

Emergency Evacuation of Tehran City: Simulation results

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Abstract

Tehran is capital of Iran in wide metropolitan area. Large-scale disasters such as earthquakes in such a city cause many casualties and economical damage. One of the most effective risk mitigation actions in such disasters is emergency evacuation. This paper evaluates the dynamics of the vehicular traffic of Tehran under an evacuation condition. The main arterials of the city of Tehran are simulated by a macroscopic traffic flow simulation model (FastLane). The dynamics of traffic in the network are assessed by means of the Network Fundamental Diagram under different loading durations. Simulation results confirm the effect of loading duration and spatial spread of density on network performance. As was previously suggested in the literature, increasing loading duration leads to higher average network flow in the recovery phase compared to maximum network flow in the loading phase. Furthermore, simulation results demonstrate a clear decrease of average velocity by increasing the spatial spread of the densities in the network. These results can be used when making decisions regarding emergency evacuation plans for the city of Tehran.

Keywords: Tehran, Evacuation, simulation, Network Fundamental Diagram

1. Introduction

Iran frequently suffers destructive natural hazards due to its geographically diverse environment. Iranian plateau is one of the seismically active areas of the world that can be characterized by active faults and high surface elevation along the Alpine earthquake belt [1]. Tehran, as the capital of Iran is also in risk of earthquakes and man-made hazards. Such hazards can be especially catastrophic in Tehran with an estimated population of 11,000,000, high density (10000/km²) and old infrastructures and buildings [2]. The risk of such disasters however, can be controlled either by primitive measures such as building earthquake resistant structures, or by reducing consequences (i.e. evacuation plan).

Evacuation plan as a risk mitigation strategy, is effective in the hazards that have warning times ranging from medium (fire, storm) to very long warning time (volcano, hurricanes). Risks of short warning time hazards such as earthquakes, however, can still be controlled by well-organized evacuation plans. In this case people are still evacuated afterwards once the danger of earthquake has been reduced. This post-hazard evacuation is needed because of the remaining danger caused for example by lack of water supply and other consumables, gas leakage and need for medical treatments.

Traffic simulation models are frequently used to support decisions when an evacuation is planned. Large-scale evacuation has been previously simulated using different traffic simulation models. These simulation models are ranging from travelers behavior in evacuation process as microscopic scale [3] to macroscopic traffic flow models (e.g. [4]) and are applied on various evacuation control scenarios such as route guidance (e.g. [5]). The focus of these simulation models is typically on traffic dynamics of the network to locate possible bottlenecks and predict evacuation times.

In this paper we evaluate the dynamics of vehicular traffic of Tehran under emergency evacuation. The main arterials of Tehran are simulated in a macroscopic multi class simulation model- called FastLane. Approximately 2 million vehicles are evacuated from center of the city towards destinations outside of the city. *Network Fundamental Diagram* assesses the dynamics of traffic in this situation. The results of this study suggest the influence of loading duration and spatial variance of density on Tehran's performance under evacuation condition. This result can help practitioners and policy makers to plan a well-organized emergency evacuation for the city of Tehran.

The remainder of this paper outlines the *Network Fundamental Diagram* concept in section 2 and then presents Tehran's evacuation framework in section 3. Section 4 draws the main conclusions of this article and discusses future research direction.

2. Network Fundamental Diagram (NFD)

Various theories have been developed in the past to describe vehicular traffic dynamics of cities in an aggregated level. One of the steps is taken by Daganzo ([6] and [7]) that relates the rate at which vehicles leave the network (trip completion rate) to the number of vehicles in the network (accumulation). Empirical data from Yokohama (Japan) [8] and Toulouse [9] support such relation between productions of the network and accumulation. The simplest way to calculate production and accumulation is arithmetic mean of link flow and density so that if network has link set Λ

$$P(t) = \frac{1}{|\Lambda|} \sum_{l \in \Lambda} q_l(t) \quad (1)$$

$$A(t) = \frac{1}{|\Lambda|} \sum_{l \in \Lambda} r_l(t) \quad (2)$$

where q_l and r_l are flow and density of link l . $P(t)$ is average network flow and $A(t)$ is average network density.

