ALLOWABLE PRIVATE VEHICLE FLOWS IN EMERGENCY VEHICLE MANAGEMENT FOLLOWING EARTQUAKE DISASTERS

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Abstract

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. Since damage to urban road network due to a strong earthquake causes congestion in other parts of the network, efficient disaster traffic management is essential. 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 Linear Programming (LP).

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.

In this paper, vehicles are classified into two categories. One is the private vehicle flow 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. 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.

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 Linear Programming (LP). The OD traffic pattern of private vehicle flows is analyzed between the upper and lower limit on OD traffic volume, the destination choice ratio for every zone and unit OD traffic volume. Estimating the allowable OD traffic volume that can be generated in and attracted to each zone based on these OD traffic pattern of private vehicle flows is examined over a 9 node network model.

OD TRAFFIC PATTERN 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 OD traffic patterns.

Following an earthquake disaster, the OD traffic pattern representing the relative ratio of OD pairs differs from that under normal conditions. First considered calculation method of the maximum number of private vehicle flows which can be loaded onto the road network under for the case where only the upper and lower limits of OD traffic volume are set for each OD pair. Here, the upper limit is the maximum OD traffic volume that can be generated in and attracted to the zone, not being biased toward a particular OD pair but including the other OD pair. On the other hand, lower limit is the minimum OD traffic volume that need to be exclusively secured for each OD pair.

Next, changes in the OD traffic pattern during the restoration process are examined. The destination choice ratio and the unit OD traffic volume are considered as the OD traffic pattern. The destination choice ratio is the ratio of OD traffic volume to the total amount of OD traffic volume generated in each zone, and the unit OD traffic volume is the ratio to the total amount of OD traffic volume loaded onto the road network. As for the destination ratio, we estimate OD traffic volume for business and commuter trips when the degraded network is restored to a certain degree. As for the unit OD traffic volume, we consider the OD traffic volume when post-earthquake recovery progressed and traffic demand as the same level as under normal conditions exists.

In this paper, we examined the case where these two ratios and upper and lower limits on each OD pair are combined. Together with this OD traffic pattern, a multi-commodity, two-modal network flow problem is formulated with LP 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.

OD TRAFFIC VOLUMES BETWEEN UPPER AND LOWER LIMITS

The OD traffic volume of private vehicle flows can be calculated using various methods, depending on how the OD traffic pattern is treated. The following factors were considered: (1) The OD traffic pattern in an earthquake disaster is different from that under normal conditions. (2) The OD traffic volume for each OD pair should be maintained to a certain degree even in an earthquake disaster. OD traffic volume is therefore calculated for the case where only the upper and lower limits on OD traffic volume are set, without any restrictions on the OD traffic pattern. Next, a two-modal LP problem of maximizing the sum OD traffic volume of private vehicle flows (U_{ij}) can be formulated, accounting for emergency vehicles (E_{mn}), to which the highest priority should be given in the maintain transportation routes. The formulae are as follows:

$$\sum_{r \in u_{ij}} U_r^{ij} = U_{ij} \qquad (i \in I, j \in J) \tag{1}$$

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

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

$$\sum_{r \in u_{ij}} E_r^{mn} = E_{mn} \qquad (m = 1,2,\cdots M, n = 1,2,\cdots,N) \tag{4}$$

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

$$U_{ij}^L \leq U_{ij} \leq U_{ij}^U \quad (i \in I, j \in J) \tag{6}$$

$$U_r^{ij} \geq 0 \quad (i \in I, j \in J, r \in u_{ij}) \tag{7}$$

$$E_{mn} \geq 0 \quad (m = 1,2,\cdots M, n = 1,2,\cdots,N) \tag{8}$$

$$E_r^{mn} \geq 0 \quad (m = 1,2,\cdots M, n = 1,2,\cdots,N, r \in e_{mn}) \tag{9}$$

$$\sum_{i \in I} \sum_{j \in J} U_{ij} \rightarrow Max \tag{10}$$

Where

U_{ij}: traffic volume on an OD pair ij
U^{ij}_r: the r-th path traffic volume on an OD pair ij
I: set of generation zones
J: set of attraction zones
E_m: total number of emergency vehicles from supply node (depot) m
E_n: total number of emergency vehicles to demand node n
E_{mn}: number of emergency vehicles from supply node m to demand node n
E^{mn}_r: the r-th traffic volume on an emergency vehicle mn
M: number of supply nodes
N: number of demand nodes
C_a: capacity of link a
${}_a\delta^{ij}_r$, (${}_a\delta^{mn}_r$):if link a is on r-th path of OD pair ij (emergency vehicle mn), then =1, otherwise =0
u_{ij} (e_{mn}): set of OD pair ij (emergency vehicle mn) altered the route
U^L_{ij}: lower limit of traffic volume on an OD pair ij
U^U_{ij}: upper limit of traffic volume on an OD pair ij
A: set of links

