Modeling the Gradual Flooding of Pickup Points in Bus-Based Flood Evacuation Planning

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In the literature about bus-based evacuation planning, although different scenario analyses for the evacuation planning have been discussed to simulate specific scenarios, however, gradual unavailability of certain pickup points to simulate earlier local floods or the evacuation operation during the floods is still missing. In this study, a scenario has been analyzed to simulate such situation. The model for short-notice bus-based evacuation under dynamic demand conditions (SBED model) is used and its suitability for this purpose is checked through a case study of the evacuation planning for Kawajma Town. The pickup points are assumed to become unavailable gradually after lapse of certain specified time due to flooding of those areas. The buses are not allowed to move to those pickup point from any other point or shelter after such time. The results indicate that the SBED model takes into account the sequence of gradual flooding of pickup points if and only if the number of buses available for evacuation operation are sufficient to complete the evacuation of all evacuees. On the contrary, if the buses are insufficient, the model maximizes the number of evacuees by performing bus trips to pickup points nearest to the shelter, irrespective to the flooding of points.

Key Words : *evacuation models, bus-based evacuation, gradual flooding*

1. INTRODUCTION

In the literature, researchers have tried to identify the various possible bottlenecks involved in evacuation planning through simulating different scenarios. The details can be found in a broad overview of evacuation transportation modeling by P.Murray-Tuite 20213[1)], while Hector LIM 2013[2)] has specifically summarized recent studies on flood evacuation planning. These scenarios include, but not limited to, demand uncertainity[3,4)], different arrival patterns of evacuees and analysis of demand variations[5,6)], identifying and analyzing different evacuation route possibilities[5,7,8)], changes in travel pattern or travel behavior[9)], traffic volume variations in before during or after disaster cases[10)], relative effectiveness of simultaneous and staged evacuations[11,12)] and so on. The techniques proposed to minimize the evacuation time specifically for car-based or personal vehicle evacuations include crossing elimination or lane based evacuation[13)], contraflow operations[14)], special signal timings[15, 16)] and shoulder lane use[17)]. While most of the models for bus-based evacuation planning focused on maximizing the number of evacuees in avaialbe warning times[18,19,20,21)].

For flood disasters, warning systems are in place as predictive tools[22)]. Unfortunately, flood events continue to affect the people causing a massive damage to the lives and properties[23)]. The transit dependent citizens suffered a lot in such disasters[24)] with majority of victims as elderly due to their limited mobility[25)]. Studies in the literature about models used for short-notice evacuations use availability of all of the pickup points throughout the modeled warning time. The buses performing the evacuation operations are assumed to be available for this time[18,19,20,21)]. Only a study by Bish[20)] assumed that buses start their trips from the yards and finsh their evacuation operation at the shelter. In real situations, like for the case of Katrina and Rita, public-transport dependent citizens could not get evacuated as the drivers were either not available, or the drivers refused to go to the danger side areas[24]. Through an effective and timely communication about the flood forecasts, risk level to different areas posed by floods can be made well realized by the residents. This can help to get evacuate the people on one side, while the bus drivers can be motivated to perform evacuation operations on the other side. The important point to be investigated in our study is that of including the evacuation under gradual flooding of pickup points within the evacuation model i.e. modeling the evacuation operation during the flood occurence.

2. THE MODEL

We have used the model for short-notice bus-based evacuation under dynamic demand conditions (SBED model), which is based on a network called the time–space network (T-S network). The T-S network technique has already been used in the literature for network flow models developed to solve the problems involving time and space issues simultaneously[5,18,21,26,27]. The SBED model and the T-S network used for the model is explained in detail in the study by Qazi et al[18]. However, to get an idea, **Fig.1(a)** shows a sample road network and **Fig.1(b)** explains the transformed T–S network diagram with nodes and arcs for each road.

