Evaluation of Disaster-Resistance of Road Network

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Agenda

I. Introduction
II. Japan has to cope with disasters
III. How transport can contribute to disaster resistance?
IV. Evaluation on benefit related with disaster-resistance
V. Further challenges
VI. Discussions
I. INTRODUCTION
Where is Gifu (岐阜)?

- North of Aichi (Nagoya). It takes about 1 hour from Centrair (Chubu International) Airport to JR Gifu Station.
- Centre of Population of Japan lies in the east of Gifu City
- Lowest below sea level, highest over 3,000m. We have hottest and coldest places within main island of Japan.
- Gifu Castle is said to be a base of Nobunaga Oda, who firstly unified Japan.

「岐阜」＝「岐山」+「曲阜」
where phoenix landed hometown of Confucius

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27th, Sep., '16 ITLS Seminar (F. Kurauchi)
Where is Gifu?

- Fantastic sightseeing sites, Takayama, Shirakawago, cormorant fishing...
Gifu University

- 6 km north from JR Gifu Station.
- Founded in 1949
- Five Faculties: Education, Regional Studies, Medicine, Engineering and Applied Biological Sciences
- 836 faculty staffs
  5,710 undergraduate students, 1,535 graduate students
- Three transport-related researchers
  - Prof. Jian Qian YING (Fac. of Regional Studies)
  - Prof. Fumitaka KURAUCHI (Fac. of Eng.)
  - Prof. Toshihiko MIYAGI (Research Professor, Fac. of Eng.)
Who am I?

- Name: Fumitaka Kurauchi
- Professor, Dept. of Civil Engineering, Gifu University
  - Chair of Transport System Design Lab.
    - 1 Oversea Researcher
    - 2 PhD students
    - 3 MSc students
    - 3 undergraduates
- Doctor of Eng. (Kyoto University, 2002)

Design of safe, secure, ecological, convenient and efficient transport network

Transport network design resilient against disaster

Ecological and convenient public transport design

Traffic management design for efficient use of road networks

Researches in TSD Lab.
II. JAPAN HAS TO COPE WITH DISASTERS
What happened on 27th, Sep?

• Aizu Great Earthquake (1611)
  ➢ M6.9, about 3,700 victims
• Flooding by Typhoon in Western Japan(1921)
  ➢ 691 victims
• Earthquake at east of Taiwan (1947)
  ➢ M7.4, 4 victims in Okinawa Islands
• Tohyamaru Typhoon (1954)
  ➢ 1,761 victims in Western Japan
• Kariyagawa Typhoon (1958)
  ➢ 1,269 victims around Kanto (Metropolitan) area
• Isewan Typhoon (1959): Largest Typhoon disaster after Meiji era
  ➢ 4,697 victims around Chubu (central Japan) area
Recent major disasters in Japan

- 1995.1 Great Hanshin Awaji (Kobe) Earthquake (M.6.8-7.3)
  - 5,500-6,400 victims
- 2004.10 Typhoon no.23
  - 99 victims all over Japan
- 2004.10 Niigata Chuetsu Earthquake
  - 65 victims
- 2005.12 Heavy snow in 2006
  - over 150 victims
- 2011.3 Great East Japan (Tohoku) Earthquake
  - 18,000-22,000 victims, Tsunami
- 2011.8 Typhoon no. 12
  - over 110 victims
- 2014.8 Heavy rain (Landslide in Hiroshima)
  - over 70 victims
- 2014.9 Eruption of Mt. Ontake (Nagano and Gifu)
  - 50-60 victims
- 2016.4 Kumamoto Earthquake
  - 88 victims
- 2016.8 Typhoon No.10
  - 20 victims in Tohoku area
How your conscious changed after Tohoku Earthquake?

What do you think it is needed as a function of social system?

Growing conscious about disaster prevention

Importance of family ties

Ensuring safety and security

Energy saving

Treatment of disable people

Environmental countermeasures

Reactivation of regional economy

According to the central government, the probability that the M8-9 class earthquake occurs within 30 years is around 90%.

(Source: http://www.data.jma.go.jp/svd/eqev/data/tokai/tokai_eq2.html)
Japan has to cope with disasters

- Japan is always facing at a risk of various natural disasters,
  - typhoon attack, heavy rain, heavy snow, volcano eruption, hot temperature, earthquake, tsunami...
- We have learnt that it is impossible to ‘beat’ the disasters...
  - It is practically impossible to apply building standards to withstand against largest possible earthquake (or other disasters).
- It’s not the matter whether Nankai Trough Earthquake comes or not, but when it comes.
- We have to be well-prepared...

