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Evacuation Time Estimation with Adaptive Control

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Abstract

Evacuation traffic prediction has gained significant importance from recent catastrophic events such as hurricanes that have occurred in Texas and in Florida. In the event of an evacuation before such catastrophe, city streets and highways experience traffic overflow that causes delay in evacuation and increases the likelihood of accidents. That said, an adaptive and resilient traffic-control needs to be developed considering such factors as location of evacuee's residence and location of shelter. To achieve adaptive traffic control during evacuation, traffic prediction is carried out ahead of time. Given the map of a locality with houses and streets, traffic prediction was automated in earlier work. In this paper, authors present the review of creation of random map, its characteristics, and identification of crowded intersections. Then the algorithm for evacuation time prediction is presented. The data with a neighborhood of 30 houses (with 5 roads and various sections) show that the adaptive traffic control could save about 7% in evacuation time over round-robin control.

1 Introduction

The rise of natural disasters poses a threat to large, urbanized cities and the people living in them [1]. During a catastrophe, such as a hurricane or an earthquake, the management of evacuation becomes a crucial step to saving the lives of citizens of the affected area. Many fatalities have occurred due to the lack of control over evacuation traffic. Managing large-scale evacuation during such a catastrophic situation is crucial. Authors in [2] have addressed adaptive traffic control framework but only for emergency vehicles. Researchers also proposed adaptive, preemptive control for electric trams but in non-disaster operations [3]. Authors in [4] also considered adaptive control in disaster evacuation based on real traffic obtained from sensors. Our work proactively predicts the traffic based on demographic information and attempts to identify clogged intersections for adaptive control. Researchers proposed deep learning to predict urban traffic behavior in [5]. However, the demographic input is not mentioned as we consider in our work. Similar work is presented in [6] and [7] with elaborate model development. In comparison, our work is based on model development and computational aspects of model implementation. Authors proposed prediction of real time traffic in [8]. In contrast, our approach is proactive based on existing demographic data. Vehicle to Infrastructure communication (V2I) is used in [9] to detect wrong way driving whereas we propose V2I for adaptive control of evacuation traffic.

Hence, the idea of developing an adaptive traffic control system naturally came especially after Hurricane Harvey that took place in Houston, Texas [10, 11]. Researchers and professionals have estimated evacuation time of a small city in [12]. However, the time calculation does not include traffic signal control algorithms that were involved. Authors in [13] have presented methods to predict the evacuation traffic over an extended time window but have not calculated the time of evacuation. The purpose of this project is to first automate the process of predicting traffic (from local demography) during disaster in intersections of road ahead of evacuation. Then this prediction is used to estimate the evacuation time of traffic under round robin and adaptive control algorithms [14]. This paper is organized as follows: overview of traffic prediction methodology and intersection identification are presented first, characteristics of generated path array and vehicle accumulation data are presented next, vehicles on each road section, extracted intersections and the detection of clogged ones are furnished after that. Then the evacuation time estimation algorithms are presented along with the results of prediction under the two algorithms. The paper concludes with recommendation of future work.

2 Overview of Prediction Methodology

Traffic prediction is based on area map of a locality. As no such digital map was readily available, we created such a map to start with, as described below. As a result, the work is divided into following steps:

1. Creating the map
2. Processing the map to predict the evacuation traffic based on source and destination
3. Identifying the critical intersections involved in evacuation
4. Estimating evacuation time based on adaptive algorithm

The above steps would facilitate creating the simulation program to implement adaptive traffic control.

Map Creation

Details of map creation have been reported in [10, 11]. As a result of the algorithmic execution steps, a two-dimensional array is created with 8 rows and 4 columns as shown in Table 1. It provides a detailed view of the route a vehicle (from each house) takes to reach the destination (shelter). Table 1 shows the actual route a vehicle takes during evacuation. Looking at the table closely it is evident that the generated map contains discontinuity. As an example, vehicle from house one takes road 5, section 5, then road 5, section 3, which indicates a jump from section 5 to section 3 of the same road (shown in red). Such discontinuities were identified and rectified such that a path contains sequential increase in sections on the same road.

Table 1: Path Array (partial) Showing Route Taken by Vehicles

House	Time	Road	Section
1	1	5	**5**
	2	5	**3**
	3	4	2
	4	4	3
	5	5	4
2	1	4	3
	0	0	0
	0	0	0
	0	0	5
	2	2	4

Table 2 contains the corrected array. As seen in this table, vehicle from house one takes road 5, section 5, then road 5, section 4, (shown in green), which indicates a continuity from section 3 to section 2 of the same road. This corrected table was next analyzed to find its characteristics.