A mixed integer linear programming formulation of SBED model uses two decision variables: (1) x_{ij}: a continuous integer variable that represents the flow of evacuees from a point i to a point j (2) y_{ij}: a binary variable that equals 1 if there is any flow of evacuees from point i to point j, otherwise takes the value 0. Then, the model is;

Minimize

$$\sum_{(i,j)\in A} t_{ij} x_{ij} \tag{1}$$

Subject to

$$\sum_{\{j:(i,j)\in A\}} x_{ij} - \sum_{\{j:(j,i)\in A\}} x_{ij} = \begin{cases} \delta i & i \in P \\ 0 & i \in S \\ -\sum_{i\in P} \delta i & i \in D \end{cases} \tag{2}$$

$$x_{ij} - C.\, y_{ij} \leq 0 \qquad (i,j) \in M,\ i \in P \tag{3}$$

$$\sum_{\{(i,j)\in M\cup Wb\}} y_{ij} \leq \mathrm{B} \qquad \text{at time } \mathrm{T_0} \tag{4}$$

$$\sum_{\{j:(i,j)\in M\cup Wb\}} y_{ij} - \sum_{\{j:(j,i)\in M\cup Wb\}} y_{ij} = 0 \qquad \forall\ \mathrm{N}\ \mathrm{T_t}\ \text{to}\ \mathrm{T_{t-1}} \tag{5}$$

$$x_{ij} \geq 0 \qquad (i,j) \in A \tag{6}$$

$$y_{ij} \in \{0,1\} \qquad (i,j) \in M \tag{7}$$

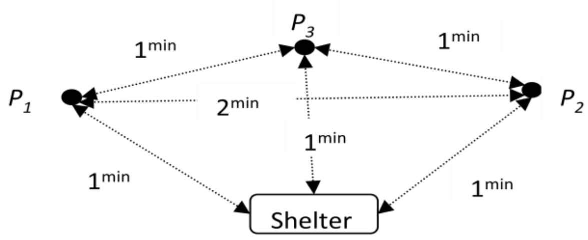

Fig. 1(a) Sample road network

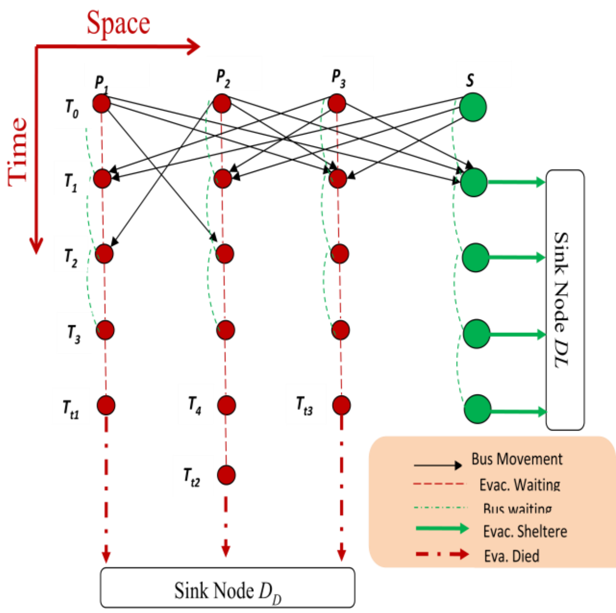

Fig. 1(b) Time-Space network diagram

where

t_{ij} = Travel time on arc ij

N = Set of shelter nodes and pickup nodes

P = Set of pickup nodes

S = Set of shelter nodes

D = Set of sink nodes (D_L and D_D)

A = Set of all types of arcs

M = Set of bus movement arcs for all types of bus movements.

W_b = Waiting arcs for bus

δ_i= Supply of evacuees at pickup point $i \in P$

C = Capacity of the bus.

B = Total number of available buses

$\mathrm{T_0}$ = Start time for evacuation

$\mathrm{T_t}$ = Warning time / flooding time of a pickup point

To model the gradual flooding of pickup points, variable warning time of the pickup points is taken in the T-S network. Waiting arcs for the bus as well well as for the evacuees are ended by this time at that particular pickup point. No more bus movement arc is drawn from/to this point. After the lapse of this warning time, sink arcs from the pickup points are drawn accordingly, as shown in **Fig.1(b).**

3. CASE STUDY

A case study for the evacuation planning of Kawajima Town, Saitama is presented in this section. Evacuation of people living therein, especially of the old ones and the people with disabilities, is proposed by the design and planning laboratory of Saitama University through running a community bus service on a small scale. At first, five evacuation areas, A, B, C, D, and E are selected to serve as the pickup points of the evacuees for proposed bus service. A building of agricultural center is specified to act as an uncapacitated shelter denoted by “S”. An approximate location of all these points is shown in **Fig.2**.