Eqn. (1) refers to the origin and destination flow conservation constraint. 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 supply node (depot) m. Eqn. (5) represents the link capacity constraints; here the emergency vehicles are considered as well as OD traffic. The OD traffic volume can be calculated as a problem of maximizing the sum of the private vehicle flows loaded onto the road network in eqn. (10) under eqn. (1) - (9) as the constraint equation, including the constraints with respect to the variables of the route flow of OD pair in eqn. (7).

The OD traffic volume that can be generated in and attracted to the zone depend on the upper and lower limits of private vehicle flows in eqn. (6). For example, if the upper and lower limits are not set, only the OD traffic volume between adjacent zones connected by a link (equal to the traffic capacity of its link) becomes the optimal solution. Moreover, the total amount of private vehicle flows in eqn. (10) also becomes the sum of the traffic capacity of each link. On the other hand, if the lower limit is set so that the proportion of the longer trip OD traffic increases, the total amount of private vehicle flows in eqn. (10) decreases, since the longer trip OD traffic tends to use more links. Also, it is possible to set the upper and lower limits to be set to equalize all the OD traffic volume. Consequently, the upper and lower limits of private vehicle flows need to be properly set in consideration of the OD traffic volume to be maintained for each OD pair following an earthquake disaster.

As shown in eqn. (11), the total amount of private vehicle flows (O_i) for each zone is obtained as the sum of the OD traffic volume generated in and attracted to each zone. The total number of vehicles (NV) including emergency vehicles loaded onto road network is given in eqn. (12).

$$O_i = \sum_{j \in J} U_{ij} + \sum_{i \in I} U_{ji} \tag{11}$$

$$NV = \sum_{m=1}^{M} \sum_{n=1}^{N} E_{mn} + \sum_{i \in I} O_i \tag{12}$$

OD TRAFFIC VOLUMES UNDER A VARYING DESTINATION CHOICE RATIO

Here, we consider OD traffic volume for business and commuter trips when the degraded network is restored to a certain degree. The destination choice ratio (q_{ij}) for business and commuter trips is considered to calculate the OD traffic volume for private vehicle flows. The OD traffic volume for private vehicle flows is calculated by two kinds of traffic volume. One is the OD traffic volume ($q_{ij} \cdot Q_i$) based on the destination choice ratio; the other is the OD traffic volume (W_{ij}); in addition to the assigned OD traffic volume ($q_{ij} \cdot Q_i$) corresponding to the destination choice ratio, using the remaining capacity of each link to accommodate as many OD traffic volume as possible. Then, the LP problem of maximizing the sum of the OD traffic volume (W_{ij}) in consideration of both the OD traffic volume ($q_{ij} \cdot Q_i$) and the emergency vehicles (E_{mn}) is formulated as follows:

$$\sum_{r \in n_{ij}} X_r^{ij} = q_{ij} \cdot Q_i \quad (i \in I, j \in J) \tag{13}$$

$$\sum_{r \in n_{ij}} W_r^{ij} = W_{ij} \quad (i \in I, j \in J) \tag{14}$$

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

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

$$\sum_{r \in u_{ij}} E_r^{mn} = E_{mn} \qquad (m = 1,2,\cdots M, n = 1,2,\cdots,N) \tag{4}$$

$$\sum_{i \in I} \sum_{j \in J} \sum_{r \in u_{ij}} {}_a\delta_r^{ij} \cdot W_r^{ij} + \sum_{i \in I} \sum_{j \in J} \sum_{r \in u_{ij}} {}_a\delta_r^{ij} \cdot X_r^{ij} + \sum_{m=1}^{M} \sum_{n=1}^{N} \sum_{r \in e_{mn}} {}_a\delta_r^{mn} \cdot E_r^{mn} \le C_a \quad (a \in A) \tag{15}$$