Network fundamental diagram is not just dependent on flow and density of each individual link but also on heterogeneity of density distribution through network. This heterogeneity can be described by form of standard deviation of the densities at each link such that:

$$S(t) = \sqrt{\frac{1}{|\Lambda|} \sum_{l \in \Lambda} (r_l(t) - A(t))^2} \quad (3)$$

The influence of spread of density in the network's performance suggests new possibilities of traffic control in exceptional events such as emergency evacuation [10]. Controlling strategy in case of evacuation can be made on this aggregated level, which is computationally more efficient using less data.

3. Tehran's Evacuation Framework in FastLane

FastLane model is an extension of LWR model ([11] and [12]). It is based on conservation of vehicles and equilibrium traffic condition [13]. These principles are complemented with multi-class and capacity drop assumptions. The model is numerically solved by Godunov scheme while maintaining dynamics of class-specific flows and densities throughout the network. However, in order to use the model to simulate Tehran's network in evacuation condition, single class traffic with capacity drop has been considered.

Evacuation scenario in this study is designed as follow:

- In total 2 million vehicles are evacuating Tehran.
- Evacuation origins are located within the city.
- Evacuation destinations are located outside of the city (Fig. 1).
- Evacuees move towards different directions to reach their destination.
- Route choices of evacuees remain constant in each tested case.

To evaluate the behavior of the network, 6 cases have been tested. Each of these cases has different loading duration at origins where the total number of evacuees (2 million) and spatial distribution of demand in origins are constant. These 6 cases consider that evacuees are entering the origins within 2 hours, 4 hours, 8 hours, 16 hours, 24 hours or 48 hours. Network Fundamental Diagram and some other properties of the traffic dynamics are compared for all these cases.

3.1. Network set up

Major arterials of Tehran are simulated as 603 links and 462 nodes in FastLane. Capacity per lane is set to 2000 veh/hr and free speed of main freeways is 100 km/hr. Free speed of ramps are

70 km/hr. Links are discretized to cell of 15 meter length where time step is 2 minutes. Figure 1 demonstrates the simulated freeways and evacuation origins and destinations of our case study.

