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REDUNDANCY ANALYSIS BY DISCRETE INFORMATION SYSTEM FOR HIGHWAY NETWORK UNDER EARTHQUAKE DISASTER

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SUMMARY

It is considered that network redundancy on transportation system is dominated by traveler's cognizance for disaster information, since a moving body itself is decision-maker. As for the 1995 Great Hanshin Earthquake Disaster, disequilibrium of traffic flow on network is nothing less than deterioration of redundancy partly because of incomplete information about disaster/traffic conditions. In order to design an adequate structure of information, this analysis model is developed by adopting information theory.

This study defines a level of redundancy on highway network with discrete disaster/traffic information as the sum of each traveler's expected amount of information. Information entropy function, plays primary role to evaluate redundancy, can yield each traveler's expected amount of information. First, the study has a fundamental assumption that a piece of information derived from discrete information system would update traveler's maximum expected utility (MEU, for short). Since each of travelers' expected utility after acquiring information signals can be yielded by posterior probability density of initial belief on the basis of the Bayesian Theorem, profit or loss of the MEU equivalent to a plain value of information can be properly evaluated. The differential in value between some imperfect and the perfect information presents a net amount of information. In this study, information entropy function employs a net amount of information as operative variable to figure out the expected amount of information.

The numerical experiments, for highway network within Koto zone, Tokyo, with both traffic demand classified into three types of risk premium for each travel path choice and information signals of travel time established by discrete probability distribution, yield some satisfactory results. These are mainly summarized as follows:

(1) The proposed model has the advantage of not computing network reliability employed in usual redundancy analyses.
(2) The margins of network redundancy on both differences of information signals and diversities of traveler's risk response behavior are respectively estimated without difficulty.
(3) The total expected amount of information is considered to become an index to evaluate network flow redundancy in case of applying against damaged network.
(4) To apply the expected amount of information to countermeasures suggests a promising possibility to help improve deteriorated traffic flow circumstances under earthquake disaster.

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INTRODUCTION

Many projects for highway infrastructure to mitigate/alleviate earthquake disaster have more intensively done than ever since the 1995 Great Hanshin Earthquake Disaster. Not only to take countermeasures to fortify each highway facility as a narrow sense of disaster prevention measurements, there also comes discussions about approaches to take incidental effects between some of the highway facilities into consideration. A scope of study on minimizing fatality scale within maximum permissible disaster has entered into examinations as new countermeasures to minimize those effects. Many studies to secure redundancy of highway network system are thought of one approach of those alike.

Although highway network system plays a vital role from immediately after an earthquake, almost all disaster prevention projects done by the administration and public sectors in Japan are categorized as the narrow sense of measurements. If anything, highway maintenance/preparation projects have been deployed by way of ostensible reasons for disaster prevention projects to secure highway network redundancy. It seems that the common understanding for disaster prevention projects, not to fortify physical strength to facilities but to secure transportation system, is lacking in those projects. Any project not being clearly established by highway redundancy assessment methods is likely to have misgivings and many controversial problems partly because of indistinctiveness of the purpose to carry out its project and a lack of constraint for budget spending.

Meanwhile, various sorts of law and ordinances to help facilitate actions against earthquake disaster had already been enacted by many municipal administrative bodies in Japan. For example, The Earthquake Disaster Countermeasures Ordinance, fully revised version of The Earthquake Disaster Prevention Ordinance, enacted by Tokyo Metropolitan Government at 2001, has been put into effect. The ordinance enforces actions to usual measurements to secure safety for public facilities, preparedness of the first-stage quake-response rescue action, establishment of disaster information system to help improve living condition for city dwellers, promotion to arrange refuge/relief organizations, and so on. In order to accomplish wide rage of those requirements appropriately/precisely, any countermeasures to minimize functional deterioration of highway transportation system during the aftermath of earthquake disaster must be taken into consideration.

Highway network redundancy can have a typical feature to evaluate functional deterioration of its system. It is quite likely that no one can deny this point of view. In addition, it seems that network redundancy depends on traffic information. There are some studies analyzing relations between transportation information and its flow. Kobayashi et al. [1] studied a suitable information-providing role based on rational expectations incorporating with driver's learning process. Mun et al. [2] analyzed the information role of road prices to apply some reasonable route navigation measures. Iida et al. [3] proposed the method of surveying and analyzing the dynamics of route choice behavior considering the effects of traffic information. On the other hand, Yamamoto et al. [4] proposed the basic model by entropy function to evaluate network redundancy. However, the author does not yet come across any study to analyze relations between role of traffic information and network redundancy. Therefore, this paper focuses on an analysis for network redundancy. The proposed analysis model, incorporating with network flow analysis, is based on the method to estimate value of information as well as information theory.

