# DETERMINATION OF ALLOWABLE PRIVATE VEHICLE FLOWS CONSIDERING CLASSIFICATION OF OD TRIP IN EARTHQUAKE DISASTER

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**Abstract:** This paper aims at developing a decision making tool which can potentially be used in managing the emergency vehicles and controlling the private vehicle flows during an earthquake disaster. In particular, the paper deals with the problem of controlling the private vehicle flows which can be generated in and attracted to each zone considering the classification of OD trips and determining the location of the emergency vehicles depot. The problem to be addressed is formulated as a multi-commodity, two-modal (private vehicle flows and emergency vehicle) network flow problem based on the concept of network flow theory and integer linear programming (IP).

## 1. INTRODUCTION

Damage to lifeline network systems due to a strong earthquake, in road networks, gas pipelines, electric power systems and water supply systems, influence urban functions in the disaster area after the quake. In particular, impassable of roads and streets exert block transportation in evacuation, restoration and rescue. During a disaster emergency, transportation is critical in minimizing the loss of life and maximizing the efficiency of the rescue operations, even when only part of the road network is damaged.

Since damage to urban road network causes congestion in other parts of the network, efficient disaster traffic management is essential (Odani et al., 1996; Nakagawa et al., 1996).

It is necessary to balance travel demand (traffic flow on a link) and traffic supply (the capacity of a network) in tackling traffic congestion (Tomita et al., 1995). This paper discuss the determination of allowable private vehicle flows aimed at ensuring that travel demand does not exceed road network capacity under deterioration of traffic function in the road network.

Haghani et al. (1996) formulated a complex multi-commodity, multi-modal network flow problem with time windows in the context of disaster relief management which could be solved relatively easily. This model dealt with the problem of determining the routing and scheduling of emergency vehicles but did not formulate the OD traffic volume for private vehicle flows. Masuya et al. (1996) and Kurauchi et al. (1997) calculated the maximum trip generation and attraction volume that can be borne by in that part of the network remaining intact after an earthquake. Results showed that moderate traffic demand control is needed in an emergency, however these models didn't consider emergency vehicles.

This paper aims at developing a decision making tool which can potentially be used in managing the emergency vehicles and controlling the private vehicle flows during an earthquake disaster. In particular, the paper deals with the problem of controlling the private vehicle flows which can be generated in and attracted to each zone considering the classification of OD trips and determining the location of the emergency vehicles depot.

In this paper, vehicles are classified into two categories. One is the private vehicle flows that read to be controlled when travel demand exceeds the capacity of a network. The other category is emergency vehicles carrying supplies and relief personnel, which are not controlled during a disaster emergency. The private vehicle flows is also formulated considering the classification of OD trips, namely internal-internal trip, internal-external trip, external-internal trip and through trip (external-external trip).

The problem to be addressed is formulated as a multi-commodity, two-modal (private vehicle flows and emergency vehicle) network flow problem based on the concept of network flow theory and integer linear programming (IP). Determination method are introduce to estimate the allowable private vehicle flows that would allow the most efficient use of a degraded road network, given emergency vehicle operation.

## 2. CLASSIFICATION OF PRIVATE VEHICLE FLOWS

When considering measures to control traffic demand to maintain traffic flow immediately after an earthquake, it is necessary fully to understand the extent to which private vehicle flows can be generated in and attracted to a degraded road network. As with road network capacity, OD traffic volume is defined by network characteristics (road network pattern, kink capacity) and flow characteristics. The flow characteristics can be considered to include land use pattern, trip distribution (OD traffic pattern), modal split and traffic assignment. This paper discusses the OD traffic volume based on the classification of private vehicle flows considering OD traffic patterns.

The OD trips of private vehicle flows are classified into two categories. One is the trips with origins and/or destinations inside the disaster area described as local trips. The other category is the trips with origins and destinations outside the disaster area described as through trips. Following an earthquake disaster, it is difficult to prohibit running of the local trips generated in and attracted to the zones inside the disaster area. However, the through trips, which pass the road network inside the disaster area, can make a detour to the other routes of road network outside the disaster area.

There are three different types of local trips : internal-internal local trips, where both the origin and destination of the trip lie inside the disaster area, internal-external trips, where the trip destination lies outside the area, external-internal trips, where the trip origin lies outside the area. The unit OD traffic volume and the destination choice ratio are considered as the OD traffic pattern representing the relative ratio of OD pair. The unit OD traffic volume is the ratio to the total amount of OD traffic volume loaded onto the road network, and the destination choice ratio is the ratio of OD traffic volume to the total amount of OD traffic volume generated in each zone.

In this paper, we examined the case where these three local trips and OD traffic pattern on each OD pair are combined. Together with classification of private vehicle flows, a multi-commodity, two-modal network flow problem is formulated with IP mathematical programming, with consideration given to emergency vehicles used in rescue, relief operations restoration, and transport of emergency relief. Thus the OD traffic volume of private vehicle flows following an earthquake disaster is examined from many perspectives.

## 3. OD TRAFFIC VOLUME CONSIDERING EMERGENCY VEHICLES

The OD traffic volume of private vehicle flows can be calculated using various methods, depending on how the types of local trips or OD traffic pattern is treated. The following factors were considered: (1) The external-external trips (through trips) is restricted not to pass the road network inside the disaster area and is made to make a detour to the other routes of road network outside the disaster area. (2) The private vehicle flows for each OD pair is only local trips, namely internal-internal local trips, internal-external trips and external-internal trips. (3) The emergency vehicles are assigned to the priority route secured inside the disaster area.