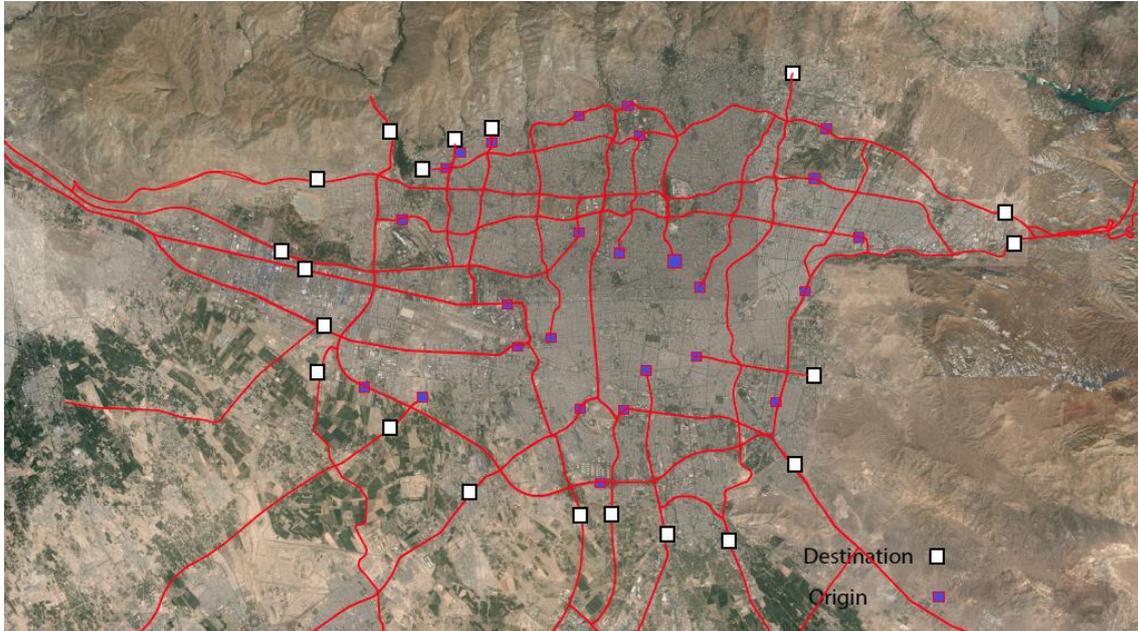


Figure 1 Simulated freeways, origins and destinations on the map of Tehran

3.2. Evacuation loading durations

In order to evaluate the traffic dynamics in an evacuation process, different cases has been considered where approximately 2 million vehicles entering the network in duration of 2, 4, 8, 16, 24 or 48 hours. Figure 2 shows number of vehicles that exit to the destinations compare to demand at origins in each case. As it can be seen, decreasing the loading duration decreases the number of successful evacuees. In the other words, in low loading durations (e.g. 2,4 hours) most of the evacuees cannot enter the main arterials and evacuate from the city. In this case, number of vehicles that the network accommodates, might be even lower than nominal capacity of the network. This phenomenon is especially can happen when gridlock forms.

Gridlock is forming when traffic in part of the network is coming to complete standstill. This can break the equilibrium state of traffic and creates hysteresis. In Figure 3 formation and dissipation of gridlocks is shown in 2 hours loading duration case.

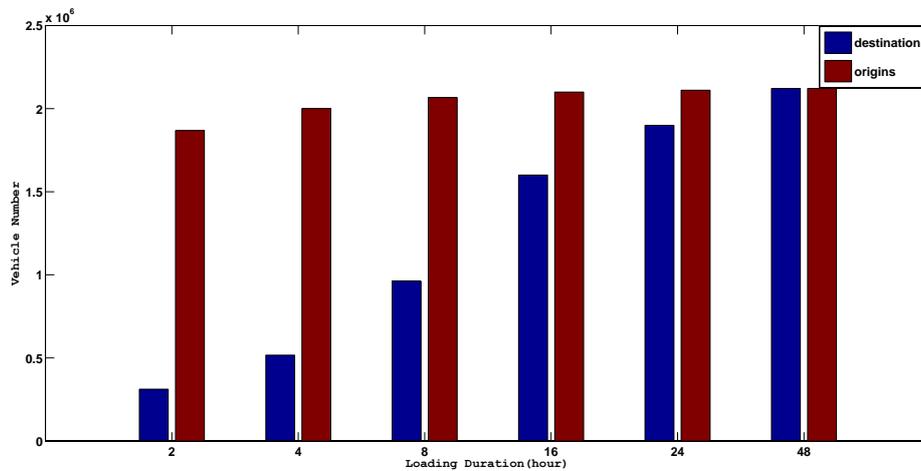


Figure 2 Number of vehicles at origins and destinations for different evacuation cases

