wider application. Our research to date has yielded a potential method for analysis of vulnerability in terms of the spatial or topological configuration of the network. Further research is needed to:

- develop better and more comprehensive vulnerability metrics
- refine techniques for identifying network weaknesses
- extend and refine the use of network vulnerability indicators for use in studies of critical infrastructure and the implications of network degradation
- develop techniques for recommending and evaluating cost-effective risk management and remedial responses
- develop visualisation tools for interpreting and communicating results

Candidate vulnerability metrics belong to a composite set including:

- indices of network connectivity and accessibility
- probability distributions for travel times and costs to specified destinations
- measures of change in the utility of travel
- spatial distributions of changes in the above metrics
- indices of risk, including expected values of costs, changes in these values under different conditions, propensity for component failure, and performance thresholds.

This set of measures needs to reflect both the intensity of vulnerability and its extent, both spatially and demographically, across a study region. Validation of the techniques will require careful appraisal of the modelled consequences of network failure for real world systems.

In terms of research outcomes we envisage the development of a method for network scanning that might be termed 'incident audit' – something akin to road safety audit. The aim is to provide a method that can identify where infrastructure failure will have the worst consequences for movement of people and goods. It will include tools for engineers and planners to determine critical network locations, and devise strategies and remedial measures to safeguard network performance.

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RELIABILITY EVALUATION OF THE RAILWAY NETWORK IN THE TOKYO METROPOLITAN AREA

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1. INTRODUCTION

In the Tokyo metropolitan area, more than 60% of commuter uses the railway system. Therefore, when railway accident occurs in the system, many passengers are restricted to move. Inside the Yamanote line which is a ring railway of Tokyo, many lines have been equipped so that passengers can move using other alternative routes when an accident occurs. However, there is no alternative line outside of the Yamanote line. Therefore, when the railway accident occurs in the area, rail service is suspended and so many passengers are constrained to move. It means that it causes social.

There are many research works which analyzed the reliability of transportation network. However, most of them, such as Asakura (1998), focused on the reliability of a road network. Therefore, we research on the reliability of railway network in this study. Fujiu. (2004) investigated the occurrence of railway accident in the Tokyo metropolitan area. They analyzed the frequency of the accident occurrence, the reason of the accident and the duration of down time of rail service and estimated the probability distribution of accident occurrence and duration of down time.
In this research, the procedure which calculates loss of time cost caused by railway accident is developed. Furthermore, the monetary social cost is also calculated considering value of time.

2. DATA

The Ministry of Land, Infrastructure and Transport of Japan maintained the Railway Accident Statistics (RAS). It describes the detail of the accident such as date of accident, cause of accident, site of accident, duration of down time of service operation and number of casualties.
In this research, the accidents which are reported in this statistics are investigated. Then, the investigated area in this study is decided as the same area covered by Annual Report of Urban Transport (1997) because we have to use another kind of data such as number of passengers in each line. Finally, total number of accident analyzed in this study is 537.
Fig. 1 shows the distribution of the accident occurred in 2002. The size of circle indicates the number of accident as shown in explanatory note in the figure.

3. ANALYSIS OF RAILWAY ACCCIDENT

3.1. SITUATION OF ACCIDENT OCCURRENCE

In this section, the statistical distribution of the accident occurrence is investigated. The number of events which occurs at random per unit time follows Poisson distribution. Therefore, it is assumed that the number of occurrence of railway accident follows Poisson distribution.

Total number of accident occured in the investigated area is 537. It means that the average number of accident in a day is 1.471. This number is adopted as a parameter of Poisson distribution. Then, goodness-of-fit test of statistical distribution is examined. As the results, it is verified that the number of accident occurs in a day follows the Poisson distribution. Fig. 2 shows the distribution of railway accident occurrence.

3.2 SITE OF ACCIDENT

In this section, the site of accident is examined. The share of the accident occurrence in each railway line is shown in Fig. 3. It is shown that many accidents have occurred in certain railway lines such as JR Yamanote line and JR Keihin Tohoku line. These are most heavily used lines in this area.

Meanwhile, it is also shown that many accidents occurred in the lines such as JR Joban line, JR Utsunomiya line and Tobu Tojo line. These lines connect city center and suburbs. Therefore, there is no alternate lines which substitute these lines when railway accident happens.

3.3 CAUSE OF ACCIDENT

Causes of accident are classified into 49 types in RAS. In this study, these types of accident are thoroughly classified into 8 categories as shown in Table-1. The share of the causes of railway accident is shown in Fig. 4.
As shown in the figure, the accident caused by "Suicide" has the highest proportion. In addition, it is shown that the accident caused by "Vehicle Accident" and "Human Disaster" have also high proportion. These types of accident are out of control of railway operator. Therefore, it indicates that that it is impossible to avoid the occurrence of the railway accident completely.