$$Q_i \ge Q_i^L \qquad (i \in I) \tag{16}$$

$$W_{ij} \ge 0 \qquad (i \in I, j \in J) \tag{17}$$

$$W_r^{ij} \ge 0 \qquad (i \in I, j \in J, r \in u_{ij}) \tag{18}$$

$$X_r^{ij} \ge 0 \qquad (i \in I, j \in J, r \in u_{ij}) \tag{19}$$

$$E_{mn} \ge 0 \quad (m = 1,2,\cdots M, n = 1,2,\cdots,N) \tag{8}$$

$$E_r^{mn} \ge 0 \quad (m = 1,2,\cdots M, n = 1,2,\cdots,N, r \in e_{mn}) \tag{9}$$

$$\sum_{i \in I} \sum_{j \in J} W_{ij} \rightarrow Max \tag{20}$$

Where

X^{ij}_r, W^{ij}_r : the r-th traffic volume on an OD pair ij

q_{ij}: destination choice ratio on an OD pair ij $\left(\sum_{j \in J} q_{ij} = 1 \quad i \in I \right)$

Q_i: total amount of OD traffic volume generated from zone i

Q^L_i: lower limit of total amount of OD traffic volume generated from zone i

Eqn. (13) represents the origin and destination flow conservation constraint based on the destination choice ratio. Eqn. (15) represents the link capacity constraints; here the emergency vehicles are considered as well as OD traffic. Eqn. (16) represents the lower limit of total amount of OD traffic volume generated from the zone, and it is best to set the lower limit by balancing how many OD traffic volume should be generated in each zone. Consequently, the problem of maximizing the sum of the OD traffic volumes (W_{ij}) in eqn. (20) is presented including eqn. (13) - (19), (2)-(4) and (8)-(9) as constraint equations.

Eqn. (21) represents the private vehicle flows generated in and attracted to each zone and as shown eqn. (22), 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. (23).

$$V_{ij} = \sum_{i \in I} \sum_{j \in J} (W_{ij} + q_{ij} \cdot Q_i) \tag{21}$$

$$O_i = \sum_{j \in J} V_{ij} + \sum_{i \in I} V_{ji} \tag{22}$$

$$NV = \sum_{m=1}^{M} \sum_{n=1}^{N} E_{mn} + \sum_{i \in I} O_i \tag{23}$$

OD TRAFFIC VOLUMES CONSIDERING UNIT OD TRAFFIC VOLUME

This section describes the calculation of OD traffic volume when post-earthquake recovery has progressed and travel demand is at the same level as under normal conditions. In this case, the OD traffic volume for private vehicle flows is calculated by, as mentioned in Section 4, two kinds of traffic volume: the OD traffic volume ($p_{ij} \cdot F$) based on the unit OD traffic volume; and the OD traffic volume (Z_{ij}). In addition to the assigned OD traffic volume ($p_{ij} \cdot F$) corresponding to the unit OD traffic volume, using the remaining capacity of each link to accommodate as many OD traffic volume as possible. Therefore, the LP problem of maximizing the sum of the OD traffic volume (Z_{ij}) when varying both the OD traffic volume ($p_{ij} \cdot F$) and the emergency vehicles (E_{mn}) is formulated as follows:

$$\sum_{r \in u_{ij}} Y_r^{ij} = p_{ij} \cdot F \qquad (i \in I, j \in J) \tag{24}$$

$$\sum_{r \in u_{ij}} Z_r^{ij} = Z_{ij} \qquad (i \in I, j \in J) \tag{25}$$

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

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

$$\sum_{r \in u_{ij}} E_r^{mn} = E_{mn} \quad (m = 1, 2, \cdots M, n = 1, 2, \cdots, N) \tag{4}$$

$$\sum_{i \in I} \sum_{j \in J} \sum_{r \in u_{ij}} {}_a\delta_r^{ij} \cdot Y_r^{ij} + \sum_{i \in I} \sum_{j \in J} \sum_{r \in u_{ij}} {}_a\delta_r^{ij} \cdot Z_r^{ij} + \sum_{m=1}^{M} \sum_{n=1}^{N} \sum_{r \in e_{mn}} {}_a\delta_r^{mn} \cdot E_r^{mn} \leq C_a \quad (a \in A) \tag{26}$$