HIGHWAY NETWORK REDUNDANCY AND TRAFFIC INFORMATION

Usual network system, made up of a graph structures, generally has highly redundancy in features. The network system can be roughly classified into two of the types. Either of the system characterizes its own network redundancy. One is lifeline network system, carrying single-commodity by cable and pipe network, such as power-transmission line, telephone network, and water service network. Redundancy of those is affected by failure of some elements within the system. Highway network system can be defined as the other one, since its redundancy is widely different in respect of carrying multi-commodities. Since respective "commodities" is considered as one decision-maker (i.e. driver and traveler), his or her every cognizance against network failure/disruptions dominates network redundancy. It is indeed characteristics of evaluating network redundancy, while behavior of decision-maker to detour failure/disruption routes is common sense in a manner.

It is a fact that there are highly congested streets, while many streets with no traffic also ubiquitously come into existence. For example, aerial photographs, taken in Hanshin area stricken by the 1995 Great Hanshin Earthquake Disaster, confirmed that there simultaneously existed some few busy streets and many uncrowded roads. It is considered that the root of the outbreak of terrible disorder and deadlock of network flow lay in imbalance route choice of drivers. Lacking information about damage (i.e. failure/disruptions) and network flow conditions from immediately after the quake, drivers' route choices must have been jammed into a few commutation routes and/or familiar routes. No other alternative had travelers. It might have been possible to minimize malfunction in transportation system in case that some pieces of suitable information or some items of feasible route guidance were offered.

This paper is based on an assumption that there exists interdependency between network redundancy and traffic information system. The assumption can induce an implication to analyze whether to provide traffic information secures network redundancy. Therefore, the paper analyses interdependence between information structure and network redundancy, from the scope of value of information.

VALUE OF INFORMATION

The outline of analytical method for role of information providing and its value is reviewed in this chapter. Although the case described by discrete probability function will be discussed below, so be continuous probability function as well.

Zero Information

Let set space of each event on feasible circumstances denote $\boldsymbol{\Theta}=\{\theta_1,\cdots,\theta_i,\cdots,\theta_n\}$, where i indicates each event number. The probability density function of the initial belief for each θ_i is defined as $\xi(\theta_i)$. And let set space of each available behavior by a traveler denote $\boldsymbol{B}=\{b_1,\cdots,b_j,\cdots b_m\}$, where j indicates each behavior number. It is defined that a traveler can earn utility $u(\theta_i,b_j)$ at the time traveler puts b_j into action on θ_i event. Therefore, a traveler's expected utility $U_\xi(b)$ at the time traveler puts b into action on θ_i is presented by

$$\begin{aligned} U_\xi(b) &= E_\theta\{u(b,\theta)\} \\ &= \sum_i u(b,\theta_i)\xi(\theta_i) \end{aligned} \qquad (1)$$

, where $E\{\cdot\}$ signifies expectations operator.

The maximum expected utility (MEU, for short) given the optimum behavior b^o is represented as

$$\underset{b\in B}{Max}\; U_\xi(b^0) = U_\xi(b^0) \equiv U^o(\xi) \qquad (2)$$

Perfect Information

Let hypothetical circumstances exist. There exists a perfect information system. This system is treated on the assumption that the system can recognize the occurrence of an incident in real time and perfectly/precisely can provide that information in no time gap. Since information signal from the system reflects an actual event perfectly, traveler needs not distinguish between the outbreak of an incident and the release of signals. Therefore, a traveler's utility given the optimal behavior b_θ when a traveler can recognize the event θ_i as truth is represented by

$$u(b_\theta,\theta)=\underset{b\in B}{Max}\ u(b,\theta) \qquad (3)$$

Being under the perfect information system, the MEU is

$$U^\infty(\xi)=E\{u(b_\theta,\theta)\}=\sum_i u(b_\theta,\theta_i)\xi(\theta_i) \qquad (4)$$