Transport has an important role to cope with disasters!
III. HOW TRANSPORT CAN CONTRIBUTE TO DISASTER RESISTANCE?
How transport contributes in an emergent situation?

Disaster occurs!

- Primary evacuation (moving to safe location)
- Carrying emergency supplies (water etc)

Emergency corresponding period

- Humanitarian logistics (supporting evacuees)
- Debris transport
- Restoration-related transport

Recovery period

- Humanitarian logistics (supporting evacuees)
- Debris transport
- Recovery-related transport

Reconstruction and preparation period

- Construction works
- Robust and reliable transport system
How transport researchers can contribute?

Disaster occurs!

Lifesaving emergency period (evacuation period)

- Primary evacuation (moving to safe location)
- Carrying emergency supplies (water, etc.)
- Humanitarian logistics (supporting evacuees)
- Debris transport
- Restoration-related transport
- Humanitarian logistics (supporting evacuees)
- Debris transport
- Recovery-related transport
- Construction works
- Robust and reliable transport system
- Signal control, congestion management, etc.
- Evacuation planning (route, mode)
- Shelter location planning

Emergency corresponding period

- Humanitarian logistics (supporting evacuees)
- Debris transport
- Restoration/recovery strategies (of transport system)
- Congestion management, traffic information provision
  - Location design of stockpiles

Recovery period

- Humanitarian logistics (supporting evacuees)
- Debris transport
- Recovery-related transport
- Improving robustness and resiliency of transport network
- Shelter location planning
- ....

Reconstruction and preparation period
IV. EVALUATION ON BENEFIT RELATED WITH DISASTER-RESISTANCE
## Benefit evaluation of road investment

<table>
<thead>
<tr>
<th>Indices</th>
<th>Direct effect</th>
<th>Indirect effect</th>
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<tbody>
<tr>
<td></td>
<td>Road user</td>
<td>Public works</td>
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<td>By using roads</td>
<td>Government Spending</td>
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<td>Travel time/cost saving</td>
<td>Decrease of investment cost for public facilities</td>
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<td>Reduction of traffic accidents</td>
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<td>Improving LoS of roads</td>
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<td>Improving safety and comfort of pedestrians</td>
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<td>Tax revenue</td>
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<td>National tax</td>
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<td>Neighbour community</td>
<td>Environmental issues</td>
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<td>Air pollution</td>
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<td>Citizens’ life</td>
<td>Road space use</td>
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<td>Ensuring alternative roads during disasters</td>
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<td>Increase of opportunities</td>
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<td>Improving public services</td>
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<td>Population Increase</td>
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<td>Regional economy</td>
<td>Increase of jobs/incomes</td>
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<td>Decrease of price of goods</td>
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<td>Increase of asset value</td>
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</table>

Normally only 3 benefits are considered.

(source: Cost-Benefit-Analysis Manual, MLIT)
Current method to evaluate robustness of road network (MLITT)

- **Network**
  - **Centroids:** Prefectural capitol and major regional cities
  - **Links:** Roads predetermined as ‘1st priority emergency routes’ in Disaster-prevention Planning of the Prefecture.

- **Method**
  - **Shortest path search** is carried out and the result is compared with and without road investment.
  - Narrow roads (<5.5m) and roads with potential dangers (with the risk of landslides, rock fall or avalanche) are excluded in the disaster case.

- **Criteria**
  - **Robustness:** the network is not robust if either the travel time or distance is more than 150% of the normal network in the disaster case. (OD-based)
  - **Importance:** the OD pairs connecting important nodes are more important. (OD-based)

- Discussing the impact of new road investment by checking the changes of these criteria.
Limitations on the current method

• This method does not fit with cost-benefit analysis.
  ➢ The impact of investment cannot be evaluated by the monetary value.

• Regardless of the efficiency of the investment (usually evaluated by cost-benefit ratio), the road may be built if it really contributes to increase the robustness.

Methods linking with cost benefit analysis and avoiding the double counting of the benefit should be developed.
Benefit of improving disaster-prevention functions

Evaluation of disaster-related works

Reducing expected loss by the disaster

Reducing anxiety of the risk of being disconnected

Road users

- Time loss by detouring and congestion
- Opportunity loss by not reaching destination

Local citizens

Anxiety by losing connections to other areas
Benefit for road users

• Time loss
  - Total travel time at the base case (without disaster) and the study case (with disaster) is calculated and compared, using static user equilibrium approach.
  - The travel time is further calculated with new road section. The reduction of total travel time with and without the road investment is set as the benefit of reducing the loss of travel time.