Travel times between these five pickup points and the shelter were observed through a field bus survey. After providing a cushion for loading and unloading of evacuees alongwith their luggage, the data of travel times used in the model is as shown in **Table 1.** To estimate the number of evacuees using the community bus service for their evacuation to a public shelter, 10% of people of age over 65 years are considered. The flood is expected to expand in different areas of the town gradually. A flood propagation simulation was prepared by the hydraulics lab of Saitama University for this purpose. After providing a margin for safe bus operation, time to get flooded for each pickup point and get isolated from rest of the points is summarized in **Table 1.**

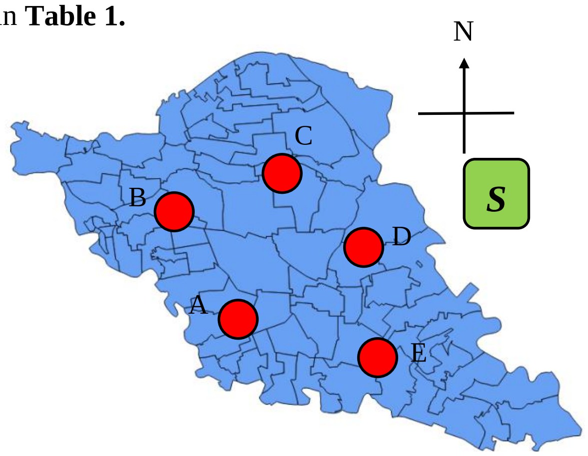

Fig.2 Kawajima Town with selected pickup points and shelter

Table 1 Travel times, Evacuees and Flooding Time Data

From / To	Travel Times (min)						No. of Evac.	Flooding Time (hrs)
	A	*B*	*C*	*D*	*E*	*S*		
A	0	10	15	20	10	25	207	5.5
B	10	0	10	15	15	20	209	2.5
C	15	10	0	10	15	20	125	7.5
D	20	15	10	0	10	10	147	8
E	10	15	15	10	0	15	83	8
S	25	20	20	10	15	0	-	-

For the case of normal evacuation, model is prepared for a maximum warning time of 8 hrs as three of the five pickup points get flooded by this time and the need for running the model is seized for only two points. Whereas, for the second case of gradual flooding, flood times shown in **Table 1** are used as warning times for each pickup point. A comprehensive T–S network diagram is constructed for all of the said three different cases, by considering 5 minutes as the time unit. i.e. for 8 hrs warning time, 96 time units are used in the T-S network diagram. Only one bus at a time is allowed to move and/or wait between any two nodes in the network. A bus capacity of 25 people is used for the proposed community bus.

4. RESULTS AND DISCUSSION

The model was written in and solved by using the optimization toolbox function (intlinprog) for mixed integer linear programming of Matlab R2014a. The computer used for this purpose has a 64-bit operating system and Intel(R) Core (TM) i5-2400S CPU @ 2.50 GHz, 2.50 GHz processor with an installed memory (RAM) of 4.00 GB. The maximum run-time for the model was changed to 3 hrs for all model runs.

The summary of results for the three cases is tabulated in **Table 2.** The evacuation of all 771 evacuees was completed by using three buses for both cases 1 and 2. The results for the two cases are also shown graphically in **Fig.3** below. By looking at **Fig.3,** we can observe that pattern of evacuation for the case 2 is apparently similar to that of case 1. Does it mean that the effect of gradual flooding proved to be negligible and the resulted bus trip pattern for the case 2 remained similar to that of the case 1?. More precisely, the SBED model could not take into account the priority of pickup points induced in the T-S network diagram through variable warning times. For such analysis, firstly we need to compare the bus trip patterns for the model runs to see whether or not, there is any effect of gradual flooding on the resulted bus trip output. Secondly, the bus trip patterns of the output of the model runs for all three buses of the case 2 itself need to be investigated in more details.

Table 2 Summary of the results for the two cases

No. of buses	Number of evacuees for the	
	Case 1	*Case 2*
1	395	380
2	672	655
3	771	771