Imperfect Information System and Bayesian Theorem

Let set space of signals released from an information system denote $\boldsymbol{X}=\{x_1,\cdots,x_k,\cdots,x_l\}$, where k notes the signal number. The structure of the system is represented by conditional probability density function $f(\cdot|\theta)$ given the occurrence of each event θ_i. The probability density function is defined as

$$\sum_k f(x_k|\theta_i)=1.0 \qquad (5)$$

Employing initial belief $\xi(\theta)$, hence, marginal probability density for the signal x is presented as

$$f(x_k)=\sum_i \xi(\theta_i)f(x_k|\theta_i) \qquad (6)$$

Now let Bayesian Theorem consider. The theorem can estimate posterior probability distribution by prior probability distribution. According to that viewpoint, posterior probability distribution of initial belief, with a signal released by a system, about the occurrence of an actual present event, can be properly yielded. Therefore, the posterior probability density of initial belief $\xi(\cdot|x)$ given signal x is

$$\xi(\theta_i|x_k)=\frac{\xi(\theta_i)f(x_k|\theta_i)}{\sum_{i\in\boldsymbol{\Theta}}\xi(\theta_i)f(x_k|\theta_i)} \qquad (7)$$

Procuring the signal from a system, an individual traveler will be able to decide one's own action, after updating initial belief by employing posterior probability density. The expected utility given action b is represented as

$$U(b|\xi(\cdot|x_k))=\sum_i u(b,\theta_i)\xi(\theta_i|x_k) \qquad (8)$$

Utility given the optimal action b_{x_k} to maximize expected utility is

$$U(b_{x_k}|\xi(\cdot|x_k))=\underset{b}{Max}\sum_i u(b,\theta_i)\xi(\theta_i|x_k) \qquad (9)$$

Conclusively, the maximum expected utility $U^{I_x}(\xi)$ employing an information system is yielded as

$$\begin{aligned}U^{I_x}(\xi)&=E_x\{U(b_x|\xi(\cdot|x))\}\\&=\sum_k\sum_i u(b_{x_k},\theta_i)\xi(\theta_i|x_k)f(x_k)\\&=\sum_k U(b_{x_k}|\xi(\cdot|x_k))f(x_k) \qquad (10)\end{aligned}$$

Value of Information System

The paper defines that a plain value of information, with employing the perfect information system, is margin of the maximum expected utility between with the perfect information and with the zero information as

$$V^\infty(\xi)=U^\infty(\xi)-U^0(\xi) \qquad (11)$$

The case of an imperfect information system, similarly, a plain value of information V^{I_x} is margin of utility between with some pieces of information and with the zero information as

$$V^{I_x}(\xi) = U^{I_x}(\xi) - U^0(\xi) \tag{12}$$

A pain value of information with the zero information also must be $V^0(\xi) = 0$.

VALUE OF INFORMATION AND HIGHWAY NETWORK REDUNDANCY

Here let the assumption in former chapter consider again. That was whether highway network redundancy has interdependent relationship with traffic information system. Provided that this mutuality actually exists, one implication follows: highway network redundancy depends on traffic information. For example, having the perfect information, a traveler would be able to determine one's own firm behavior substitute for the maximum utility whatever incident outbreaks. The other hand, being under circumstances with imperfect information, it seems that a traveler would aim at taking appropriate choice of behavior to maximize one's own expected utility, by updating initial belief with signal an imperfect information system releases. Therefore, the assumption will be deductively confirmed so long as travelers' behavioral standard as above is accepted.

To measure value of information signifies voluntary reaction by travelers toward the components in a set space of behavioral alternatives essentially held in redundant highway network system. From the point of view, the proposed evaluation model as below is considered to become a model to sufficiently yield one index to evaluate redundancy highway network system has. In order to measure a level of redundancy, entropy function [5] plays fundamental role of the study.

Now the paper defines a plain value of information by an information system as an amount of information, and similarly the sum of every traveler's expected amount of information H as a evaluate index of network redundancy. Naturally, redundancy for the perfect information becomes the maximum.

A proportion of a plain value of information $V^{I_x}(\xi)$ by an information system to a plain value of information $V^{\infty}(\xi)$ by the perfect information system equals a net amount of information as

$$p_i = \frac{V^{I_x}(\xi)}{V^{\infty}(\xi)} \tag{13}$$

Employing entropy function, to calculate entropy itself produces the ith traveler's expected amount of information,

$$h_i = -p_i \log_2(p_i) - (1-p_i)\log_2(1-p_i) \tag{14}$$

Note that h_i makes the maximum at 1.0 given p_i = 1/2. Since transformation $p_i^{'} = 1/2\, p_i$ can derive the maximum h_i given p_i = 1.0, formula (14) is operated by transformation $p_i^{'} = 1/2\, p_i$ as

$$\begin{aligned} h_i^{'} &= |J| \cdot h_i = 2h_i \\ &= 2\left\{-p_i^{'}\log_2(p_i^{'}) - (1-p_i^{'})\log_2(1-p_i^{'})\right\} \end{aligned} \tag{15}$$

, where J = Jacobian.

