510 Project Paper
Bus Evacuation in Wildfire

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1 Introduction

People are always threatened by natural disasters, such as wildfires or tsunamis. When encountering similar events, people are always required to conduct large-scale evacuations as much as possible to reduce the number of people affected. In the past, research has always focused on the self-evacuation of cars, for example, Julia Romanski et al. [1] considered an evacuation planning model for the affected people in a flood scenario. From the perspective of self-evacuation, they used the most efficient use of the road network's traffic capacity as the objective function, and used a two-stage benders decomposition to solve it, and obtained the best solution. Based on their research, KA Isalm et al.[2] considered the impact of the evacuation sequence in the evacuation plan on self-evacuation fairness and proposed two new objective functions: (1) minimizing the maximum inconvenience; (2) minimizing the average inconvenience, thus an evacuation model was constructed and a new MIP-LNS heuristic algorithm was proposed to solve it. Finally, it was tested on a large-scale road network in Texas. The results showed that it achieved a good balance between evacuation efficiency and fairness.

However, this kind of self-evacuation always seems to conflict with the goal of evacuation. To maximize the efficiency of transportation and reduce the number of disaster-stricken evacuees, it is necessary to concentrate administrative efforts on the unified evacuation and management of the affected people. From this point of view, standing at the intersection of self-evacuation and unified evacuation, Lu et al.[3] considered that shared mobility and carpooling can be used to evacuate the masses. He developed a multi-driver system based on a vehicle spatio-temporal network. The network flow model is solved using the Lagrangian relaxation method, and the results show that it can support more personalized travel for passengers while meeting evacuation demands.

However, the above evacuation methods still rely on cars with smaller capacities to assist people in evacuation, which still cannot meet the demands of most evacuees. Considering the public welfare attributes of evacuation vehicles and some disadvantaged groups who lack transportation tools, it is obvious that public traffic evacuation is a more effective evacuation method because it can be managed uniformly and accommodate large-scale evacuees more effectively. Given the characteristics of remote and isolated communities that are more susceptible to disasters, Krutein et al.[4] developed a public transportation evacuation model based on limited resources, to minimize evacuation time and optimal resource allocation, and extended it to a two-stage stochastic model. For planning problems, numerical experiments were finally conducted to verify their method. Zhao et al.[5] proposed a round-trip bus evacuation model based on unfixed routes while optimizing bus dispatching and route planning. The model aims to reduce the total evacuation time, including in-vehicle travel time and waiting time. In addition, a two-layer algorithm integrating the insertion algorithm and edge exchange algorithm is designed to obtain the suboptimal solution of the model.

Our purpose is to form a set of pick-up and delivery schedules for evacuation that can be performed by buses. We assume that a large number of evacuees who need to be evacuated gather at some stations(evacuation points) in the road network, and the buses will iteratively travel between the site and the safe point to achieve the shortest possible evacuation. Considering the advancement of the isolated community evacuation model design mentioned above, we will conduct modeling based on their research.

2 Model

2.1 Problem Description

The Bus Evacuation Problem consists of the planification of a large-scale evacuation. In an emergency situation, such as wildfires in our project, it's necessary to evacuate a large zone with the help of public transportation. This kind of evacuation is mainly intended for transit-dependent people, who cannot leave the zone by themselves due to different mobility problems.

In our project, an evacuation scenario is composed of the following elements:

- **Depots**: Points where buses are located at the beginning of the whole evacuation process.
- **Evacuation Points**: Points distributed in the city where people can take on buses to make evacuation.
- **Safe Points**: Points located outside the endangered zone, where the evacuees will be delivered by the buses. Each safe point should have its own capacity.
- **Buses**: Public transport vehicles that can pick up and deliver the evacuees. Each of them will have the same capacity.
- **Evacuees**: People who need to make an evacuation to escape from the endangered zone. All evacuees will wait at the evacuation points.

Then we can assume an evacuation scenario shown in the following model diagram in Figure 1.