$$F \geq F^L \tag{27}$$

$$Z_{ij} \geq 0 \qquad (i \in I, j \in J) \tag{28}$$

$$Z_r^{ij} \geq 0 \qquad (i \in I, j \in J, r \in u_{ij}) \tag{29}$$

$$Y_r^{ij} \geq 0 \qquad (i \in I, j \in J, r \in u_{ij}) \tag{30}$$

$$E_{mn} \geq 0 \quad (m = 1,2,\cdots M, n = 1,2,\cdots,N) \tag{8}$$

$$E_r^{mn} \geq 0 \quad (m = 1,2,\cdots M, n = 1,2,\cdots,N, r \in e_{mn}) \tag{9}$$

$$\sum_{i \in I} \sum_{j \in J} Z_{ij} \rightarrow Max \tag{31}$$

Where

Y^{ij}_r, Z^{ij}_r: the r-th traffic volume on an OD pair ij

p_{ij}: unit OD traffic volume on an OD pair ij $\left(\sum_{i \in I} \sum_{j \in J} p_{ij} = 1 \right)$

F: traffic demand

F^L: lower limit of traffic demand

Eqn. (24) represents the origin and destination flow conservation constraint based on the unit OD traffic volume. The problem of maximizing the sum of the OD traffic volume (Z_{ij}) in eqn. (31) is presented including the constraint equations (24) - (30), (2)-(4) and (8)-(9), as described in Section 4. Eqn. (32) and (33) represent the OD traffic volume generated in and attracted to each zone and the total amount of private vehicle flows (O_i) for each zone, respectively. The total number of vehicles (NV) including emergency vehicles loaded onto road network is given in eqn. (34).

$$V_{ij} = \sum_{i \in I} \sum_{j \in J} (Z_{ij} + p_{ij} \cdot F) \tag{32}$$

$$O_i = \sum_{j \in J} V_{ij} + \sum_{i \in I} V_{ji} \tag{33}$$

$$NV = \sum_{m=1}^{M} \sum_{n=1}^{N} E_{mn} + \sum_{i \in I} O_i \tag{34}$$

NUMERICAL EXAMPLE

To illustrate the discussion in the previous Section, let us consider the 9-node road network depicted in Figure 1 and the unit OD traffic volume under normal conditions listed in Table 1 (upper right half). The traffic capacity of each link is 1800 on a normal road network. Then, calculation of the road network capacity under the unit OD traffic volume in Table 1 gives 12944. Let the travel demand under normal conditions be equal to the OD traffic volume corresponding to the road network capacity listed in Table 1 (lower left half). The LP models were solved using the LINDO software What'sBest.

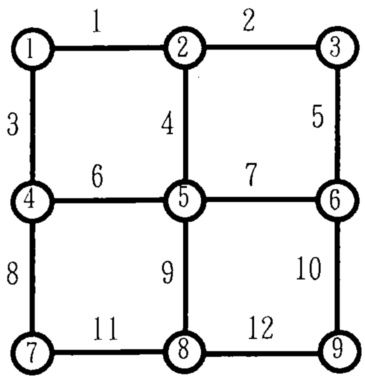

Figure 1 - Test road network

Table 1 - Unit OD traffic volume and OD traffic volume

	1	2	3	4	5	6	7	8	9	sum
1		0.0427	0.0294	0.0427	0.0301	0.0157	0.0294	0.0157	0.0107	0.1082
2	553		0.0427	0.0191	0.0396	0.0191	0.0157	0.0191	0.0157	0.1069
3	380	553		0.0157	0.0301	0.0427	0.0107	0.0157	0.0294	0.1082
4	553	248	204		0.0396	0.0191	0.0427	0.0191	0.0157	0.1069
5	390	512	390	512		0.0396	0.0301	0.0396	0.0301	0.1394
6	204	248	553	248	512		0.0157	0.0191	0.0427	0.1069
7	380	204	139	553	390	204		0.0427	0.0294	0.1082
8	204	248	204	248	512	248	553		0.0427	0.1069
9	139	204	380	204	390	553	380	553		0.1082
sum	1401	1384	1401	1384	1805	1384	1401	1384	1401	

Various calculation are carried out using a degrade road network where the traffic capacity has been reduced to 1200 for links connected to the central node 5, and 600 for all other links. Calculation of the road network capacity on a degraded road network gives 5282, less than half the correspond capacity on a normal road network. The following three cases are taken into account of emergency vehicles such as ambulance, rescue and relief transportation, with nodes 2 and 8 used as the depot node (supply node). Case 1 does not take account of emergency vehicles in order to evaluate the resultant impact on them. In case 2, node 2 and 8 are used as the depot nodes to delivery 100 emergency vehicles to the other demand nodes (evacuation spots). Case 3 uses only node 2 as the depot node to delivery 100 vehicles to the other demand nodes.