A standardized expected amount of information $h_i^{''}$, not affected the number of travelers, is derived by the sum of every traveler's net amount of information P as

$$h_i^{''} = 2\left[-\left(\frac{p_i^{'}}{P}\right)\log_2\left(\frac{p_i^{'}}{P}\right) - \left\{1-\left(\frac{p_i^{'}}{P}\right)\right\}\log_2\left\{1-\left(\frac{p_i^{'}}{P}\right)\right\}\right] \tag{16}$$

Consequently, the total expected amount of information by an information system is formulated as

$$H = \sum_i h_i^{''} \tag{17}$$

VIEWPOINT OF TRAVELERS' BEHAVIOR AND INFORMATION STRUCTURE

Behavioral Pattern of Travelers

Physical damage is mainly composed of disruptions on highway network, obstructions on streets by debris from collapsed buildings, and stoppages by damaged bridges. Functional damage is traffic jam with no doubt. Those two types of damage figure out discrete set space of events $\boldsymbol{\Theta}$ through a post-earthquake. Damage has a great influence on each traveler's utility about travel time. A disutility is due to awful traffic congestion and detours almost all the travelers often suffer. The physical/functional damage is regarded as "damage to traveler".

As for risk analysis, usual analyses generally distinguish between something damaged and its cause. Functional damage on highway network system, however, is hard to analyze on that point, since disadvantage-taker and cause defendant directly/indirectly is often considered the same one. With regard to this, travelers are self-incurred-and-taker of damage. It is almost not practicable to distinguish between the cause and the result in damaged network flow. The paper defines traveler as "self-manager" or "self-controller" against risk, hazard, and damage. Travelers may be able to alleviate their disutility or conversely may intentionally suffer disutility by behaving riskily.

On the other hand, public institution, stands on neutral point, provides traffic and damage information to maximize collective utility of the masses. Each traveler receives its information to maximize one's own utility. The standpoint of public institution neutrally has effects only on cognitive interdependence relations between a set space of events and a set space of actions each traveler can take.

Let trip behavior between an origin and destination (O-D pair) consider. The paper defines behavioral pattern of travelers as follows:

(1) Travelers do not have all pieces of information about components in a discrete set space of actual events $\boldsymbol{\Theta}$.
(2) Experiencing in trips among O-D pairs (such as commuting, shopping, dinning, leisure, and so on) before earthquake, respective travelers, however, implicitly hold probability distribution $\xi(\theta)$ given their own initial belief substitutive for $\boldsymbol{\Theta}$.
(3) With traffic and damage information released by a system, expectations of initial belief ξ would be updated and then a discrete set space of every behavior $\boldsymbol{B}$ would vary depending on his or hers own risk-response behavior toward expectations of actual event. Therefore, travelers cannot recognize real state without initial belief ξ empirically travelers acquired.
(4) Traveler's risk-response is categorized as "risk-averse", "risk-neutral", and "risk-preferable" behavior in the paper.
(5) His or hers own risk premium represents each risk-response behavior. All kinds of von-Neumann and Morgenstern utility function (VNM function, for short) usually meets all of the risk-response behavior, since an absolute risk aversion function derived from the VNM function play a vital role to determine scale of response.

Information Structure

The paper defines information system and its structure as follows:

(1) Informant is the public sector only.
(2) The public sector has monitoring system to observe traffic condition and damage incident.
(3) Information is about travel time among some specific O-D pairs.
(4) An information system constitutes a random variable of real event. A system releases "Z value" or "value of probability" of event yielded through rescaling the observed actual expectations and variance by using standard normal table or by approximation.

REDUNDANCY ESTIMATION MODEL

Network Flow Model

A procedure dubbed "traffic assignment" or "trip assignment" can estimate traffic network flow. Trips from a given origin to a given destination are assigned to the network's links, or more precisely, routes between a given origin and destination. Employing "incremental trip assignment model" [6] develops this evaluation model. The calculation procedure is, as simply summarized, to load the aggregated origin-destination demand into the shortest path incrementally (usually 10% or 20% of demand), and to keep updating link travel costs in the process. Although the incremental trip assignment model is basically old-fashioned model, the solution obtained with the approach clearly constitutes an approximation to the exact solution (i.e. equilibrium trip assignment model [7] and stochastic equilibrium trip assignment model [8]).