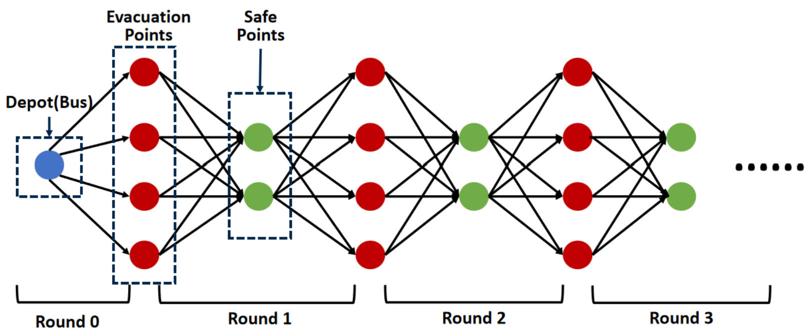


Figure 1: Model diagram. According to the model diagram, we assume at the beginning of the evacuation, All buses will leave the depot and go to evacuation points to pick up evacuees. In the subsequent process, buses will continue to travel between evacuation points and safety points until all evacuation demands are met.

2.2 Mathematical Model

In this section, we will introduce the details of our model. In our model, we have 3 kinds of nodes[6]: D, P, and S. D is the set of depots, depots will be the origin of the evacuation process. P is the set of evacuation points, all evacuees will wait here to take buses. And S is the set of safe points, all evacuees will be dispatched here by buses B, we set each bus has the same capacity Q, each evacuation $p \in P$ has some evacuation demand d_p, and for each safe point $s \in S$, it has limit capacity C_s, time cost between depot $d \in D$ and evacuation point $p \in P$ is $\tau_{dp} \geq 0$, and time cost between evacuation point $p \in P$ and safe point $s \in S$ is $\tau_{ps} \geq 0$. To better model the evacuation process, we consider the process of buses picking up evacuees from the evacuation point and transporting them to a safe point as a round evacuation $r \in R$.

we set several decision variables as follows:

(1) x_{ps}^{br}: whether a bus $b \in B$ transport evacuees from the evacuation point $p \in P$ to the safe point $s \in S$ in the round $r \in R$.

(2) t_{to}^{br}: The time it takes the bus $b \in B$ to travel from the evacuation point to the safe point in the round $r \in R$.

(3) t_{re}^{br}: The time it takes the bus $b \in B$ to return from the safe point to the evacuation point in the round $r \in R$.

(4) n_p^{br}: Number of people picked up by the bus $b \in B$ at the evacuation point $p \in P$.
(5) t_{max}: The maximum total evacuation time.
(6) t_{avg}^{br}: The average waiting time for evacuees get on the bus $b \in B$ in the round $r \in R$.
We have two kinds of objective functions:
(1) Minimize the duration of the evacuation. This is, to minimize the time of the bus that takes the longest to complete its evacuation schedule (min-max function):

$$\textbf{minimize} \quad t_{max} \tag{1}$$

(2) Minimize the total waiting time for evacuees:

$$\textbf{minimize} \quad \sum_{b \in B} \sum_{r \in R} t_{avg}^{br} \tag{2}$$

Our bus evacuation problem's constraints formulation can be written as follows:

$$t_{to}^{br} \geq \sum_{p \in P} \sum_{s \in S} \tau_{ps} x_{ps}^{br}, \forall b \in B, r \in R \tag{3}$$

Constraint(3) represents the time the bus $b \in B$ travels from evacuation points to safe points in round $r \in R$.

$$t_{re}^{br} \geq \tau_{ps} \cdot (\sum_{i \in P} x_{is}^{br} + \sum_{j \in S} x_{pj}^{b(r+1)} - 1), \forall b \in B, p \in P, s \in S, r \in R-1 \tag{4}$$

Constraint(4) represents the time the bus $b \in B$ returns from safe points to evacuation points in round $r \in R$. It should be noted that for the convenience of modeling, we directly assume that the time cost between evacuation points and safe points is the same.

$$t_{max} \geq \sum_{r \in R} (t_{to}^{br} + t_{re}^{br}) + \sum_{p \in P} \sum_{s \in S} \tau_{dp} x_{ps}^{b0}, \forall b \in B \tag{5}$$

Constraint(5) represents the total evacuation time must be greater or equal to the evacuation time of any bus.