3.4 DURATION OF DOWN TIME OF SERVICE OPERATION

Duration of down time is examined in this section. The data of maximum duration of down time is reported in RAS. It is a suspended time length of most delayed train. If we adopt this reported duration as the loss of time for every passenger who is influenced by railway accident, we would overestimate total loss of time. Therefore, in this study, the loss of time of passenger is defined as the half of maximum duration of down time.
It is assumed that duration of down time follows Weibull distribution whose probability density function is shown in (Eq. 1).

$$f(x) = \frac{mx^{m-1}}{\alpha}\exp\left(-\frac{x^m}{\alpha}\right) \qquad \text{(Eq. 1)}$$

"m" and "α" are parameters which determine function form and scale. The values of these parameters are estimated by causes of accident and then goodness-of-fit test of statistical distribution is executed. As the results, it was verified that the duration of down time caused by accident follows Weibull distribution.

Probability density functions which are estimated by causes of accident are shown in Fig. 5.

4. PROCEDURE OF ESTIMATING THE DAMAGE OF RAILWAY ACCIDENT

In this study, only the loss of time of passengers is considered as the damage of railway accident. And we can infer the damage in terms of monetary amounts using the concept of value of time. The procedure of estimating loss of time cost is shown in Fig. 6. Detail of the estimation procedure is described below.

Step-1: Determination of number of accident in a day

A random number is generated with Poisson distribution which is identified in former section. Then, number of accident occurs in a day is determined.

Step-2: Determination of site of accident

A random number is generated with uniform distribution. And the railway line where the accident occurs is determined with considering the share of the accident occurrence of each railway line as shown in Fig. 3.

Step-3: Determination of section where railway service is interrupted

A random number is generated with uniform distribution. And the section where railway service is interrupted is determined.

Step-4: Determination of cause of accident

A random number is generated with uniform distribution. And cause of railway accident is determined with considering the share of the causes of the accident as shown in Fig. 4.

Step-5: Determination of duration of down time of service operation

A random number is generated with Weibull distribution which is identified in former section. The duration of down time is determined considering the cause of accident.

Step-6: Determination of number of passengers who are influenced by the accident in terms of loss of time

Number of passenger who is supposed to pass through the section where accident occurred is calculated using the transportation census (2000) of the Tokyo metropolitan area.

Step-7: Determination of the damage in terms of loss of time

Total loss of time is calculated by multiplying duration of down time by total number of passenger who is damaged by accident. Furthermore, the damage in terms of monetary amounts is inferred by multiplying total loss of time by value of time. In this study value of time is assumed as JPY 2000 per hour.

5. CALCULATION OF THE DAMAGE OF RAILWAY ACCCIDENT

In this chapter, the damage caused by railway accident is estimated through the procedure described in chapter 4.

Number of passenger who has difficulty in moving when accident occurs is calculated by the following two methods, (a) and (b). Transportation census data is utilized because it includes the information of commuting route of pass users.

(a) It is assumed that the railway service is suspended in the interval between neighbor stations of the station where the accident occurs. And then, it is assumed that the passengers who are supposed to pass through this interval, to get on and to get off at the station in this interval and to transfer at the station in this interval are damaged by the accident.

(b) It is assumed that the railway service is suspended all along the line where the accident occurs. And then, it is assumed that the passengers who are supposed to use this line are damaged by the accident.

Fig. 7 shows the results of calculations. The level of damage is classified by several categories in the figure. Total loss of time cost in a year is about JPY 3,600 million in case (a), and JPY 14,700 million in case (b).

6. SUMARRY AND FURTHER STUDY

In this study, statistical distributions related to the railway accident are identified. One is the distribution of number of accident occurrence in a day and another is the distribution of duration of down time caused by accident. Moreover, the procedure to calculate the loss of time cost of the passenger who has difficulty in moving is proposed. Finally, through simulation experiment of railway accident occurrence, total amount of loss of time cost is calculated. As the result of experiment, the loss caused by railway accident amounts to between 3,600 million yen to 14,700 million yen.

Since several strong assumptions are adopted in this study, the problems mentioned below should be resolved in further study.

- When a railway accident occurs, passenger changes the route for moving. However, it is not considered in this study at all.
- In this study, it is assumed that the probability of accident occurrence is equal for all stations. Actually, many accident occurs at the stations such as Shinjyuku St. and Ikebukuro St., where large number of passenger uses.
- Only the pass user is considered to calculate number of passenger who has difficulty in moving.

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