First, the OD traffic volume considering the upper and lower limits are estimated. The upper limits for each OD pair is set at the OD traffic volume under normal conditions listed in Table 1. Lower limits are set at 0, 50, and 100 shown in Table 2 and Figure 2. For each of the emergency vehicle cases, the total amount of OD traffic volume for each lower limits are calculated, and shown in Table 2 and Figure 2. These results suggest that the number of emergency vehicles and depot nodes affect the OD traffic volume of private vehicle flows.

Table 2 . otal amount of OD traffic volume between upper and lower limits of OD traffic volume

Lower limit	0	50	100
case 1	8036	7224	6000
case 2	7480	6574	5100
case 3	7172	6143	4500

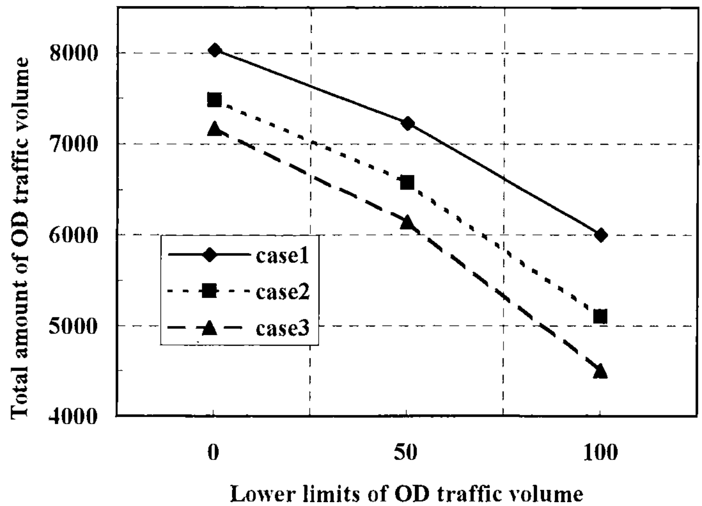

Figure 2 - Total amount of OD traffic volume between upper and lower limits of OD traffic volume

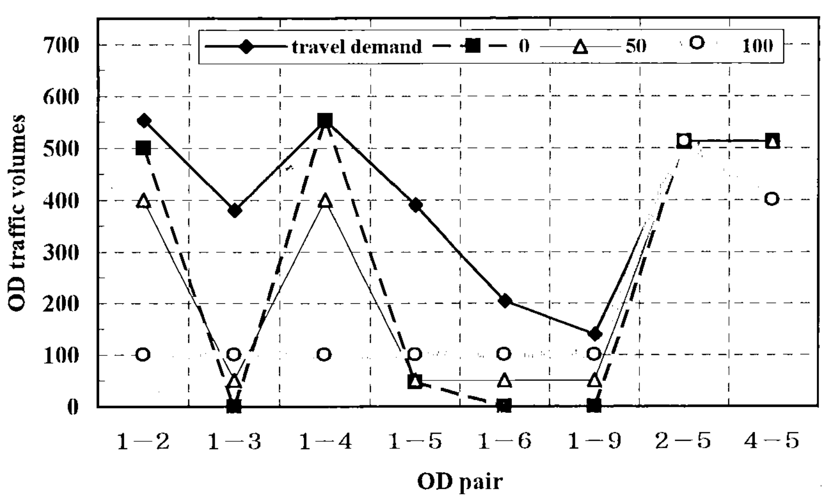

Figure 3 - OD traffic volume for each OD pair

When the lower limits of each OD pair is set at a large value, the total amount of the OD traffic volume decreases. This is because smaller lower limits only allow specific OD pairs to be generated and attracted, increasing the total amount of OD traffic volume. Conversely, larger lower limits allow longer trip OD pairs to be generated and attracted, as a result, the total amount of OD traffic volume decrease. When no consideration is given to emergency vehicles and no upper limits are set the total amount of OD traffic volume is 9600. This value equals the sum of the traffic capacity of links. Regarding OD pairs, only the OD traffic volume between adjacent zones connected by a link can be generated and attracted, as illustrated by 600 of OD 1-2 and 1200 of OD 2-4. In this example, the OD traffic volume to equalize the value of each OD pair equals 133.