$$t_{avg}^{br} \geq \sum_{p \in P} \sum_{s \in S} x_{ps}^{br} \cdot [\sum_{r_1 \in r} (t_{to}^{br_1} + t_{re}^{br_1}) + \sum_{p \in P} \sum_{s \in S} \tau_{dp} x_{ps}^{b0}], \forall b \in B, r \in R \tag{6}$$

Constraint(6) represents the total waiting time of evacuees boarding bus b in round r.

$$\sum_{p \in P} \sum_{s \in S} x_{ps}^{br} \leq 1, \forall b \in B, r \in R \tag{7}$$

Constraint(7) represents for bus b, it can only choose at most one pair of evacuation points and safe points for evacuation in round r.

$$\sum_{p \in P} \sum_{s \in S} x_{ps}^{br} \geq \sum_{p \in P} \sum_{s \in S} x_{ps}^{b(r+1)}, \forall b \in B, r \in R-1 \tag{8}$$

Constraint(8) represents the flow constraints between evacuation points and safe points. If the process of evacuation is not finished, the safe points will be the transshipment points, so this inequality will take the $=$ sign; If the process of evacuation is finished, the safe points will be the demand points, and this inequality will take $\geq$ sign.

$$\sum_{p \in P} \sum_{s \in S} x_{ps}^{b0} = 1, \forall b \in B \tag{9}$$

Constraint(9) represents all buses must go to any evacuation point to pick up evacuees at the beginning of the evacuation.

$$n_p^{br} \leq Q \cdot \sum_{s \in S} x_{ps}^{br}, \forall b \in B, p \in P, r \in R \tag{10}$$

Constraint(10) represents bus capacity must not be exceeded.

$$\sum_{b\in B}\sum_{s\in S}\sum_{r\in R} n_p^{br} x_{ps}^{br} \geq d_p, \forall p \in P \tag{11}$$

Constraint(11) represents all evacuees must be picked up from the evacuation points.

$$\sum_{b\in B}\sum_{s\in S}\sum_{p\in P} n_p^{br} x_{ps}^{br} \leq C_s, \forall s \in S \tag{12}$$

Constraint(12) represents capacity of safe points must not be exceeded.

$$|R| = \lfloor \frac{\sum_{p\in P} d_p}{Q} \rfloor + 1 \tag{13}$$

Constraint(13) represents the maximum number of rounds required for a bus to evacuate all passengers.

$$x_{ps}^{br} \in \{0, 1\}, \forall b \in B, r \in R, p \in P, s \in S \tag{14}$$

Constraint(14) represents x_{ps}^{br} are binary variables.

$$t_{max}^{br}, t_{re}^{br}, t_{to}^{br}, t_{avg}^{br} \geq 0, \forall b \in B, r \in R \tag{15}$$

Constraint(15) represents the total evacuation time, average waiting time, and the time buses travel between evacuation points and safe points should be larger than 0.

$$n_p^{br} \geq 0, \forall b \in B, p \in P, r \in R \tag{16}$$

Constraint(16) represents the number of evacuees on the bus b in round r at evacuation point p should be larger than 0.

3 Experiment and Results

3.1 Simple Numerical Experiment

In this section, we will create a simple numerical experiment to prove whether our model is feasible or not. First, we assume that there is only one depot, two evacuation points, and two safe points as shown in Table 1 below. The available buses are variable and the bus capacity is variable. The specific demand, capacity, and cost matrix are shown in Table 2 and 3 as follows. The scenario will be shown in the following Figure 2.

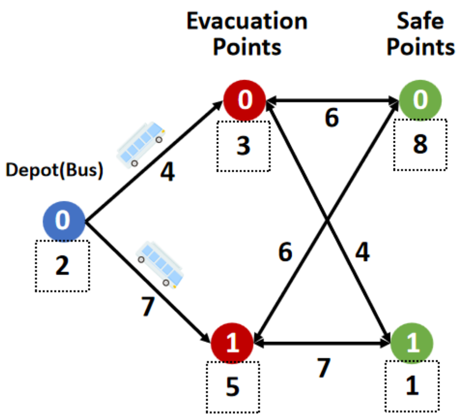


Figure 2: Simple Numerical Experiment.