• Opportunity loss
  - The OD pair is treated as ‘unreachable’ when travel time is more than 8 hours. This assumes that travellers will give up travelling if the travel time is more than 8 hours.
  - The opportunity loss by the disconnection is valued as much as 8 hours in our calculation.
Benefit for road users

Traditional evaluation (Travel time saving)

Benefit of reducing transport-related cost

Total travel time

without road investment

with road investment

P₀
normal condition

P₀
normal condition

P₀
normal condition

P₀
normal condition

Prob.

Prob.
Benefit for local citizens

Assumption

Local citizens have an anxiety of being isolated when a disaster occurs by some roads being disconnected.

Anxiety may be relaxed by constructing new road since the number of paths increases.

Benefit of ensuring alternative routes = Benefit of reducing anxiety
Benefit of ensuring alternative route

The utility of local citizens changes when the number of alternative routes to city hall (base at emergency) increases.

⇒ The utility should increase when the number of routes are larger.

We use the amount of money that equilibrates the expected utility with and without investment, $CV$ (compensating variation).

$$\sum_{i} P_{io} V (H_{io}, m_{io}, \Omega_{io}) = \sum_{i} P_{iw} V (H_{iw}, m_{iw}, \Omega_{iw} - CV)$$

Without investment

With investment

The value that equilibrate the expected utility

$= WTP$

$$H_{iw} = \kappa_i \ln(n_{iw} + 1) + 1$$

Probability that scenario $i$ occurs
(without road investment)

Number of days disconnected

Number of distinct paths

Living environment $H$

Price of services

Income

Living environment $H$

Number of distinct paths

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Benefit of ensuring alternative route

If all the attributes other than the number of routes are unchanged before and after the disaster…

\[ WTP = CV = \left[ 1 - 1 / \left\{ \prod_i \left( \frac{H_{iw}}{H_{i0}} \right)^{P_i} \right\} \right] \gamma \]

\[ Benefit = \sum_r \left( \text{Number of households} \right) \times CV_r \]

\( \gamma \) : parameter expressing impact by changing the number of alternative routes

should be estimated
Quantifying the anxiety

Logit model

Expected utility without road investment

Expected utility with road investment

\[ EU_{i0} = \alpha(P_i \ln H_{i0}) + \beta(P_i \ln \Omega) \]

\[ EU_{iw} = \alpha(P_i \ln H_{iw}) + \beta\{P_i \ln(\Omega - AoE)\} \]

\[ \gamma = \frac{\alpha}{\beta} \]

Environment H: Environment, \( P_i \): Prof. \( i \) occurs

Income: Annual income, AoE: Payment

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Overview of questionnaires

- Areas: Gifu, Niigata and Nagano
- Method: Web-based questionnaire
- Samples: 826

60% of people are living at the area that might be isolated.

Questions

- Individual attributes (gender, age, income, job, family structure)
- Household characteristics
  - Any family members visiting hospital regularly? If so, how often?
  - Any family members need additional treatment for mobility?
  - Availability of cars (own private car? own driving license?)
  - Closest council office (travel distance and mode)
- Related to disasters
  - Your community is at the risk of isolation when disaster happens?
  - Have you experienced any disaster? (If so, what type and when?)
  - Do you stockpile water, food and/or medicine for the disaster?
Imagine a natural disaster that is approximately coming once every 100 years. By such disaster, your community might be isolated for 1 days. But by the new road investment, this situation will be improved and at least 1 route is ensured even at the disaster. However you need to pay 500 yen annually to carry out this road investment. Do you agree with this road investment?
Estimation result

<table>
<thead>
<tr>
<th>variables</th>
<th>estimates</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\alpha$: level of environment (H)</td>
<td>3.51**</td>
</tr>
<tr>
<td>$\beta_1$ (income; without experience of disaster)</td>
<td>263**</td>
</tr>
<tr>
<td>$\beta_2$ (income; with experience of disaster)</td>
<td>80.1*</td>
</tr>
<tr>
<td>variance</td>
<td>1.45**</td>
</tr>
<tr>
<td>Likelihood ratio</td>
<td>0.123</td>
</tr>
</tbody>
</table>

$\gamma = \frac{\alpha}{\beta}$

**: 1% significant, *: 5% significant

- All parameters are signification (with 5% level)
- Different result by the experience of disaster.