Figure 3 shows the OD traffic volume that can be loaded on a degraded road network for each lower limit corresponding to emergency vehicles under case 2. These result suggest that the OD traffic volume depend on factors such as lower limits and the trip length of OD pairs (e.g., OD 1-3 and OD 1-4). Therefore, when managing emergency vehicles and controlling private vehicle flows following an earthquake disaster, it is necessary to set the upper and lower limits of OD traffic volume depending on how many the OD traffic volume for OD pair should be generated and attracted.

Table 3 shows the destination choice ratio for each OD pair based on the unit OD traffic volume under normal conditions listed in Table 1. The upper limit of OD traffic volume for V_{ij} in eqn. (21) is set at the OD traffic volume listed in Table 1, as in previous case of considering the upper and lower limits. The lower limits of total amount of OD traffic volume (Q_i) generated from zone i are set at 0, 100, 200, 300 and 400 shown in Table 4 and Fig. 4. Table 4 and Figure 4 show the total amount of OD traffic volume calculated for each of the emergency vehicle cases and for each lower limit.

As in the case of considering the upper and lower limits, increasing the number of emergency vehicle decrease the OD traffic volume of private vehicle flows and the number of depot nodes markedly decrease the OD traffic volume. The total amount of OD traffic volume decreases according as the lower limit of total amount of OD traffic volume generated from zone increase. Figure 5 shows the OD traffic volume for each lower limit corresponding to emergency vehicles under case 2. The minimum OD traffic volume for each OD pair is secured under the lower limit of total amount of OD traffic volume generated from zone.

Table 3 - Destination choice ratio for each OD pair

	1	2	3	4	5	6	7	8	9	sum
1	0.0000	0.1974	0.1356	0.1973	0.1392	0.0726	0.1356	0.0726	0.0496	1.0000
2	0.1998	0.0000	0.1997	0.0895	0.1850	0.0895	0.0735	0.0895	0.0736	1.0000
3	0.1356	0.1973	0.0000	0.0726	0.1392	0.1973	0.0496	0.0726	0.1356	1.0000
4	0.1998	0.0895	0.0735	0.0000	0.1850	0.0895	0.1998	0.0895	0.0735	1.0000
5	0.1081	0.1419	0.1081	0.1419	0.0000	0.1419	0.1081	0.1419	0.1081	1.0000
6	0.0735	0.0895	0.1998	0.0895	0.1850	0.0000	0.0735	0.0895	0.1998	1.0000
7	0.1356	0.0726	0.0496	0.1973	0.1392	0.0726	0.0000	0.1973	0.1356	1.0000
8	0.0735	0.0895	0.0735	0.0895	0.1850	0.0895	0.1997	0.0000	0.1998	1.0000
9	0.0496	0.0726	0.1356	0.0726	0.1392	0.1973	0.1356	0.1973	0.0000	1.0000

Table 4 - Total amount of OD traffic volume with varying destination choice ratio

Lower limit	0	100	200	300	400
case 1	8036	7890	7555	7221	6887
case 2	7480	7240	6905	6571	6237
case 3	7172	6869	6537	6147	5667

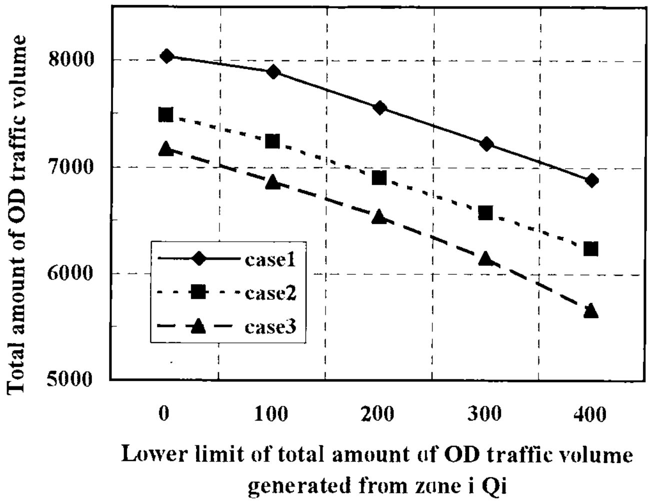

Figure 4 - Total amount of OD traffic volume with varying destination choice ratio