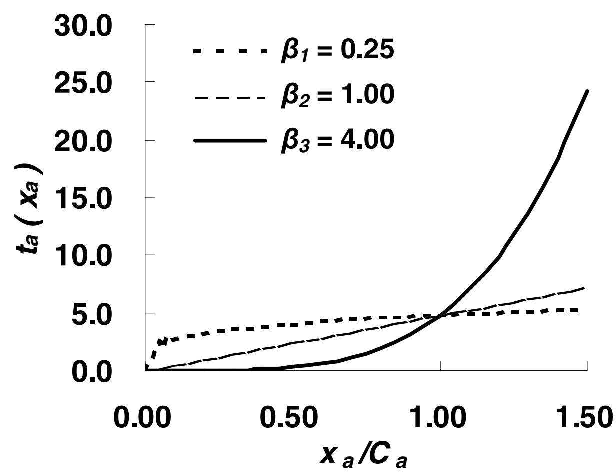

Figure-1 Cost Performance by B.P.R. Function

Travelers' Risk Response

As mentioned above, behavior of an individual traveler is categorized as risk-averse, risk-neutral, and risk-preferable behavior, respectively. Assuming that a risk response behavior is corresponding to utility (i.e. travel time or travel cost), the idea to consider link travel cost function be appropriately adopted. Although there are some cost functions, the analysis employs the B.P.R. function (U.S. Bureau of Public Roads [9]) because of a fundamental reason to analyze risk response behavior. The function illustrated in **Figure-1** is

$$t_a(x_a) = t_a(0)\left[1.0 + \alpha\left(\frac{x_a}{C_a}\right)^{\beta}\right] \quad \in \boldsymbol{A} \qquad (18)$$

, where $\boldsymbol{A}$ = set of links, x_a = volume of link a, $t_a(x_a)$ = link travel cost, $t_a(0)$ = free flow travel cost, C_a = link capacity, α, β = parameter.

A general utility function representing risk response behavior requires some valid preconditions such as: (1) monotonous increase (or decrease), (2) strict convexity (or concavity), (3) practicability of second derivative. In addition, (4) an absolute risk aversion function representing a scale of risk aversion (i.e. risk premium) is needed to define [10, 11]. As shown in **Figure-1**, the B.P.R. function sufficiently meets condition (1) and (2) in regard to range of any x_a. Since the derivatives of the function are

$$\frac{d\, t_a(x_a)}{d\, x_a} = t_a(0)\alpha\,\beta\left(\frac{x_a}{C_a}\right)^{\beta-1} \qquad (19)$$

$$\frac{d^2 t_a(x_a)}{d^2 x_a} = t_a(0)\alpha\,\beta\,(\beta-1)\left(\frac{x_a}{C_a}\right)^{\beta-2} \qquad (20)$$

, condition (3) is also satisfied. Now an absolute risk aversion function is usually formulated by

$$r_a(x) = -\frac{U''(x)}{U'(x)} < 0 \qquad (21)$$

Therefore, the derivatives of the B.P.R. function are similarly yielded as

$$r_a(x_a) = -\frac{\beta - 1}{x_a} < 0 \tag{22}$$

$$r_a'(x_a) = -\frac{\beta - 1}{x_a^2} < 0 \tag{23}$$

As derived formula (22) and (23) above, the condition (4) needed as an absolute risk aversion function is reasonably fulfilled by the B.P.R. function. It is also understood that parameter β can manipulate risk response behavior. Since to vary parameter β will make changes a cost between the O-D pairs in demand assignment process, individual traveler will assign to different route in accordance with different β depending on minimum cost path in network.

The Solution Model

The framework of the proposed solution model is illustrated in **Figure-2**. Computation procedure commences with given network structure, O-D pair demands, every traveler's initial belief, and information signals. In the setting stage of network structure, capacity, free flow speed, and distance of link as well as parameter α, β is claimed to yield link cost by B.P.R. function. The parameter β becomes the more important factor, since the parameter manipulates traveler's risk response behavior (i.e. minimum path between the O-D pairs). Generally, strictly convex, linear, and strictly concave function respectively represents risk-averse, risk-neutral, and risk-preferable behavior. Therefore, B.P.R. function can formulate every behavior by β. In addition, it is considered that the iterative approach consequently constitutes an approximation to the exact solution of a well-balanced state of network flow with traffic information. When the given number of iterations is over, the process to estimate value of information follows. Ultimately, the expected amount of information is yielded.