### 3.1 OD Traffic Volume considering Unit OD Traffic Volume

A two-modal IP problem of maximizing traffic demand (F) of private vehicle flows ($p_{ij} \cdot F$) can be formulated, accounting for emergency vehicles ($E_{mn}$), to which the highest priority should be given to maintain transportation routes. The OD traffic volume of private vehicle flows is local OD trips generated in or attracted to the zone inside the disaster area. The formulae are as follows:

$$\sum_{r \in n_{ij}} Y_r^{ij} = p_{ij} \cdot F \qquad (i \in I - I_o, j \in J - J_o) \tag{1}$$

$$\sum_{m=1}^{M} E_{mn} \geq E_n \qquad (n = 1,2,\cdots,N) \tag{2}$$

$$\sum_{n=1}^{N} E_{mn} \leq y_m \cdot E_m \qquad (m = 1,2,\cdots,M) \tag{3}$$

$$\sum_{m=1}^{M} y_m \leq P \tag{4}$$

$$\sum_{i\in I}\sum_{j\in J}\sum_{r\in n_{ij}} {}_a\delta_r^{ij} \cdot Y_r^{ij} + \sum_{m=1}^{M}\sum_{n=1}^{N}\sum_{r\in e_{mn}} {}_a\delta_r^{mn} \cdot E_r^{mn} \leq C_a \quad (a \in A) \tag{5}$$

$$Y_r^{ij} \geq 0 \tag{6}$$

$$E_{mn} \geq 0 \qquad (m = 1,2,\cdots,M \quad n = 1,2,\cdots N) \tag{7}$$

$$E_r^{mn} \geq 0 \qquad (m = 1,2,\cdots,M \quad n = 1,2,\cdots N, r \in e_{mn}) \tag{8}$$

$$F \to Max \tag{9}$$

Where

$Y_r^{ij}$: the r-th path traffic volume on an OD pair ij

$p_{ij}$: unit OD traffic volume on an OD pair ij generated in or attracted to the zone inside the disaster area

$$\left( \sum_{i\in I_i}\sum_{j\in J_i} p_{ij} + \sum_{i\in I_i}\sum_{j\in J_o} p_{ij} + \sum_{i\in I_o}\sum_{j\in J_i} p_{ij} = 1 \right)$$

I: set of generation zones $(I = I_i \cup I_o)$

J: set of attraction zones $(J = J_i \cup J_o)$

$I_i$: set of generation zones inside the disaster area

$J_i$: set of attraction zones inside the disaster area

$I_o$: set of generation zones outside the disaster area

$J_o$: set of attraction zones outside the disaster area

$E_m$: total number of emergency vehicles from candidate depot m

$E_n$: total number of emergency vehicles to demand node n

$E_{mn}$: number of emergency vehicles from candidate depot m to demand node n

$E_r^{mn}$: the r-th path traffic volume on an emergency vehicle mn

M: number of candidate depots

N: number of demand nodes

$y_m$: if we locate at candidate depot m then =1, otherwise =0

P: number of depots to locate

$n_{ij}$ ($e_{mn}$):set of OD pair ij (emergency vehicle mn) altered the route

${}_a\delta_r^{ij}$(${}_a\delta_r^{mn}$): if link a is on r-th path of OD pair ij (emergency vehicle mn), then =1, otherwise =0

$C_a$: capacity of link a

A: set of links

Eqn. (1) refers to the origin and destination flow conservation constraint based on the unit OD traffic volume. Eqn. (2) represents the constraints with respect to the total number of emergency vehicles necessary for transportation including relief supplies, rescue and relief operations at each demand node n. Eqn. (3) also represents the constraints with respect to the total number of emergency vehicles from the candidate depot m. Eqn. (4) say that at most P depots can be located. Eqn. (5) represents the link capacity constraints; here the emergency vehicles are considered as well as OD traffic. The OD traffic volume of private vehicle flows can be calculated as a problem of maximizing the travel demand loaded onto the road network in eqn. (9) under eqn. (1) - (8) as the constraint equation.

As shown in eqn. (10), the total amount of private vehicle flows ($O_i$) for each zone is obtained as the sum of the OD traffic volume generated in each zone inside the disaster area. The total number of vehicles (NV) including emergency vehicles loaded onto road network inside the disaster area is given in eqn. (11).

$$O_i = \sum_{j \in J} p_{ij} \cdot F \tag{10}$$

$$NV = \sum_{m=1}^{M} \sum_{n=1}^{N} E_{mn} + \sum_{i \in I} O_i \tag{11}$$

### 3.2 OD Traffic Volume considering Destination Choice Ratio

Here, we consider dividing the OD traffic volume into the internal-internal trips and internal-external (external-internal) trips. The internal-external and external-internal trips can be easily controlled to generate in and attract to each zone compared with the internal-internal trips. In this paper, the unit OD traffic volume is applied in the internal-internal local trips and the destination choice ratio is applied to the internal-external and external-internal trips respectively. Then the IP problem of maximizing the total amount of OD traffic volume (Qi) in consideration of both the OD traffic volume and the emergency vehicles is formulated as follows:

$$\sum_{r \in n_{ij}} U_r^{ij} = p_{ij} \cdot F \qquad (i \in I_i, j \in J_i) \tag{12}$$

$$\sum_{r \in n_{ij}} V_r^{ij} = q_{ij} \cdot Q_i \qquad \begin{pmatrix} i \in I_i, j \in J_o \\ i \in I_o, j \in J_i \end{pmatrix} \tag{13}$$