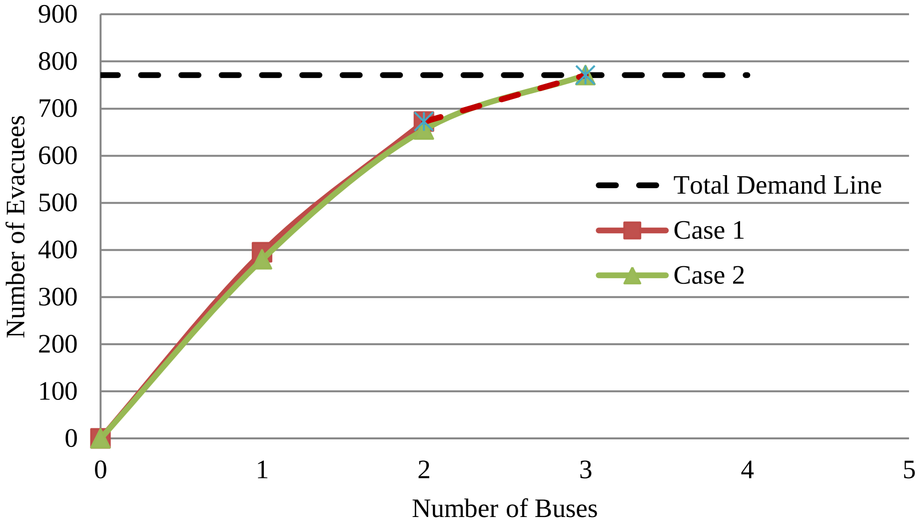

Fig.3 Number of evacuees with number of buses used for the two cases

(4.1) Bus trip pattern analysis

To observe in detail the bus trip patterns for the two cases, the trip patterns for one bus are compared as tabulated in **Table 3** and shown in **Fig.4** below. The order of priority of evacuating the pickup points as indicated in **Table 3** is found as D, E, C, B and then A for the two cases (1 and 2). The order of priority for the model runs of case 1 and case 2 is exactly the same as that of the order of travel times from the shelter. i.e. pickup point D is the nearest one from the shelter with travel time of 10 min only. Then comes point E with travel time of 15 min and so on. The pickup point A is the farthest one with travel time of 25 min to the shelter. Similar pattern was observed for the case 2 while using two buses. As the bus trip pattern follows the priority order of travel times of pickup points to shelter irrespective of the flooding times of the pickup points, it means that the SBED model is not suitable for modeling the scenario of gradual flooding of pickup points. For this let us look at the complete output for the case 2 using one bus, two buses and three buses. The evacuees by using one bus case were 380 that were increased to 655 for the two buses with 355 by one bus, say B1 and 305 by the second bus, say B2. For the case of three buses the evacuation completed in 81 time units (6 hrs and 45 min) and the number of evacuees by each bus again shuffled to 250, 250 and 271 by B1, B2 and B3 respectively. One of the main reason for shuffled / different number of evacuees by the same bus, say B1, in three model runs is that of restricting the maximum number of bus movements between any of the two points to one bus only. The model re-arranges the bus trips every time when additional bus is put into the evacuation operation.

Table 3 Details of the bus trip output using one bus

P/up Point	Travel time to shelter	No. of evac-uees	No.of Evacuees sheltered by One-Bus			
			Case 1		Case 2	
			Evac.	Evac. (%)	Evac.	Evac. (%)
A	25	207	0	0	0	0
B	20	209	73	35	25	12
C	20	125	100	80	125	100
D	10	147	147	100	147	100
E	15	83	75	90	83	100
Priority order of evacuating the pickup points			D E C B A		D E C B A	

The summary of results for the case 2 for three different model runs by using one bus , two buses and three buses is presented in **Table 4**. For the case of using one bus or two buses, the priority of pickup points was based on the distance to shelter (and the number of evacuees) only, irrespective to the flooding of the pickup points. This output is quite similar to a no-notice evacuation model output, for which the evacuees at all points are assigned equal importance. The people not possible to save at any of the point equally contribute in the model objective function value. However, when the input number of buses were increased to three, the priority order is found exactly the same as that of the gradual flooding of the pickup points. i.e. B, A, C, E, and then D as shown in **Table 4**. Hence, the suitability of SBED model for modeling the gradual flooding is justified and the priority of the pickup points based on flooding pattern is preferred over the minimum travel time to the shelter criteria, if and only if the busses are available to evacuate the farther pickup points as well.