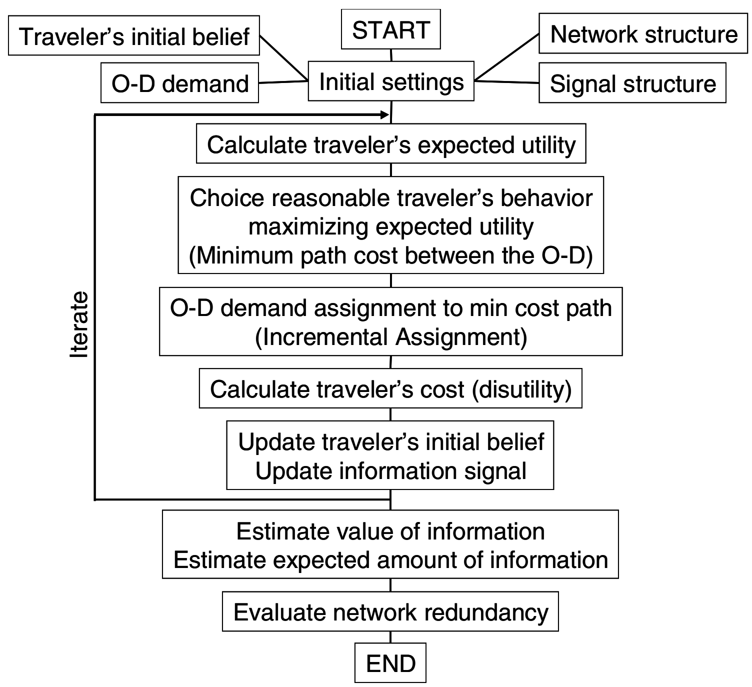

Figure-2 Framework of the Solution Model

NUMERICAL EXPERIMENT

Example Calculation

In this section, in order to examine fundamental features in proposed model, an analysis of interdependence between traffic information to provide and network flow redundancy is experimentally exemplified with highway network within Koto zone, Tokyo. Simplifying computation, real highway network is refigured as **Figure-3**. The example also does not explicitly establish network damage and individual traveler is treated as aggregate demand corresponding to its O-D pair. The network structure is shown in **Figure-3**. Each O-D demand is shown in **Table-1** As shown in **Table-1**, the number of O-D pairs is 5. Each traveler's utility by discrete behavior b_j on each discrete event θ_i is shown in **Table-2**. The information signals given each discrete event θ_i are shown in **Table-3**.

The initial belief matrix, presented in **Table-1**, signifies the probability density $\xi(\theta_i)$ of initial belief for each event which travelers have in advance. Each discrete event θ_i is established to illustrate each flow rate of links x_a/C_a, and then its likelihood of the occurrence signifies the probability density of traveler's initial belief. The initial belief is randomly established in the case. The sum of $\xi(\theta_i)$ given each event always must be 1.0. The utility matrix signifies the joint utility $u(b_j,\theta_i)$ when traveler takes b_j into action on the event θ_i. Each utility in the example has differentials so as to reflect three types of risk-response behavior. This disutility is, equivalent to link travel cost, yielded by B.P.R. function given β = 0.25, 1.00, and 4.00, respectively and given α = 0.96. Signal matrix or likelihood matrix for each discrete event is shown in **Table-3**. This is the conditional probability of signal x_k given event θ_i, namely $f(x_k|\theta_i)$. The conditional probability is set in a hypothetical manner that unique signal x_k corresponding to the event θ_i is primarily released with the higher likelihood and the balance (i.e. 1.0 - $f(x_a|\theta_i)$) is evenly shared by another signal. One example of information signal, internally yielded then updated in the sequence of iterative calculating process, is presented.

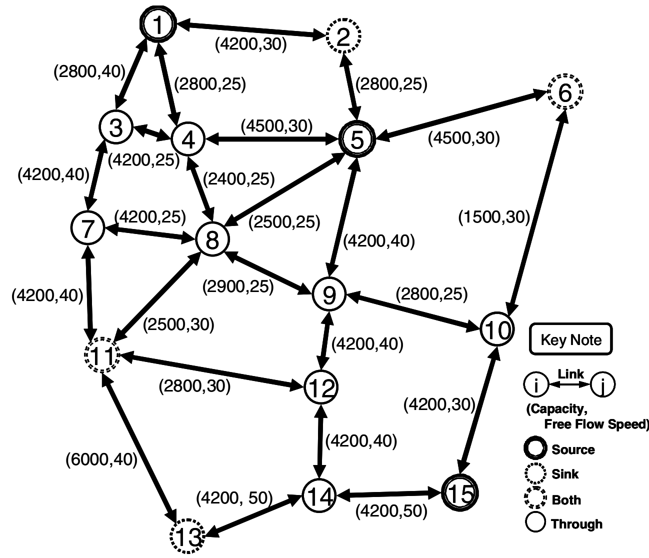

Figure-3 Example Network

Table - 1 O-D Demand and Initial Belief

O-D pairs	No.	Demand (veh.)	Initial Belief for Event θ_i				
			θ_1	θ_2	θ_3	θ_4	θ_5
1 - 13	1	2000	0.300	0.200	0.050	0.400	0.050
5 - 11	2	1000	0.030	0.220	0.400	0.150	0.200
6 - 13	3	5000	0.100	0.150	0.050	0.450	0.250
11 - 6	4	1500	0.200	0.200	0.200	0.200	0.200
15 - 2	5	3000	0.010	0.010	0.996	0.010	0.010