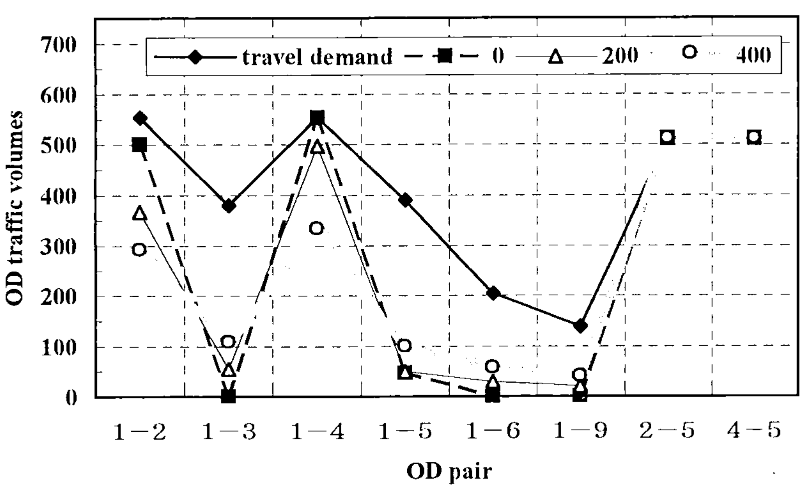

Figure 5 - OD traffic volume for each OD pair

Table 5 - Total amount of OD traffic volume with varying unit OD traffic volume

Lower limit	0	1000	2000	3000	4000
case 1	8036	7856	7489	7121	6753
case 2	7480	7206	6839	6471	6025
case 3	7172	6845	6462	6034	5425

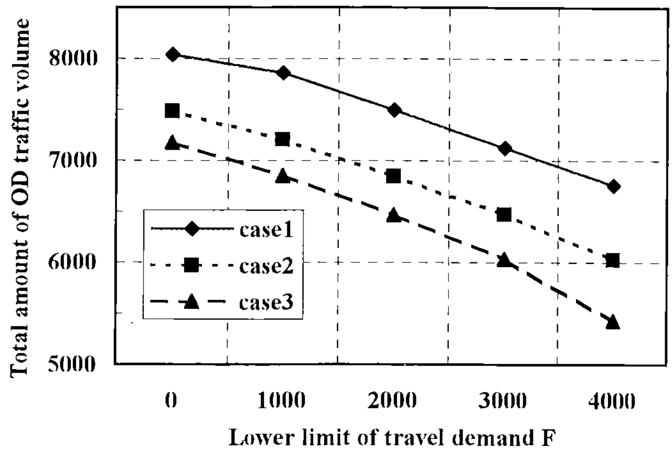

Figure 6 - Total amount of OD traffic volume with varying unit OD traffic volume

The OD traffic volume (W_{ij}) using the remaining capacity of each link to accommodate as many OD traffic volume as possible depend on its trip length. For example, when OD 1-4 is compared with OD 1-6 for 400 of Q_i, the OD traffic volume of OD 1-4 with shorter trip is 334 compared with 58 of OD 1-6 which has a longer trip length as shown in Figure 5. Therefore, it is important to set the lower limits of total amount of OD traffic volume considering how many the OD traffic volume should be generated in each zone.

Table 5 and Figure 6 show the result when the unit OD traffic volume for each OD pair is taken account. Increasing the lower limit of travel demand make the total amount of the OD traffic volume decrease to 5282, the road network capacity mentioned previously. The effect of the emergency vehicles and depot on the total amount of the OD traffic volume is the same as the case of the destination choice ratio as shown in Table 5 and Figure 6. This result stems from the fact that the destination choice ratio is set based on the unit OD traffic volume, and that the lower limit of the sum OD traffic volume generated from each zone is set at the same value. Therefore, the general trend of the OD traffic volume for each OD pair turned out to be similar to that of the destination choice ratio.

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, the vehicles are classified into two modes: emergency vehicles for rescue, relief operation and restoration, and private vehicle flows. A two-modal, multi-commodity LP 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 upper and lower limit of the OD traffic volume, the destination choice ratio for every zone and the unit OD traffic volume.

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 spatial allocation of depot nodes for emergency vehicles on the total amount of OD traffic volume 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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