$\gamma_1$ (for people without experience of disaster) : 0.01335
$\gamma_2$ (for people with experience of disaster) : 0.04382

We use this value for further case study
Case study

Benefit of road investment

- Traditional benefit
  - Travel time saving
    - Travel cost saving and reduction of accident not considered here

Benefit of disaster-related function

- Reducing time and opportunity loss
- Ensuring alternative route

The proposed method is applied to Gifu road network (to evaluate Hida area)

- Mountainous area, risk of isolation.
- Road closures by heavy rain is considered.
- Many road sections with traffic restriction by heavy rainfall in the area.
Traffic restriction by heavy rain

- The road will be closed when the rainfall exceeds certain predetermined amount, to avoid accidents caused by rock falls or land slides.
OD pairs to evaluate the benefit of ensuring alternative route

From communities to city hall
Scenario of road closure

Heavy rain is considered.

- Based on historical climate data of 21 years, heavy rain more than 50mm/h is defined and scenarios are created.
- Once it happened, we assume that road sections are closed for 1 day.
- The traffic restriction will not be applied to a new road built by the investment.
# Records of heavy rains

<table>
<thead>
<tr>
<th>Scenario ID</th>
<th>Voronoi cell ID</th>
<th>Frequency within 21 years</th>
</tr>
</thead>
<tbody>
<tr>
<td>No.</td>
<td>年</td>
<td>月</td>
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<tr>
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<td>2 1998</td>
<td>9</td>
</tr>
<tr>
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<td>19 2006</td>
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<td>15 2004</td>
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<td>11 2001</td>
<td>8</td>
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<td>5</td>
<td>18 2004</td>
<td>10</td>
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<td>15</td>
<td>21 2008</td>
<td>7</td>
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</table>

Frequency within 21 years

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New road investment

w1 Western part of Nohi Highway
w2 w1+eastern part of Nohi Highway (avoiding current road section with traffic restriction by heavy rainfall).

w3 A bypass avoiding current road section with restriction
w4 Planned road connecting from Ishikawa Pref to Shirakawago
**Result**

- **w2** has largest disaster-prevention related benefit
  - Travel time saving during normal situation is small.
  - Probability that heavy rain occurs is rather large.
- **w1** and **w2** seem to be effective to improve the robustness against disaster.
- **w4** does not improve disaster-prevention related benefit, but traditional benefit (travel time saving) is the largest.

### Table

<table>
<thead>
<tr>
<th></th>
<th>w1</th>
<th>w2</th>
<th>w3</th>
<th>w4</th>
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</thead>
<tbody>
<tr>
<td>Benefit (100 million yen/year)</td>
<td>10.4</td>
<td>12.7</td>
<td>-0.003</td>
<td>0.003</td>
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<tr>
<td>Traditional benefit</td>
<td>2.4</td>
<td>19.5</td>
<td>-0.4</td>
<td>34.8</td>
</tr>
</tbody>
</table>

- **Traditional benefit**: reducing time and opportunity loss, Ensuring alternative routes
Disaster-prevention related benefit

- Benefit of reducing time and opportunity loss is larger.
- Benefit of ensuring alternative routes values around 100 million yen for w1 and w3, but very small for w3 and w4.
Findings and Limitations

• Findings
  ➢ The benefit of improvement of disaster resistance is **not small** in disaster-prone areas.
  ➢ Most of them are the benefit of **reducing time and opportunity loss**.

• The proposed method assumes...
  ➢ **unchanged travel demand** even with disasters. However, we know that people at the risk of isolation are rather well-prepared and can cope with isolation for a few days.
  ➢ **perfect information** like scenario occurrence probability, the number of ensured paths, and we applied user equilibrium assignment. These assumptions are unrealistic, and needs to be relaxed.
  ➢ **other factors are unchanged**. However, road network investment may change land use. To evaluate the robustness of ‘community connectivity’, such side effects should be considered.

• The amount of disaster-prevention related benefit is small, and the value may become even smaller when we discuss about less frequent events.
V. FURTHER CHALLENGES
Further challenges

• Research question
  - By road investment, the locations of ‘key’ infrastructures such as hospitals, shopping malls and/or council branches may change and can be concentrated to the more convenient area, and the daily living relies more on transport network. May it eventually make communities more vulnerable against disasters?

• Methodology
  - Check whether such side effect exists or not by investigating the relationship among road investment, key infrastructure locations change and robustness against disasters.
  - Develop indicators for robustness considering the structural change of the society.
  - Evaluate road investment considering these side effects.
THANK YOU

V. DISCUSSIONS

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