Strategic Routing and Scheduling for Evacuations

Extended Abstract

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ABSTRACT

Evacuation planning is an essential part of disaster management where the goal is to relocate people under imminent danger to safety. Although government authorities often prescribe routes and schedule, evacuees generally behave as self-interested agents and may choose their actions in a selfish manner. It is crucial to understand the degree of inefficiency this can cause to the evacuation process. In this paper, we present a strategic routing and scheduling game (*Evacuation Planning Game*, EPG), where evacuees choose their route and time of departure. We prove that every instance of EPG has at least one pure strategy Nash equilibrium. We then present a polynomial time algorithm (*Sequential Action Algorithm*, SAA), for finding equilibria in a given instance. We also provide bounds on how bad an equilibrium state can be compared to a *socially optimal* state. Finally, we use Harris County of Houston, Texas as our study area and construct a game instance for it. Our results show that, SAA can efficiently find equilibria in this instance that have social objective close to the optimal value.

KEYWORDS

Strategic routing and scheduling; Evacuation planning; Equilibrium; Price of anarchy

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1 INTRODUCTION

Evacuation plans are designed to ensure the safety of people living in areas that are prone to natural and/or man-made disasters. Large-scale evacuations have been carried out during past hurricane seasons in Florida, Texas, Louisiana, and Mississippi. For instance, about 2.5 million people were ordered to evacuate from Florida before the landfall of Hurricane Ian (2022) [3, 12]. Other examples of hurricanes when such large scale evacuations were carried out include Ida (2021), Laura (2020), Irma & Harvey (2017). It is, therefore, necessary to have evacuation plans in place to ensure the sustainability of cities/communities. Government authorities often prescribe routes and schedule to evacuees so that the evacuation process can be done in a safe and orderly manner. Hence, existing research works have focused on finding optimal evacuation routes and schedule [2, 4, 6, 7, 10]. However, evacuees may act as self-interested agents and they may choose their routes and departure time in a selfish manner [9, 11]. It is crucial to understand the effect of such selfish behavior on evacuation planning.

Our contributions in this paper are as follows: **first**, we present a strategic routing and scheduling game (Evacuation Planning Game, EPG) where: (i) players choose their route and time of departure, (ii) we use dynamic flows to model time-varying traffic, and (iii) we consider confluent routes. These three aspects of our game formulation make it a novel contribution. **Second**, we show that every instance of our game has at least one pure strategy Nash equilibrium. **Third**, we present a polynomial-time algorithm (Sequential Action Algorithm, SAA) to find equilibria in a given instance of EPG. This is particularly useful, because finding optimal confluent routes and schedule is NP-hard and hard to approximate [7]. **Fourth**, we provide theoretical bounds on how bad an equilibrium can be compared to a socially optimal state. **Finally**, we construct a game instance for Harris County of Houston, Texas, and evaluate the performance of SAA on it. Our results show that, for this game instance, SAA finds equilibria that have social objective values close to the optimal social objective.

2 GAME FORMULATION

We first introduce some preliminary terms. A **road network** is a directed graph $\mathcal{G} = (\mathcal{V}, \mathcal{A})$ where every edge $e \in \mathcal{A}$ has (i) a capacity $c_e \in \mathbb{N}$ representing the number of vehicles that can enter the edge at a given timestep and (ii) a time $\tau_e \in \mathbb{N}$ representing the time it takes to traverse the edge. An **evacuation network** is a road network that specifies $\mathcal{E}, \mathcal{S}, \mathcal{T} \subset \mathcal{V}$, representing a set of source, safe and transit nodes respectively. For each source node $k \in \mathcal{E}$, $W(k)$ represents the set of evacuees at source node k.

Given a road network, a **single dynamic flow** is a flow f along a single path with timestamps a_v, representing the arrival time of the flow at vertex v, that obeys the travel times. In other words, for

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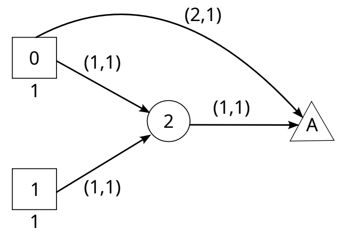

P_0 \ P_1	$[1, 2, A]$, $[(0, 1)]$	$[1, 2, A]$, $[(1, 1)]$	$[1, 2, A]$, $[(2, 1)]$
$[0, 2, A]$, $[(0, 1)]$	$(-M_2, -M_2)$	$(-2, -3)$	$(-2, -4)$
$[0, 2, A]$, $[(1, 1)]$	$(-3, -2)$	$(-M_2, -M_2)$	$(-3, -4)$
$[0, 2, A]$, $[(2, 1)]$	$(-4, -2)$	$(-4, -3)$	$(-M_2, -M_2)$
$[0, A]$, $[(0, 1)]$	$(-2, -2)$	$(-2, -3)$	$(-2, -4)$
$[0, A]$, $[(1, 1)]$	$(-3, -2)$	$(-3, -3)$	$(-3, -4)$
$[0, A]$, $[(2, 1)]$	$(-4, -2)$	$(-4, -3)$	$(-4, -4)$