Table 1: Simple Numerical Experiment

Set	Depot(D)	Evacuation Points(P)	Safe Points(S)	Buses(B)
Setting 1	1	2	2	1
Setting 2	1	2	2	2
Setting 3	1	2	2	3

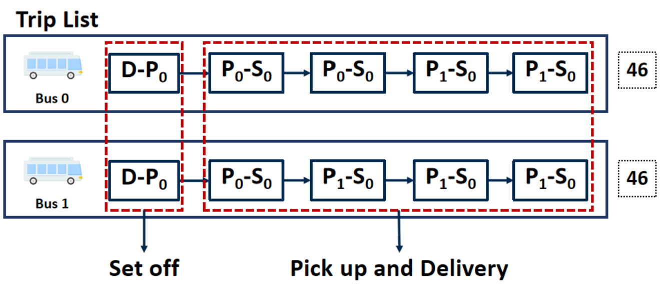
Table 2: Demand and Capacity Setting

	Evacuation Points(P)	Safe Points(S)
Demand 1	3	-
Demand 2	5	-
Capacity 1	-	8
Capacity 2	-	1

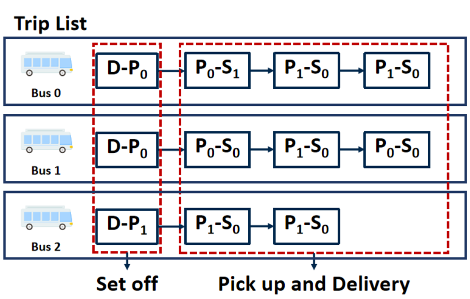
Table 3: Time Cost Martix

	P_1	P_2	S_1	S_2	D
P_1	-	-	6	4	4
P_2	-	-	6	7	7
S_1	6	6	-	-	-
S_2	4	7	-	-	-
D	4	7	-	-	-

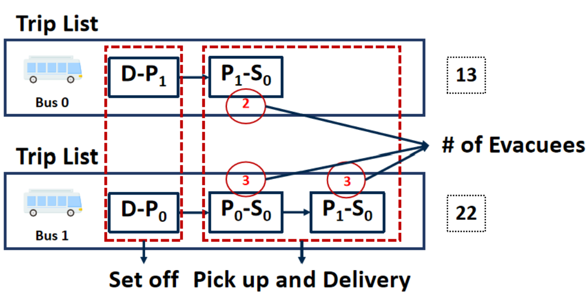
We select 3 experiments to make results visualization in Figure 3:



(a) $Q = 1$, $|B| = 2$. The total evacuation time is equal to 46



(b) $Q = 1$, $|B| = 3$. The total evacuation time is equal to 34.



(c) $Q = 3$, $|B| = 2$. The total evacuation time is equal to 22.

Figure 3: Experiments Result. The trip list of each bus in each sub-figure contains two parts. The initial square represents the bus going from the depot to the evacuation point, and the subsequent squares represent the round-trip process of the bus between the evacuation point and the safe point.

According to the above experiments, we can make a sensitive analysis of capacity and number of buses. For setting 1,2, and 3, we can assume bus capacity has values from 1 to 8, we can get the results shown in Figure 4:

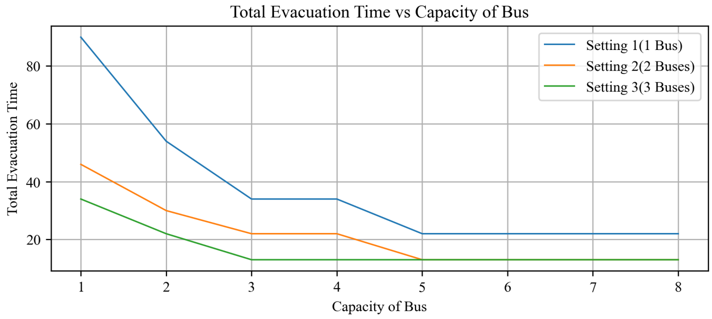


Figure 4: Evacuation Results for Setting 1, 2, and 3. It can be seen that as the number of buses increases, it can effectively reduce the number of evacuation rounds, thereby reducing the total evacuation time; at the same time, as the bus capacity increases, the total bus evacuation time can also be effectively reduced.