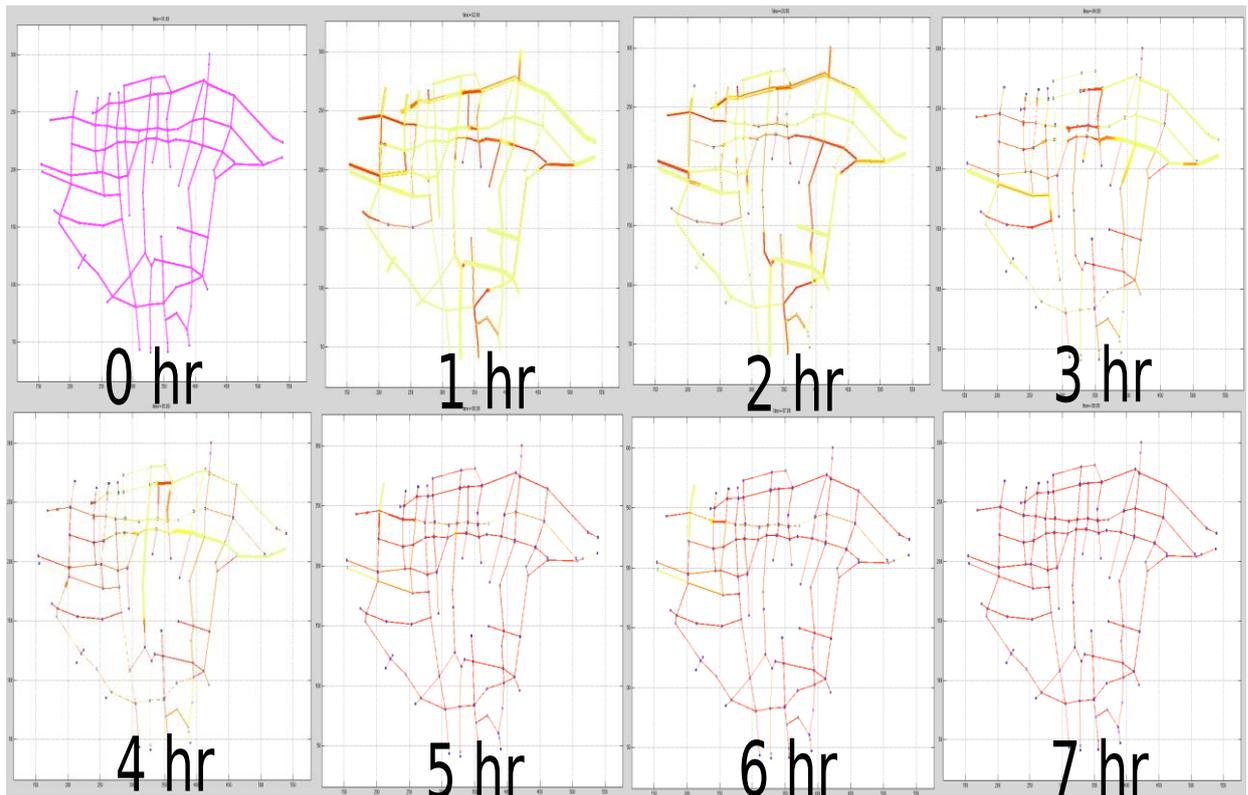


Figure 3 Evolution of gridlocks over time and space for 2 hours loading duration (red color represents zero velocity).

3.3. Results and discussions

Dynamics of traffic in evacuation scenario of Tehran is assessed by means of Network Fundamental Diagram. Simulation results of 6 different evacuation cases are summarized in terms of NFDs in Figure 4.

Large hysteresis loop is formed in shorter loading durations. This hysteresis loop suggests high spread of congestion throughout the network in recovery phase. As vehicles leave network, some parts of the network become completely empty with zero flow where some other parts have still congestion. This heterogeneity of density results to hysteresis loop in NFD. In longer loading duration (e.g. 48 hours) hysteresis loop shrinks mainly because of less congestion in the network.

Increasing loading duration is also decreasing maximum average network flow. However, this decrease should not be interpreted as decrease of capacity of the network. With a fixed demand, increasing loading duration results to lower number of vehicles that are entering (also exiting) the network at each time steps. As a result average flow of the network is also decreasing proportional to the number of vehicles that are entering the network at each time step.

In fact, increasing loading duration minimize the difference between maximum production in loading and recovery phases (Figure 5). This is due to the low spatial distribution of congestion (standard deviation) in both loading and recovery phases.

Another interesting effect of spatial spread of densities can be seen on average network velocity. Figure 6 demonstrates standard deviation of densities for all simulated cases versus average network velocity. As standard deviation increases- meaning that congestion spread widely through network- average speed of the network decreases.