Table 2: Path Array (partial) after Removing Discontinuities

Vehicle	Time unit	Road	Section
1	1	5	**5**
	2	5	4
	3	4	2
	4	4	3
	5	5	4
2	1	4	3
	0	0	0
	0	0	0
	0	0	5
	2	2	4

Map Dynamics

By analyzing the above table for all the houses, the number of road sections taken by a vehicle from each house can be calculated. As seen in Table 3, vehicles traverse different number of road sections. It implies that the houses are not equidistant, rather they are widely spread. This distribution indicates randomness of the generated path data array implying its proximity to a real map.

Table 3: Road Sections Traversed by Vehicles

# of Road Sections Traversed to Shelter	# of Vehicles
1	0
2	1
3	3
4	1
5	3

Traffic on each Section

Next step was to calculate the total number of vehicles at a specific section of road. Following table shows the number of vehicles at each road section at different time units.

Table 4: Vehicle Accumulation Data at Road Sections

Time unit	Road	Section	Vehicles
1	1	2	0
2	1	2	0
3	1	2	0
4	1	2	0
5	1	2	0
1	1	3	0
2	1	3	1
3	1	3	0
4	1	3	0
5	1	3	1
1	1	4	0
2	1	4	0
3	1	4	2
4	1	4	0
5	1	4	0
1	1	2	0
2	1	2	0
3	1	2	0
4	1	2	0
5	1	2	0

As we look at the road / section pairs of Table 4, it is observed that (for a specific road section) the number of vehicles at different time points are different. Moreover, as we look at similar time points of different road / sections, it is observed that (for a specific time point) the number of vehicles at different road sections are also different. This variation clearly indicates randomness in vehicle data and is more representative of real-life situation.

Identification of the Intersections

From the vehicle accumulation data at road sections, road intersections and vehicle accumulation at each intersection are identified.

Table 5: Derived Intersection List

Intersection	Road section pairs
I-1	Road 5, Section 5 and Road 5, Section 3

I-2	Road 5, Section 3 and Road 4, Section 2
I-3	Road 4, Section 2 and Road 4, Section 3
I-4	Road 4, Section 3 and Road 4, Section 5
I-5	Road 4, Section 5 and Road 2, Section 4
I-6	Road 4, Section 5 and Road 5, Section 2
I-7	Road 5, Section 2 and Road 1, Section 4
I-8	Road 1, Section 4 and Road 3, Section 3
I-9	Road 3, Section 3 and Road 1, Section 3

From previous data, we can accumulate the number of vehicles in every intersection. The vehicles accumulated in the intersection can easily be calculated by summing the vehicles on each section at a specific time point. Vehicle accumulation at three final intersections (leading to shelter) is included in Table 6 in chronological order. The intersections with highest number of vehicles over a time period become the candidates for adaptive control.

Table 6: Vehicle Accumulation at Final Intersections

Intersections	**Time unit**	**Vehicles**
I-1	1	1
	2	2
	3	0
	4	0
	5	0
I-7	1	2
	2	1
	3	0
	4	0
	5	0
I-14	1	1
	2	2
	3	1
	4	0
	5	0

Estimation of Time

Time estimation has two parts. The first part is the vehicle travel time, needed to cross the intersection / junction. The other part is the light switching time, needed to switch from one direction to the next. Steps of estimation are listed below.

Algorithmic steps:

1. To find on which road / section the shelter is located at.
2. To find which intersections the other side of this road / section is connected to. From these intersections, each vehicle would take one time unit to reach the shelter (successive vehicles take one additional unit of time).
3. To calculate the time needed to evacuate the final intersections.
4. To find other intersections directly connected to these final intersections, from these intersections, each vehicle would take one time unit to reach the final intersections.
5. To calculate the time needed to evacuate these intersections (to reach the final intersections), then to the shelter.
6. To continue the above steps until all intersections are covered.

The algorithm is executed for two control strategies: Round robin and Adaptive. In Round robin strategy, vehicles in each direction is allowed to proceed according to a fixed sequence whereas in Adaptive strategy, the direction with highest number of vehicles is allowed to proceed.

3 Results and Discussion

Executing this algorithm has generated the following tables with estimated time. In Table 7, time calculation is shown for Round Robin strategy. The intersections I-1, I-7, and I-14 are the final intersections leading to the shelter. The sequence of vehicle movement is the same i.e. I-1, then I-7, then I-14 for all time points. For example, at time point 1, I-1 has one vehicle, I-7 has two vehicles, and I-14 has one vehicle. As such the total time to clear these vehicles is 4 units as shown in the first row under travel time. In addition, the switching time 3 units from one intersection to the other. In this way the other two rows of Table 7 are filled, and the total time is calculated.

Table 7: Round Robin Time Estimation (Final Intersections)

Time point	**Sequence**	**Travel Time (in units)**	**Switching time (in units)**
1	I-1, then I-7, then I-14	1+2+1 = 4	3
2	I-1, then I-7, then I-14	2+1+2 = 5	3
3	I-1, then I-7, then I-14	1	3

Total Round Robin time = 4 + 5 + 1 + 3 + 3 + 3 = 19 units.