If we consider the objective function (2) instead of (1), which means that we want to minimize the total waiting time for evacuees, we can get the following results. According to Table 4, 5, and 6, we can notice that when we try to minimize the objective function (1) and (2) at the same time, the total evacuation time under the objective function $t_{max}^{(2)} \geq t_{max}^{(1)}$, this means that minimizing the waiting time of evacuees in the network will prolong the total evacuation time to a certain extent, but this prolongation will decrease with the increase in number of vehicles and vehicle's capacity.

Table 4: Total Evacuation Time for Different Objective Function(Q=1)

# of Bus	1	2	3
Total evacuation time (2)	90	46	34
Total evacuation time (1)	90	46	34

Table 5: Total Evacuation Time for Different Objective Function(Q=2)

# of Bus	1	2	3
Total evacuation time (2)	54	33	28
Total evacuation time (1)	54	30	22

Table 6: Total Evacuation Time for Different Objective Function(Q=3)

# of Bus	1	2	3
Total evacuation time (2)	34	22	14
Total evacuation time (1)	34	22	13

3.2 Real-world Numerical Experiment

In this section, we will create a real-world numerical experiment to prove whether our model is feasible or not. The location of depot, evacuation points, and safe points are shown in Table 7 below. The available buses are variable, and the bus capacity is 37. When facing a wildfire, we assume that all roads will be cleared, so vehicles are allowed to evacuate at the maximum speed limit on the road, which can ensure the safety and efficiency of evacuation to a certain extent. This can ensure the safety and efficiency of evacuation to a certain extent. To simulate a wildfire, we will simply assume the distance between the fire point and the evacuation point. Assuming that the flame spreads in a uniform circle, we can close specific evacuation points based on the time the fire reaches. The specific demand, capacity, and cost matrix are shown in Table 8 and 9 as follows, for our project, the distance between the depot, evacuation points, and safe points are calculated by Manhattan Distance. The scenario will be shown in the following Figure 5 and 6.

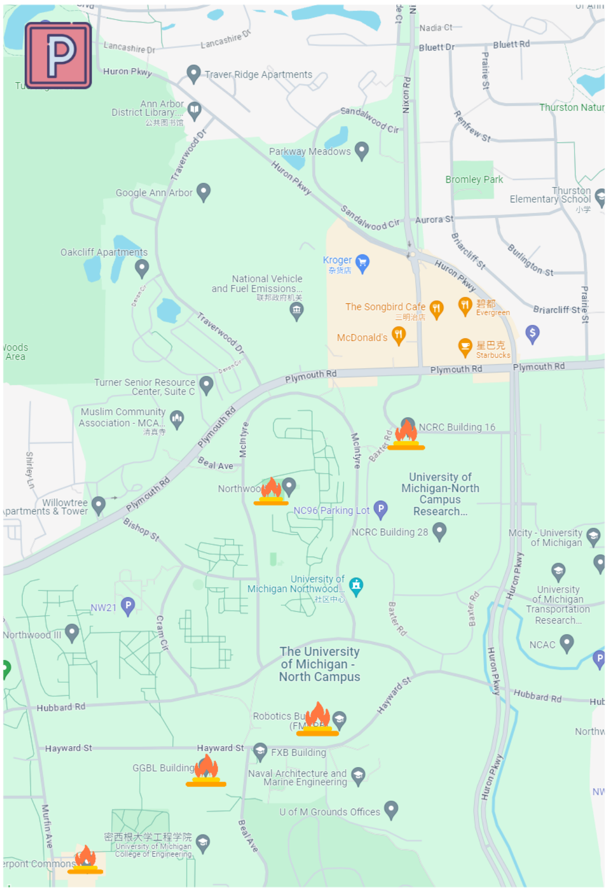


Figure 5: Real-World Scenario 1. Five evacuation points are shown in this figure.

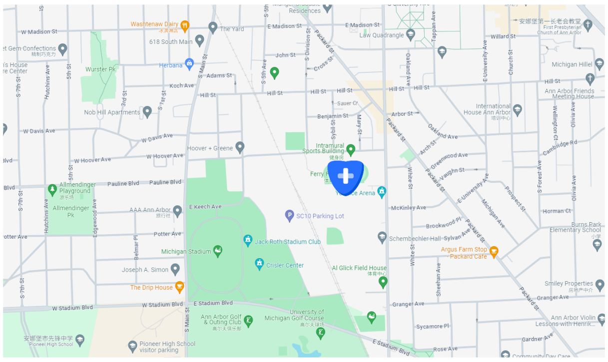


Figure 6: Real-World Scenario 2. IMSB is setting as the safe point.