$$\sum_{m=1}^{M} E_{mn} \geq E_n \qquad (n = 1,2,\cdots,N) \tag{2}$$

$$\sum_{n=1}^{N} E_{mn} \leq y_m \cdot E_m \qquad (m = 1,2,\cdots,M) \tag{3}$$

$$\sum_{m=1}^{M} y_m \leq P \tag{4}$$

$$\sum_{i \in I} \sum_{j \in J} \sum_{r \in n_{ij}} {}_a\delta_r^{ij} \cdot U_r^{ij} + \sum_{i \in I} \sum_{j \in J} \sum_{r \in n_{ij}} {}_a\delta_r^{ij} \cdot V_r^{ij} + \sum_{m=1}^{M} \sum_{n=1}^{N} \sum_{r \in e_{mn}} {}_a\delta_r^{mn} \cdot E_r^{mn} \leq C_a \tag{14}$$

$$U_r^{ij} \geq 0 \tag{15}$$

$$V_r^{ij} \geq 0 \tag{16}$$

$$E_{mn} \geq 0 \qquad (m = 1,2,\cdots M \quad n = 1,2,\cdots N) \tag{7}$$

$$E_r^{mn} \geq 0 \qquad (m = 1,2,\cdots,M \quad n = 1,2,\cdots N, r \in e_{mn}) \tag{8}$$

$$F \geq F^L \tag{17}$$

$$Q_i \geq Q_i^L \tag{18}$$

$$\sum Q_i \rightarrow Max \tag{19}$$

Where

$U_r^{ij}$: the r-th path traffic volume on an internal-internal OD pair ij

$V_r^{ij}$: the r-th path traffic volume on an internal-external or external-internal OD pair ij

$F^L$: lower limit of internal-internal travel demand based on the unit OD traffic volume

$Q_i$: total amount of OD traffic volume generated from zone i based on the destination choice ratio

$Q_i^L$: lower limit of total amount of OD traffic volume generated from zone i based on the destination choice ratio

$q_{ij}$: destination choice ratio on an an internal-external or external-internal OD pair ij

$$\left( \sum_{j \in J_o} q_{ij} = 1 \quad i \in I_i, \ \sum_{j \in J_i} q_{ij} = 1 \quad i \in I_o \right)$$

Eqn. (12) represents the origin and destination flow conservation constraint for internal-internal trips based on the unit OD traffic volume. Eqn. (13) represents the origin and destination flow conservation constraint for internal-external and external-internal trips based on the destination choice ratio. Eqn. (14) represents the link capacity constraints; here the emergency vehicles are considered as well as OD traffic. Eqn. (17) and (18) represent the lower limit of travel demand (F) and total amount of OD traffic volume ($Q_i$) respectively. Consequently, the problem of maximizing the total amount of OD traffic volume (Qi) in eqn. (19) is presented including eqn. (12) - (18), (2)-(4) and (7)-(8) as constraint equations.

Eqn. (20) represents the private vehicle flows generated in and attracted to each zone and as shown eqn. (21), the total amount of private vehicle flows ($O_i$) of each zone is obtained as the sum of the OD traffic volume. The total number of vehicles (NV) including emergency vehicles loaded onto road network is given in eqn. (22).

$$V_{ij} = (p_{ij} \cdot F + q_{ij} \cdot Q_i) \tag{20}$$

$$O_i = \sum_{j \in J} V_{ij} \tag{21}$$

$$NV = \sum_{m=1}^{M} \sum_{n=1}^{N} E_{mn} + \sum_{i \in I} O_i \tag{22}$$

## 4. NUMERICAL EXAMPLE

To illustrate the discussion in the previous chapter, let us consider the road network depicted in Figure 1. The road network has 19 centroids ( 13 centroids inside the disaster area and 6 centroids outside the disaster area) and 100 links. The unit OD traffic volume under normal conditions listed in Table 1. The traffic capacity of link 1, 2, 4, 7 ,10,13 is for instance 1200, link 3, 41, 83 is 480, link 5 is 1440, link 6, 9 is 2475, link 8 is 2880 and link 62 is 2160 on a normal road network respectively. Then, calculation of the road network capacity under the unit OD traffic volume in Table 1 gives 21400. This value is equivalent to the acceptable flow of minimum cut (link 13, 41, 62, 83) shown in Figure 1. The LP and IP models were solved using the LINDO software What'sBest.

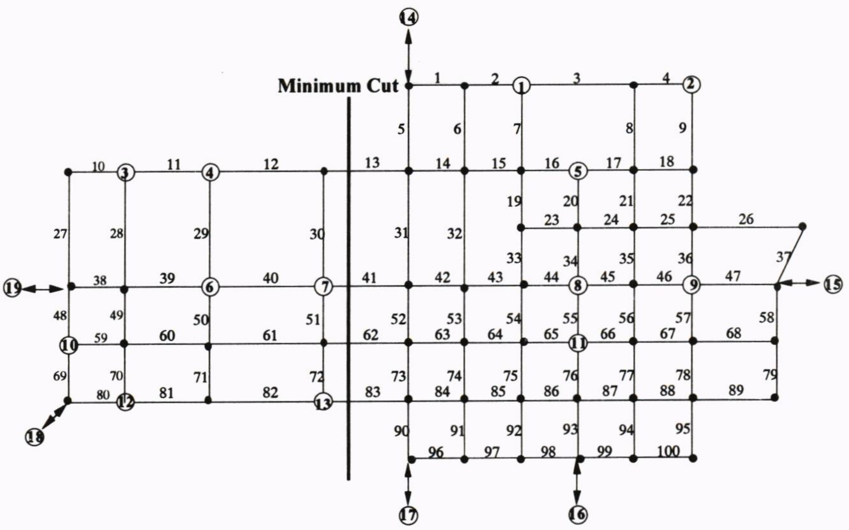


Figure 1. Test Road Network

Table 1. Unit OD Traffic Volume ($1.0\times10^{-2}$)

| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **1** | 0.00 | 0.07 | 0.03 | 0.04 | 0.08 | 0.05 | 0.00 | 0.08 | 0.06 | 0.00 | 0.06 | 0.00 | 0.05 | 0.33 | 0.24 | 0.08 | 0.00 | 0.00 | 0.05 |
| **2** | 0.07 | 0.00 | 0.02 | 0.06 | 0.12 | 0.04 | 0.00 | 0.12 | 0.11 | 0.00 | 0.17 | 0.00 | 0.05 | 0.41 | 1.02 | 0.36 | 0.02 | 0.00 | 0.08 |
| **3** | 0.03 | 0.03 | 0.00 | 0.10 | 0.13 | 0.18 | 0.00 | 0.13 | 0.08 | 0.02 | 0.17 | 0.07 | 0.09 | 0.29 | 0.26 | 0.47 | 0.10 | 0.02 | 0.64 |
| **4** | 0.03 | 0.04 | 0.12 | 0.00 | 0.12 | 0.12 | 0.00 | 0.12 | 0.06 | 0.00 | 0.21 | 0.05 | 0.07 | 0.48 | 0.67 | 0.35 | 0.13 | 0.00 | 1.01 |
| **5** | 0.10 | 0.11 | 0.10 | 0.08 | 0.00 | 0.30 | 0.00 | 0.30 | 0.25 | 0.01 | 0.38 | 0.06 | 0.21 | 0.57 | 1.24 | 1.04 | 0.28 | 0.10 | 0.57 |
| **6** | 0.04 | 0.07 | 0.15 | 0.11 | 0.35 | 0.00 | 0.00 | 0.35 | 0.13 | 0.02 | 0.36 | 0.09 | 0.15 | 0.37 | 0.43 | 0.48 | 0.21 | 0.09 | 0.65 |
| **7** | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.38 | 0.67 | 0.00 | 0.00 | 0.00 | 0.37 |
| **8** | 0.10 | 0.11 | 0.10 | 0.08 | 0.30 | 0.30 | 0.00 | 0.00 | 0.25 | 0.01 | 0.38 | 0.06 | 0.21 | 0.69 | 1.60 | 1.04 | 0.28 | 0.10 | 0.74 |
| **9** | 0.08 | 0.10 | 0.07 | 0.07 | 0.27 | 0.10 | 0.00 | 0.27 | 0.00 | 0.00 | 0.27 | 0.07 | 0.09 | 0.47 | 1.46 | 0.83 | 0.14 | 0.03 | 0.34 |
| **10** | 0.00 | 0.00 | 0.02 | 0.02 | 0.02 | 0.02 | 0.00 | 0.02 | 0.00 | 0.00 | 0.04 | 0.03 | 0.02 | 0.01 | 0.00 | 0.03 | 0.00 | 0.00 | 0.11 |
| **11** | 0.08 | 0.13 | 0.14 | 0.23 | 0.44 | 0.37 | 0.00 | 0.44 | 0.31 | 0.03 | 0.00 | 0.14 | 0.31 | 0.52 | 1.50 | 1.59 | 0.44 | 0.17 | 0.79 |
| **12** | 0.01 | 0.03 | 0.07 | 0.06 | 0.10 | 0.10 | 0.00 | 0.10 | 0.08 | 0.03 | 0.21 | 0.00 | 0.14 | 0.12 | 0.00 | 0.35 | 0.17 | 0.08 | 0.38 |
| **13** | 0.05 | 0.05 | 0.08 | 0.08 | 0.25 | 0.16 | 0.00 | 0.25 | 0.13 | 0.03 | 0.33 | 0.11 | 0.00 | 0.27 | 0.37 | 1.04 | 0.22 | 0.14 | 0.47 |
| **14** | 0.32 | 0.46 | 0.20 | 0.42 | 0.59 | 0.41 | 0.00 | 0.69 | 0.41 | 0.02 | 0.83 | 0.12 | 0.25 | 0.00 | 0.00 | 3.03 | 1.09 | 0.00 | 0.00 |
| **15** | 0.28 | 1.13 | 0.21 | 0.60 | 1.41 | 0.57 | 0.62 | 1.65 | 1.54 | 0.00 | 1.86 | 0.07 | 0.43 | 0.00 | 0.00 | 0.00 | 0.65 | 0.00 | 0.69 |
| **16** | 0.09 | 0.17 | 0.45 | 0.35 | 1.52 | 0.65 | 0.00 | 1.52 | 0.95 | 0.01 | 2.19 | 0.36 | 1.01 | 1.93 | 0.00 | 0.00 | 0.00 | 1.10 | 2.17 |
| **17** | 0.05 | 0.02 | 0.11 | 0.12 | 0.39 | 0.27 | 0.00 | 0.39 | 0.21 | 0.00 | 0.65 | 0.16 | 0.31 | 0.57 | 0.77 | 0.00 | 0.00 | 0.00 | 0.74 |
| **18** | 0.00 | 0.00 | 0.02 | 0.02 | 0.14 | 0.08 | 0.00 | 0.14 | 0.03 | 0.00 | 0.20 | 0.11 | 0.11 | 0.00 | 0.00 | 1.13 | 0.00 | 0.00 | 0.00 |
| **19** | 0.03 | 0.14 | 0.76 | 1.00 | 0.73 | 0.72 | 0.35 | 0.89 | 0.36 | 0.13 | 0.99 | 0.46 | 0.50 | 0.00 | 0.58 | 3.30 | 0.87 | 0.00 | 0.00 |