Table - 2 Utility for Travelers

$u(b_j, \theta_i)$		Discrete Event θ_i				
		θ_1	θ_2	θ_3	θ_4	θ_5
Utility by behavior b_j	b_1	-3.552	-4.225	-4.675	-5.024	-5.398
	b_2	-1.440	-2.880	-4.320	-5.760	-7.680
	b_3	-0.039	-0.622	-3.149	-9.953	-31.457

Table - 3 One Example of Information Signal

$f(x_k/\theta_i)$		Discrete Event θ_i				
		θ_1	θ_2	θ_3	θ_4	θ_5
Information signal (Iteration at 1500)	x_1	0.152	0.212	0.212	0.212	0.212
	x_2	0.203	0.188	0.203	0.203	0.203
	x_3	0.000	0.000	1.000	0.000	0.000
	x_4	0.197	0.197	0.197	0.212	0.197
	x_5	0.198	0.198	0.198	0.198	0.208

Table - 4 Expected Amount of Information and Estimated Utility

Iteration (3000) Final result	O - D pairs				
O-D pair No.	1	2	3	4	5
Origin	1	5	6	11	15
Destination	13	11	13	6	2
Demand	2000	1000	5000	1500	3000
$U^{Ix}(\xi)$	-3.9120	-4.1238	-4.7573	-3.9910	-3.1785
$U^{0}(\xi)$	-3.9120	-4.7393	-4.8330	-4.4160	-3.1785
$U^{\infty}(\xi)$	-2.5731	-3.2308	-3.8649	-2.8464	-3.1475
$\sum V^{Ix}(\xi)$	84.6375	615.9065	81.8670	356.6270	25.0528
$\sum V^{\infty}(\xi)$	4016.8500	4525.3500	2904.15000	4708.8000	92.9640
p_i	0.02107	0.13610	0.02819	0.07574	0.26949
h_i"	0.29482	1.14787	0.37046	0.77395	1.68146

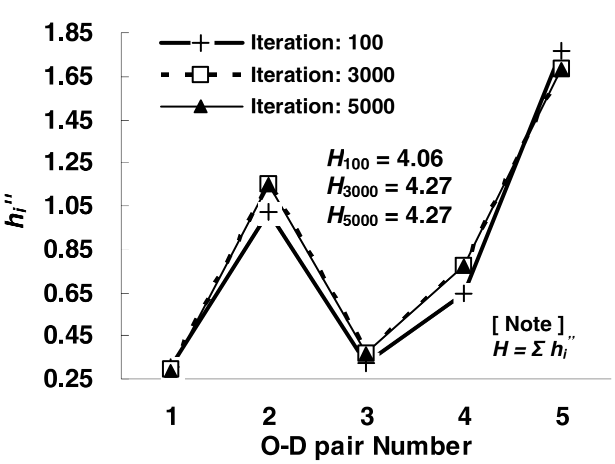

Figure-4 Expected Amount of Information

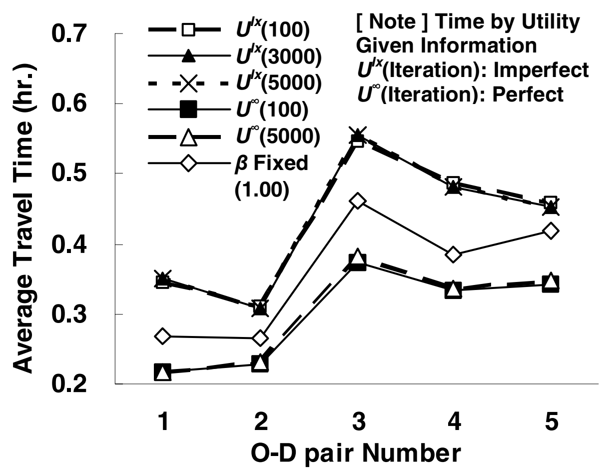

Figure-5 Travel Time between the O-D

The computation executed for the number of iterations = 100, 3000 and 5000, respectively. Consequently, the posterior probability distribution $\xi(\theta_i|x_k)$ and the marginal probability distribution $f(x_k)$ was also respectively estimated in each iteration. Besides, it was reasonably confirmed that conditional utility by b_j behavior given x_k, i.e. $U(b_j|x_k)$, by employing the updated initial belief for each the event, is well estimated.