Table 7: Location Setting

Points	Location
Depot	Tuebingen Park
Evacuation Points	NCRC, Northwood, Robotic building, GGB, Pirepoint Common
Safe points	IMSB

Table 8: Demand and Capacity Setting

	Demands(P)	Capacity(S)
NCRC	400	-
Northwood	1000	-
Robotic building	200	-
GGB	300	-
Pirepoint Common	200	-
IMSB	-	3000

Table 9: Time Cost Martix

	P_1	P_2	P_3	P_4	P_5	S_1	D
P_1	-	-	-	-	-	8.08	2.36
P_2	-	-	-	-	-	7.63	2.18
P_3	-	-	-	-	-	6.69	3.02
P_4	-	-	-	-	-	6.4	2.74
P_5	-	-	-	-	-	5.71	2.66
S_1	8.08	7.63	6.69	6.4	5.71	-	-
D	2.36	2.18	3.02	2.74	2.66	-	-

In our real-world experiment, we set the objective function (1) as our optimization goals. In the experiment, we set five different numbers of buses, and the total evacuation time are shown in Figure 7. The available time to perform the evacuation will always depend on the situation and the people in charge of the planification. Since the wildfire was active for four days, spreading through the wildland to the urban area, and the evacuations were performed gradually, an evacuation of 5 hours with 3 buses for the whole zone seems a good approximation.

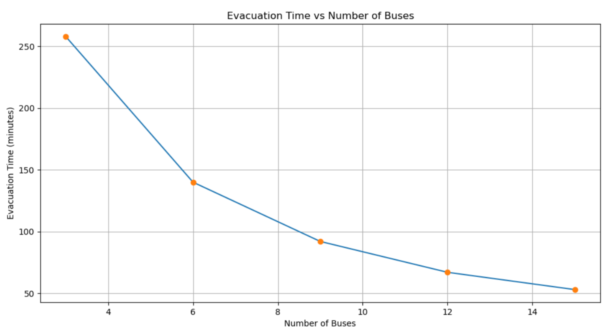


Figure 7: Real-World Experiment result. It can be seen that as the number of buses increases, it can effectively reduce the total evacuation time; however, as the number of buses increases, the rate of decline in evacuation time decreases gradually.

4 Conclusion

In our project, we solved the Bus Evacuation Problem, using a model to minimize the total duration of the evacuation (or minimize the total waiting time of the evacuees), building constraints for total evacuation time, flow-balance constraints for evacuation points and safe points, etc. For this, we used Python with Gurobi to solve this problem. To test the approach, we built the network with random values and tested the algorithm with different settings of constraints. Through the analysis of simple numerical experiments and real-world numerical experiments, we can obtain the following conclusions: (1) Our model is feasible when facing bus evacuation problems; (2) By setting two different objective functions and solving the problem, we can find that when pursuing to minimize the total waiting time of evacuees in the road network, the efficiency of evacuation will be sacrificed to a certain extent, but this situation will be alleviated with the increase in bus resources invested; (3) Through the sensitivity analysis of bus capacity and number of buses, we can know that these two variables have a significant impact on evacuation. An increase in bus capacity and an increase in the number of buses will effectively reduce the total evacuation time.

For future work, first, we plan to solve more complex problem instances considering, for example, cycles in graphs and asymmetric costs, to add different paths between evacuation points and safe points. Second, GUROBI is still insufficient in solving actual large-scale evacuation problems. Solving algorithms suitable for large-scale planning can be considered. Third, we can consider more combinations of self-evacuees and bus evacuation while taking into account road capacities.

5 Contribution

Lingyun Zhong: Literature Review, Modeling, Coding, Experiments, Visualization, Writing.
Shuyang Li: Literature Review, Experiments, Visualization, Writing.
Siqi Lian: Literature Review, Experiments, Visualization, Writing.

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