Various calculation are carried out using a degraded road network where the traffic capacity has been decreased by 50% (inner links of road network, link 6, 7, 28, 29 etc) or 75% (outer links of road network, link 1, 2, 3, 4, 9, 10, 13, 83 etc) compared with normal road network. The traffic capacity of main street (link 5, 8, 47, 62 etc) is the same as normal road network. Calculation of the road network capacity on a degraded road network gives 13970, less than 65% of the correspond capacity on a normal road network. The section of minimum cut is the same as normal road network.

First, the OD traffic volume considering the unit OD traffic volume are estimated. Table 2 shows the unit OD traffic volume excluding the external-external trips. Calculation of the road network capacity excluding the external-external trips on a degraded road network gives 15764. Restricting the external-external trips not to pass the road network inside the disaster area can increase the total amount of OD traffic volume. In this case, the section of minimum cut is the same as normal road network.

Table 2. Unit OD Traffic Volume excluding External-external Trips($1.0 \times 10^{-2}$)

| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 0.00 | 0.09 | 0.03 | 0.05 | 0.10 | 0.06 | 0.00 | 0.10 | 0.07 | 0.00 | 0.07 | 0.00 | 0.07 | 0.40 | 0.29 | 0.10 | 0.00 | 0.00 | 0.06 |
| 2 | 0.09 | 0.00 | 0.02 | 0.07 | 0.15 | 0.05 | 0.00 | 0.15 | 0.14 | 0.00 | 0.21 | 0.00 | 0.07 | 0.50 | 1.26 | 0.44 | 0.02 | 0.00 | 0.10 |
| 3 | 0.03 | 0.04 | 0.00 | 0.13 | 0.15 | 0.22 | 0.00 | 0.15 | 0.10 | 0.02 | 0.20 | 0.08 | 0.11 | 0.35 | 0.33 | 0.57 | 0.12 | 0.02 | 0.79 |
| 4 | 0.04 | 0.05 | 0.15 | 0.00 | 0.15 | 0.14 | 0.00 | 0.15 | 0.07 | 0.00 | 0.26 | 0.06 | 0.08 | 0.59 | 0.83 | 0.43 | 0.16 | 0.00 | 1.24 |
| 5 | 0.13 | 0.13 | 0.12 | 0.10 | 0.00 | 0.36 | 0.00 | 0.36 | 0.31 | 0.02 | 0.47 | 0.08 | 0.26 | 0.70 | 1.52 | 1.28 | 0.34 | 0.13 | 0.70 |
| 6 | 0.05 | 0.08 | 0.18 | 0.14 | 0.43 | 0.00 | 0.00 | 0.43 | 0.16 | 0.03 | 0.44 | 0.12 | 0.18 | 0.45 | 0.53 | 0.59 | 0.26 | 0.11 | 0.80 |
| 7 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.47 | 0.83 | 0.00 | 0.00 | 0.00 | 0.45 |
| 8 | 0.13 | 0.13 | 0.12 | 0.10 | 0.36 | 0.36 | 0.00 | 0.00 | 0.31 | 0.02 | 0.47 | 0.08 | 0.26 | 0.85 | 1.97 | 1.28 | 0.34 | 0.13 | 0.92 |
| 9 | 0.10 | 0.13 | 0.08 | 0.08 | 0.33 | 0.12 | 0.00 | 0.33 | 0.00 | 0.00 | 0.33 | 0.09 | 0.11 | 0.57 | 1.79 | 1.02 | 0.18 | 0.04 | 0.41 |
| 10 | 0.00 | 0.00 | 0.03 | 0.02 | 0.03 | 0.03 | 0.00 | 0.03 | 0.00 | 0.00 | 0.05 | 0.04 | 0.03 | 0.02 | 0.00 | 0.04 | 0.00 | 0.00 | 0.14 |
| 11 | 0.10 | 0.16 | 0.18 | 0.28 | 0.54 | 0.45 | 0.00 | 0.54 | 0.38 | 0.03 | 0.00 | 0.17 | 0.38 | 0.63 | 1.85 | 1.95 | 0.54 | 0.21 | 0.97 |
| 12 | 0.02 | 0.03 | 0.09 | 0.07 | 0.12 | 0.12 | 0.00 | 0.12 | 0.09 | 0.04 | 0.26 | 0.00 | 0.17 | 0.15 | 0.00 | 0.43 | 0.20 | 0.10 | 0.46 |
| 13 | 0.06 | 0.06 | 0.10 | 0.09 | 0.31 | 0.19 | 0.00 | 0.31 | 0.16 | 0.03 | 0.40 | 0.14 | 0.00 | 0.33 | 0.45 | 1.28 | 0.27 | 0.17 | 0.58 |
| 14 | 0.39 | 0.57 | 0.24 | 0.52 | 0.73 | 0.50 | 0.00 | 0.85 | 0.50 | 0.02 | 1.02 | 0.14 | 0.31 | | | | | | |
| 15 | 0.35 | 1.39 | 0.26 | 0.74 | 1.73 | 0.69 | 0.77 | 2.03 | 1.89 | 0.00 | 2.29 | 0.08 | 0.53 | | | | | | |
| 16 | 0.11 | 0.21 | 0.55 | 0.43 | 1.87 | 0.79 | 0.00 | 1.87 | 1.16 | 0.02 | 2.69 | 0.44 | 1.24 | | | | | | |
| 17 | 0.06 | 0.03 | 0.14 | 0.14 | 0.48 | 0.34 | 0.00 | 0.48 | 0.25 | 0.00 | 0.80 | 0.20 | 0.38 | | | | | | |
| 18 | 0.00 | 0.00 | 0.03 | 0.02 | 0.18 | 0.10 | 0.00 | 0.18 | 0.04 | 0.00 | 0.25 | 0.14 | 0.14 | | | | | | |
| 19 | 0.04 | 0.17 | 0.93 | 1.23 | 0.90 | 0.88 | 0.43 | 1.10 | 0.44 | 0.16 | 1.22 | 0.56 | 0.62 | | | | | | |