Plain value of information $V^{I_x}(\xi)$ and expected amount of information h_i" are estimated in **Table-4**. Each O-D's expected amount of information is also illustrated as **Figure-4**. Average travel time between the O-D pairs, comparing with the case by the perfect information is illustrated in **Figure-5**. In addition, each ratio of gap about average travel time between some imperfect and the perfect information is illustrated in **Figure-6**. According to the numerical experiments, some pieces of fundamental knowledge are induced:

(1) A plain value of information is subject to differences of initial belief no matter when all the travelers has the same utility.

(2) A plain value of information also produces margin with the same initial belief in case that disparity exists in traveler's utility.
(3) An expected amount of information makes differentials according to each traveler's initial belief and utility.
(4) An expected amount of information, however, becomes the larger level whenever a traveler has the higher value of the perfect information.
(5) As for the gap in average travel time between the O-D pairs, network structure such as link capacity and free flow travel time has fundamentally strong influence.
(6) However, according to comparing the changes of both expected amount of information and gap ratio of average travel time between the perfect and some imperfect information (i.e. (imperfect-perfect)/perfect)), it is understood that expected amount of information has inverse proportion relationship with gap ratio of average travel time between the types of information. That is to say, expected amount of information can become an index to evaluate travel time indirectly.
(7) In order to improve a current condition to the approximate condition with perfect information, to constitute an adequate structure of information signal assessed by expected amount of information becomes effective measures.

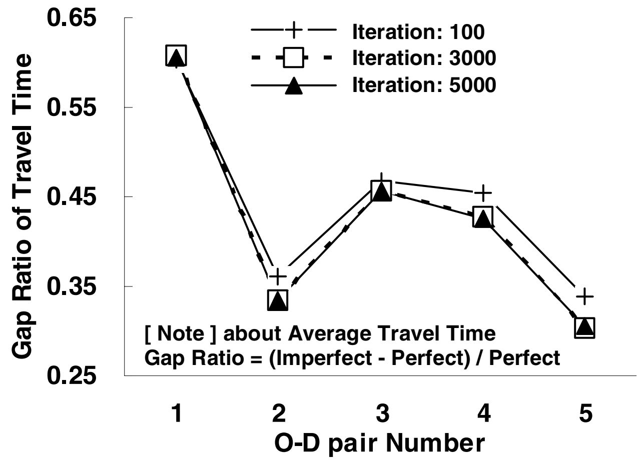

Figure-6 Gap Ratio of Average Travel Time

Ultimately, the important knowledge is recognized that the larger the total expected amount of information can be, the higher highway network flow redundancy becomes, since the sum of each traveler's expected amount of information signifies the total expected amount of information on the system. In addition, to assess a structure of information signal by expected amount of information suggests a promising possibility to help improve deteriorated traffic flow circumstances under disaster, since expected amount of information also can evaluate travel time of delay from the ideal condition. Therefore, the total expected amount of information is considered to become an index to evaluate network flow redundancy in case of applying against damaged network. Naturally, applying to specific O-D pair is also possible alike.

CONCLUSIONS

The conclusions of this study are summarized as follows:
(1) The mathematical model to evaluate highway network redundancy can be formulated by estimation of both value of traffic information and level of entropy itself.
(2) The solution model to analyze interdependence between traffic information and traveler's risk response behavior can be composed of traffic assignment model employing monotonously increase convex cost function such as B.P.R. function.
(3) The solution model can also yield each travel time with the perfect information.
(4) The proposed model has the advantage of not computing network reliability employed in usual redundancy analyses.
(5) The margins of network redundancy on both differences of information signals and diversities of traveler's risk response behavior are respectively estimated without difficulty.
(6) To analyze and design an adequate structure of information signal can be available by assessing each expected amount of information between the O-D pairs.
(7) To apply the expected amount of information to countermeasures suggests a promising possibility to help improve deteriorated traffic flow circumstances under earthquake disaster.

(8) The total expected amount of information is considered to become an index to evaluate network flow redundancy in case of applying against damaged network.

(9) To evaluate redundancy on a specific pair of nodes between the origin and destination in damaged network is also available.

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