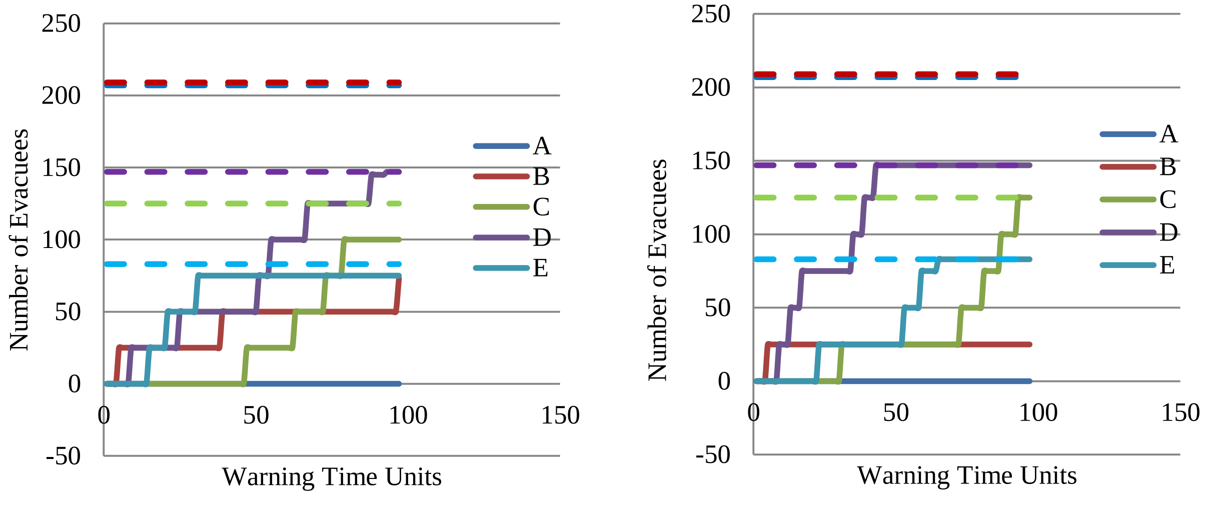

Fig.4 Number of evacuees with warning time lapsed using one bus for the two cases

Table 4 Summary of results for the case 2

Pickup Point	Travel time to shelter "S"	Total demand of evacuees	Flooding Time of point	Number of Evacuees by using		
				One Bus	Two Buses	Three Buses
A	25	207	5.5	0	150	207
B	20	209	2.5	25	150	209
C	20	125	7.5	125	125	125
D	10	147	8	147	147	147
E	15	83	8	83	83	83
Evacuation priority order of pickup points				D E C B A	D E C B A	B A C E D

Another way to restrict the bus trips to start from the preferred pickup points i.e. the points going to get flooded at earlier times is that of assigning much higher travel costs for sink arcs from these points compared to those from the others. We used this technique and assigned higher sink arc values according to flooding time of pickup points. The number of evacuees possible to shelter within the 8 hrs by using one bus for case 2 were reduced to 175 from 380. However, the evacuees were moved on priority from the points to be flooded earlier assigned higher sink arc values (A, B) to the points with lower sink arc values (C, E respectively). All of 207 evacuees at point A were shifted to point C, whereas 200 evacuees out of 209 at point B were shifted to point E. In later bus trips, bus trips were performed from the points nearest to the shelter (D) to maximize the evacuees sheltered. The number of bus trips between the pickup points were observed to be maximum for this unique case. Complete evacuation for this case was also observed by using 3 buses, but in higher evacuation completion time. It may thus be concluded that priority of evacuating the pickup points can be achieved through assigning high sink arc values but at the cost of optimality of the model output.

5. CONCLUSIONS

In this study, the model for short-notice bus-based evacuation under dynamic demand conditions (SBED model) is used and its suitability to model the gradual flooding is checked. A case study has been developed for the evacuation planning of Kawajma Town. The selected pickup points are assumed to become unavailable gradually after lapse of certain specified known time. The buses are no more allowed to move to/from that pickup point from/to any other point or shelter after such times. Two different cases, the case of normal evacuation, and the evacuation under gradual flooding of points were analysed and a comparison between the results is made to find out the difference in bus trip patterns for these cases.

It was observed that the number of evacuees were almost same for case of gradual flooding as that of normal warning time. The reason for this is higher flooding time intervals between the different pickup points. Secondly, for the bus trip patterns, the model does not consider any other factor to prioritize the evacuation of any particular point over the criteria of minimum travel time to shelter (and number of evacuees at a point) as long as the number of buses available are less than those required for complete evacuation. The model working is quite similar to no-notice evacuation models. However, once the number of buses were 3 i.e. complete evacuation is observed, the priority order of evacuation of pickup points came out to be exactly the same as that of order of gradual flooding for case 2. This finding confirms the suitability of SBED model for its use in modeling the gradual flooding of pickup points.

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