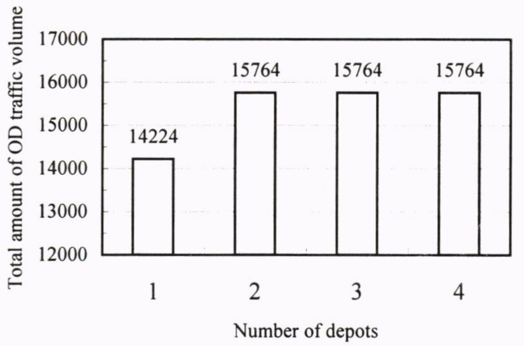


Figure 2. Total Amount of OD Traffic Volume to Each Number of Depots

The candidate depots of emergency vehicles such as ambulance, rescue and relief transportation are located at six nodes (node 14, 15, 16, 17, 18, 19) outside the disaster area shown in Figure 1. It is necessary to delivery 100 emergency vehicles to each demand node. Total number of emergency vehicles from each candidate depot is 1300. The emergency vehicles $E_{mn}$ are assigned to the route with short distance or more including the minimum-path the between candidate depot m and demand node n

For each number of depots P in eqn. (4), the total amount of OD traffic volume is calculated as shown in Figure 2. The total amount of OD traffic volume is different depending on the number of depots, though it is the same value in case of two or more depots. Figure 3 and 4 show the total amount of OD traffic volume for each location of depots. These results suggest that the number of depots and the location of depots affect the OD traffic volume of private vehicle flows. The total amount of OD traffic volume is especially influenced by the number of emergency vehicles crossing the minimum cut.

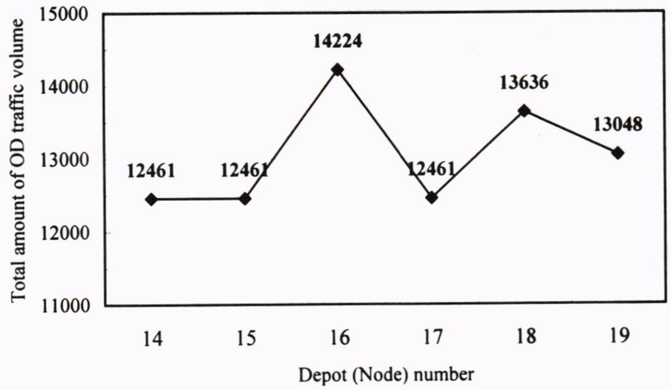


Figure 3. Total Amount of OD Traffic Volume to Each Location of Depot

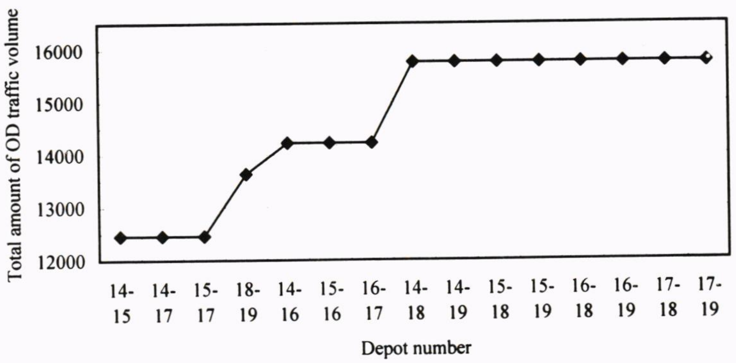


Figure 4. Total Amount of OD Traffic Volume to Each Location of Two Depots

Table 3. Unit OD Traffic Volume and Destination Choice Ratio ($1.0 \times 10^{-2}$)

| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **1** | 0.00 | 0.47 | 0.18 | 0.25 | 0.51 | 0.32 | 0.00 | 0.51 | 0.36 | 0.00 | 0.39 | 0.00 | 0.35 | 46.89 | 33.81 | 11.76 | 0.00 | 0.00 | 7.55 |
| **2** | 0.48 | 0.00 | 0.11 | 0.36 | 0.79 | 0.27 | 0.00 | 0.79 | 0.74 | 0.00 | 1.09 | 0.00 | 0.35 | 21.49 | 54.14 | 19.13 | 0.84 | 0.00 | 4.39 |
| **3** | 0.18 | 0.22 | 0.00 | 0.67 | 0.81 | 1.16 | 0.00 | 0.81 | 0.53 | 0.11 | 1.07 | 0.42 | 0.55 | 16.08 | 14.91 | 26.27 | 5.51 | 0.97 | 36.26 |
| **4** | 0.19 | 0.25 | 0.76 | 0.00 | 0.79 | 0.75 | 0.00 | 0.79 | 0.37 | 0.00 | 1.34 | 0.32 | 0.42 | 18.25 | 25.50 | 13.14 | 5.06 | 0.00 | 38.04 |
| **5** | 0.66 | 0.69 | 0.62 | 0.52 | 0.00 | 1.91 | 0.00 | 1.91 | 1.64 | 0.09 | 2.47 | 0.42 | 1.34 | 14.91 | 32.66 | 27.41 | 7.38 | 2.71 | 14.92 |
| **6** | 0.26 | 0.44 | 0.95 | 0.73 | 2.27 | 0.00 | 0.00 | 2.27 | 0.83 | 0.15 | 2.30 | 0.61 | 0.96 | 16.48 | 19.34 | 21.54 | 9.38 | 4.02 | 29.24 |
| **7** | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 26.92 | 47.31 | 0.00 | 0.00 | 0.00 | 25.77 |
| **8** | 0.66 | 0.69 | 0.62 | 0.52 | 1.91 | 1.91 | 0.00 | 0.00 | 1.64 | 0.08 | 2.47 | 0.42 | 1.34 | 15.45 | 35.94 | 23.32 | 6.28 | 2.31 | 16.69 |
| **9** | 0.50 | 0.67 | 0.42 | 0.44 | 1.74 | 0.62 | 0.00 | 1.74 | 0.00 | 0.00 | 1.75 | 0.47 | 0.59 | 14.28 | 44.63 | 25.40 | 4.38 | 0.97 | 10.35 |
| **10** | 0.00 | 0.00 | 0.16 | 0.12 | 0.13 | 0.14 | 0.00 | 0.13 | 0.00 | 0.00 | 0.27 | 0.19 | 0.14 | 8.72 | 0.00 | 21.53 | 0.00 | 0.00 | 69.76 |
| **11** | 0.50 | 0.85 | 0.92 | 1.47 | 2.82 | 2.39 | 0.00 | 2.82 | 2.01 | 0.17 | 0.00 | 0.92 | 2.00 | 10.32 | 30.06 | 31.77 | 8.72 | 3.38 | 15.74 |
| **12** | 0.09 | 0.18 | 0.46 | 0.39 | 0.62 | 0.66 | 0.00 | 0.62 | 0.50 | 0.19 | 1.34 | 0.00 | 0.91 | 10.94 | 0.00 | 31.73 | 15.12 | 7.59 | 34.61 |
| **13** | 0.31 | 0.32 | 0.50 | 0.50 | 1.62 | 1.00 | 0.00 | 1.62 | 0.84 | 0.18 | 2.12 | 0.72 | 0.00 | 10.68 | 14.69 | 41.51 | 8.77 | 5.51 | 18.84 |
| **14** | 6.76 | 9.79 | 4.19 | 8.95 | 12.60 | 8.65 | 0.00 | 14.70 | 8.69 | 0.32 | 17.64 | 2.44 | 5.27 | | | | | | |
| **15** | 2.71 | 10.90 | 2.05 | 5.80 | 13.57 | 5.44 | 6.00 | 15.92 | 14.83 | 0.00 | 17.95 | 0.64 | 4.18 | | | | | | |
| **16** | 0.98 | 1.86 | 4.84 | 3.77 | 16.41 | 6.97 | 0.00 | 16.41 | 10.22 | 0.14 | 23.61 | 3.88 | 10.90 | | | | | | |
| **17** | 1.69 | 0.85 | 4.22 | 4.38 | 14.51 | 10.24 | 0.00 | 14.51 | 7.70 | 0.00 | 24.36 | 5.99 | 11.56 | | | | | | |
| **18** | 0.00 | 0.00 | 2.50 | 1.99 | 16.60 | 9.21 | 0.00 | 16.60 | 3.85 | 0.00 | 23.19 | 12.82 | 13.23 | | | | | | |
| **19** | 0.46 | 1.93 | 10.73 | 14.19 | 10.41 | 10.14 | 4.95 | 12.63 | 5.04 | 1.85 | 14.07 | 6.51 | 7.09 | | | | | | |