Figure 1: *(Top)* Evacuation network of example EPG instance. Edges are labeled with travel time and flow capacity. Source, safe and transit nodes are denoted by squares, triangles, and circles respectively. Source nodes are labeled with number of evacuees. In this EPG instance, we have two players P_0, P_1 corresponding to source nodes $0, 1$ respectively. *(Bottom)* Utility table. Possible actions of P_0 and P_1 are shown in rows and columns, respectively. Each cell of the table corresponds to an outcome, where the first and second value are the utility values of P_0, P_1 respectively. Evacuation time upper-bound in this example is $T_{max} = 4$. In the orange outcomes, utility of both players is $-M_2$ because of capacity violation on edge $(2, A)$. The green outcome is socially optimal with the highest total utility of -4. The blue outcome (with total utility -5) is an equilibrium. *Price of Anarchy* of this instance is $5/4$.

each edge $e(u, v)$ on the path of f, $a_v = a_u + \tau_e$. A **dynamic flow** is a collection of single dynamic flows. A **dynamic confluent flow** is a collection of single dynamic flows where, if any two single dynamic flows use the same vertex (possibly at different times), their underlying path afterwards are identical.

Definition 1. *Given an evacuation network $\mathcal{G}$ and an upper bound on evacuation time T_{max}, the* ***Evacuation Planning Game (EPG)*** *is defined as follows:*

- ***Players**: We have $N = |\mathcal{E}|$ players denoted by the set $[N] = \{1, 2, ..., N\}$ where player i corresponds to the source $src_i \in \mathcal{E}$.*
- ***Actions**: Player i can take actions $a_i \in A_i$ where $A_i = R_i \times DT_i$.*
  - *R_i is the set of all possible simple paths from source src_i to any safe node in $\mathcal{S}$.*
  - *DT_i is the set of all possible departure time schedules of the evacuees at source src_i. We represent a departure time schedule 'dt' as follows: $dt = \{(t, \theta_t) \mid t \in [0, T_{max} - 1], \theta_t =$ Number of evacuees departing at timestep $t\}$*
- ***Outcome**: An outcome is the action profile $a = (a_1, a_2, ..., a_N)$. Here, each player i has chosen a particular action $a_i \in A_i$.*
- ***Utility**: Each player i has a utility function u_i. With outcome a, utility of player i is denoted by $u_i(a)$, where:*

$$u_i(a) = \begin{cases} -\sum_{l \in W(i)} t_l & \text{if Case } 1 \\ -M_2 & \text{Otherwise} \end{cases} \quad (1)$$

$$\text{where, } t_l = t_l^d + \sum_{e \in route_i} \tau_e$$

Here, t_l^d denotes the departure time of evacuee l from source src_i, τ_e denotes travel time on edge e, $route_i$ denotes the set of edges in player i's route, t_l denotes the evacuation time of evacuee l, and M_2 is a very large positive number.
Case 1 occurs, when outcome 'a' induces a dynamic flow such that:
(1) No edge on player i's route, at any point in time, exceeds its capacity.
(2) $\forall j \in [N], j \neq i$, a_i and a_j induces a dynamic confluent flow.
(3) All evacuees under player i reach a safe node within time T_{max}.

An outcome a^* is an **equilibrium** if no player has incentive to deviate unilaterally. An outcome a^* is **socially optimal** if the sum of the utility of all players is maximum in a^*, over all possible outcomes. To quantify the inefficiency of equilibria, we define *Price of Anarchy (PoA)*. Given an instance γ of EPG, let $EQ(\gamma)$ denote the set of equilibrium outcomes in γ. Let, $U(a) = \sum_{i \in [N]} u_i(a)$. Then, **price of anarchy** for the instance γ is: $\rho(\gamma) = \frac{\min_{a \in EQ(\gamma)} U(a)}{\max_{a \in A} U(a)}$. Let Γ be a set of instances of EPG. Then, the price of anarchy of Γ is: $\rho(\Gamma) = \sup_{\gamma \in \Gamma} \rho(\gamma)$.

3 THEORETICAL AND EMPIRICAL ANALYSIS

For existence of equilibria in EPG, we prove the following theorem:

Theorem 1. *Every instance of EPG has at least one pure strategy Nash equilibrium where all players get a utility greater than $-M_2$.*

We then present a polynomial-time algorithm (Sequential Action Algorithm, SAA) and prove the following:

Theorem 2. *SAA returns a pure strategy Nash equilibrium where all players get a utility greater than $-M_2$.*

We also provide bounds on the price of anarchy of EPG (over all possible instances), by proving the following:

Theorem 3. *Let Γ_{all} denote the set of all possible instances of EPG. Then, $\rho(\Gamma_{all})$ is $\Theta(\tau + M)$. Here, M denotes the total number of evacuees, and $\tau = \sum_{e \in \mathcal{A}} \tau_e$.*

For empirical analysis, we use Harris County in Houston, Texas as our study area. Using road network data from HERE maps [5], and the synthetic population data presented by Bhattacharya *et al.* [1], we construct a game instance for this area. Our experiment results show that, for this game instance, SAA finds equilibria that have social objective close to the optimal social objective. Proofs of the theorems, and details of the experiment results are provided in the full-version of the paper [8].

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