In Table 8, time calculation is shown for Adaptive strategy. The sequence of vehicle movement is dependent on the number of vehicles in each direction and is different at different time points. For example, at time point 1, I-1 has one vehicle, I-7 has two vehicles, and I-14 has one vehicle. As I-7 has the highest number of vehicles, it is allowed to proceed, followed by I-1 and I-14, respectively. As such the total time to clear these vehicles is 4 units as shown in the first row under travel time. In addition, the switching time 3 units from one intersection to the other. In this way the other two rows of Table 8 are filled, and the total time is calculated. At time point 3, only I-14 is scheduled as there are no vehicles at other intersection. As such, the switching time is only 1.

Table 8: Adaptive control (based on vehicle accumulation) Time Estimation (Final Intersections)

Time point	**Sequence**	**Travel Time (in units)**	**Switching time (in units)**
1	I-7, then I-1, then I-14	2+1+1 = 4	3
2	I-1, then I-14, then I-7	2+2+1 = 5	3
3	I-14	1	1

Total Adaptive control time = 4 + 5 + 1 + 3 + 3 + 1 = 17 units. Results from Table 7 and Table 8 imply a 10.52 % time-savings using Adaptive control in Final Intersections.

Let us consider a set of intersections that are prior to final intersections I-1, I7, and I-14. They are denoted as I-X, I-Y, and I-Z and their vehicle accumulation profile is listed in Table 9.

Table 9: Vehicle Accumulation at (Prior to) Final Intersections

Intersections	Time unit	Vehicles
I-X	1	3
	2	2
	3	0
	4	0
	5	4
I-Y	1	2
	2	3
	3	2
	4	0
	5	2
I-Z	1	4
	2	4
	3	3
	4	3
	5	6

Following the same process described above, the estimated time calculation to clear them under Round Robin policy is shown in Table 10. As before, the switching time is always 3, however, the travel time is dependent on the number of vehicles at the intersections.

Table 10: Round Robin Time Estimation (Prior to) Final Intersections

Time point	Sequence	Travel Time (in units)	Switching time (in units)
1	I-X, then I-Y, then I-Z	3+2+4 = 9	3
2	I-X, then I-Y, then I-Z	2+3+4 = 9	3
3	I-X, then I-Y, then I-Z	2+3 = 5	3
4	I-X, then I-Y, then I-Z	3	3
5	I-X, then I-Y, then I-Z	4+2+6 = 12	3

Total Round Robin time = 9 + 9 + 5 + 3 + 12 + 3 + 3 + 3 + 3 + 3 = 53 units.

Similarly, the estimated time calculation to clear them under Adaptive policy is shown in Table 11. Here, the switching time varies based on presence or absence of vehicles at intersections and the travel time varies based on the number of vehicles at the intersections.

Table 11: Adaptive control (based on vehicle accumulation) Time Estimation (Prior to) Final Intersections

Time point	Sequence	Travel Time (in units)	Switching time (in units)
1	I-Z, then I-X, then I-Y	4+3+2 = 9	3
2	I-Z, then I-Y, then I-X	4+3+2 = 9	3
3	I-Z, then I-Y	3+2 = 5	2
4	I-Z	3	1
5	I-Z, then I-X, then I-Y	6+4+2 = 12	3

Total Adaptive control time = 9 + 9 + 5 + 3 + 12 + 3 + 3 + 2 + 1 + 3 = 50 units.

From the results of Tables 10 and 11, it can be concluded that a 5.66 % time-savings is achieved using Adaptive control in Prior to Final Intersections.

Let us assume that I-X, I-Y, I-Z are connected to I-1 of Final set of Intersections. Then the total Round Robin time = 19 + 53 = 72 units for these two sets of intersections and total Adaptive control time = 17 + 50 = 67 units for the same two sets of intersections. As such, it implies an overall 6.94 % time-savings in Adaptive control for the last two sets of intersections.

4 Conclusion

During disaster evacuation, traffic control measures should be dynamic. This paper reviews the method of forming dynamic evacuation traffic during an emergency, such as a natural disaster. The model of house, road and sections are formed. Later, this model is implemented in the Visual Studio programming environment to determine the number of vehicles in each intersection of the road at a specific time point. From this traffic data, evacuation time at various intersections is predicted under Round robin and under adaptive control strategies. Simulation results show that close to 7% savings in time can be obtained by adopting adaptive algorithm over round robin algorithm.

5 Further Research

In the next phase of the project, the number of houses and the number of shelters need to be increased, and the shortest distance between the source (house) and each shelter (destination) need to be determined. Also, we will analyze solutions considering more parameters such as age and gender of residents to estimate the traffic at a time point.

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