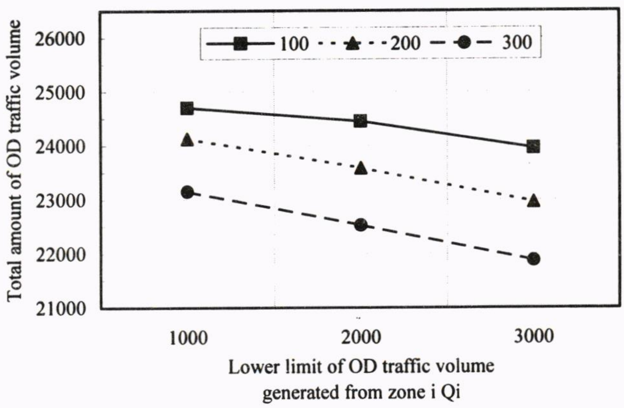


Figure 5. Total Amount of OD Traffic Volume considering Destination Choice Ratio

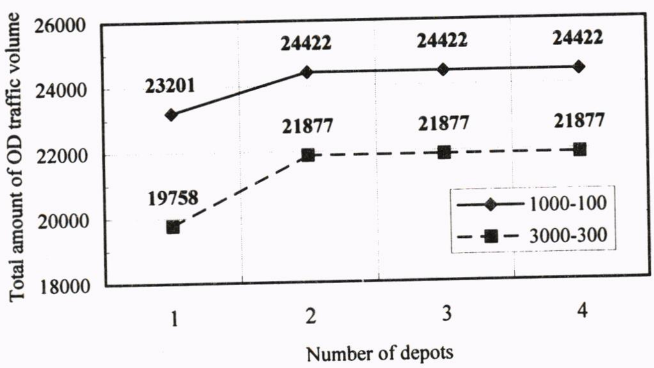


Figure 6. Total Amount of OD Traffic Volume to Each Number Depots

Table 3 shows the unit OD traffic volume for internal-internal trips and the destination choice ratio for internal-external and external-internal trips. The lower limit of internal-internal travel demand based on the unit OD traffic volume is set at 1000, 2000 and 3000. The lower limit of total amount of OD traffic volume ($Q_i$) generated from zone i is set at 100, 200 and 300. Figure 5 shows the total amount of OD traffic volume calculated for each of lower limit of travel demand and OD traffic volume. As in the case of considering each lower limit, increasing each lower limit decrease the total amount of OD traffic volume.

For each number of depots P in eqn. (4), the total amount of OD traffic volume is calculated as shown in Figure 6. The total amount of OD traffic volume is different depending on the number of depots and decrease according as the lower limit of travel demand and total amount of OD traffic volume generated from·zone increase. Figure 7 and 8 show the total amount of OD traffic volume for each location of depots. These result also suggest that the number of depots and the location of depots affect the OD traffic volume of private vehicle flows generated in and attracted to each zone.

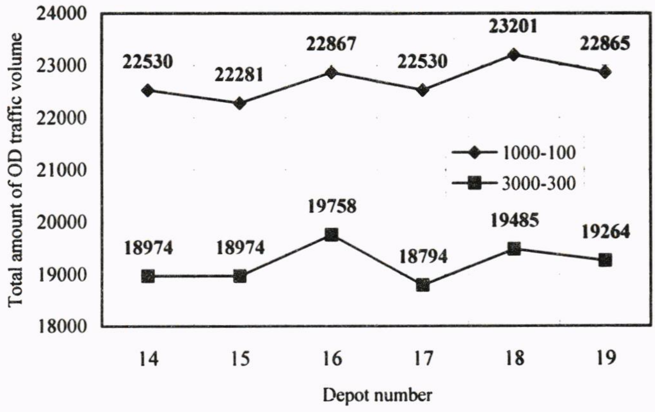


Figure 7. Total Amount of OD Traffic Volume to Each Location of Depots

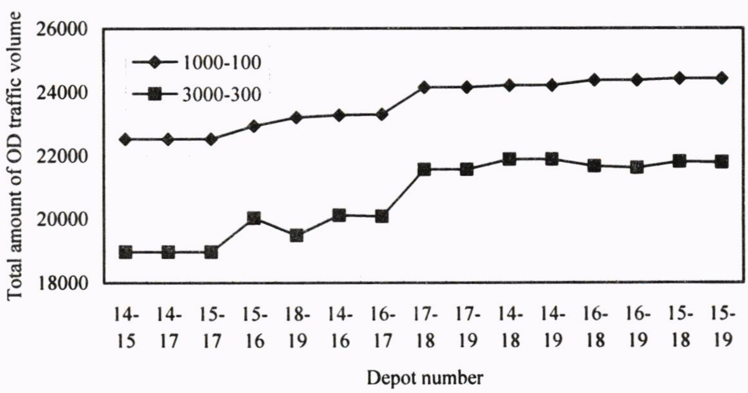


Figure 8. Total Amount of OD Traffic Volume to Each Location of Two Depots

## 5. CONCLUSION

The present study examines the determination of allowable private vehicle flows on a degraded road network when the travel demand exceed the road network capacity. In this paper, vehicles are classified into two categories. One is the private vehicle flows that read to be controlled when travel demand exceeds the capacity of a network. The other category is emergency vehicles carrying supplies and relief personnel, which are not controlled during a disaster emergency. The private vehicle flows is also formulated considering the classification of OD trips, namely internal-internal trip, internal-external trip, external-internal trip and through trip (external-external trip).

A two-modal, multi-commodity IP problem of maximizing the total amount of the OD traffic volume of private vehicle flows is formulated emergency vehicles being assigned the highest priority. The OD traffic pattern of private vehicle flows is analyzed between the unit OD traffic volume and the destination choice ratio for every zone. In particular, the paper deals with the problem of controlling the private vehicle flows which can be generated in and attracted to each zone considering the classification of OD trips and determining the location of the emergency vehicles depot.

To balance the travel demand (OD traffic volume) and the traffic supply (road network capacity on a degraded road network), OD traffic volume needs to be controlled by methods such as securing means of communication, banning business activities within the disaster area, reducing traffic by provision of food and water, providing information on public transportation and travel demand management. Traffic management, such as identifying bottleneck sections, route guidance by detour and provision of the latest information via ITS is also needed to regulate and control the traffic stream on a street.

Future research will be conducted on the recovery progress of degraded road network and its influence on changes in the OD traffic pattern. The effects of the depot location and travelling speed of emergency vehicles on evacuation, restoration and rescue time will also be analyzed based on this study. Since enlargement of the road network rapidly increases the number of OD pairs and variables, the research will include an application to an actual road network.

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