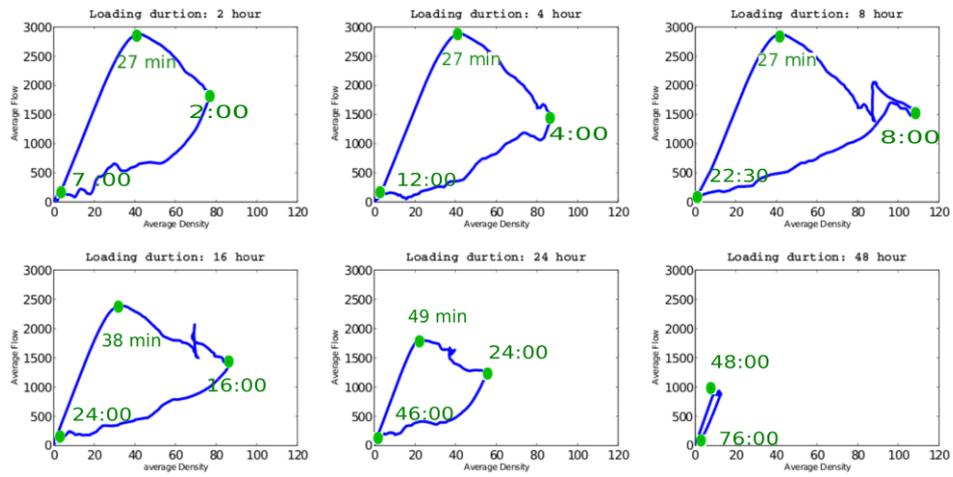


Figure 4 Network Fundamental Diagram for different loading durations

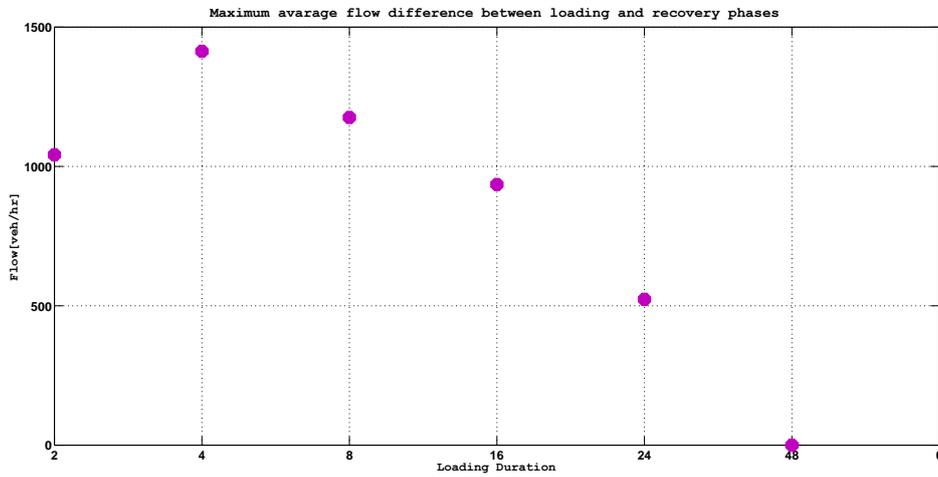


Figure 5 Differences between maximum network production in loading and recovery phases

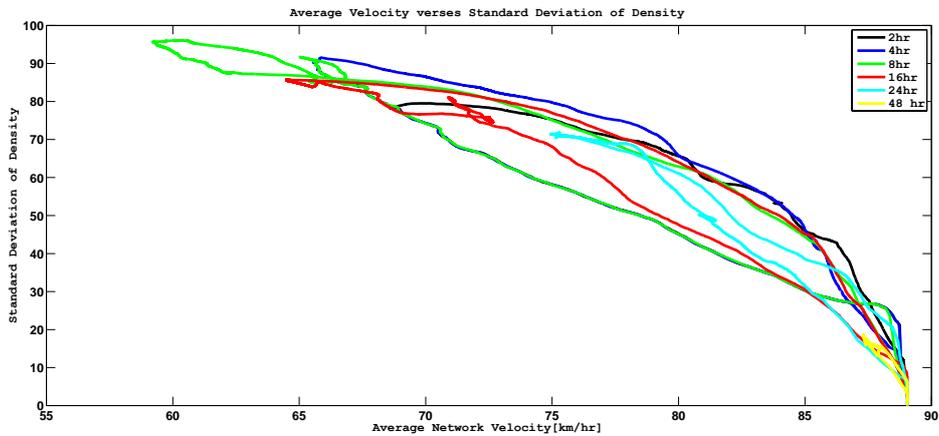


Figure 6 Standard deviation of densities versus average network velocity for all loading cases.

4. Conclusion and future research

This study explores some of the traffic flow dynamics of Tehran under evacuation condition. Major arterials of Tehran have been simulated by a first order multi-class traffic flow simulation model (FastLane). Approximately two million vehicles are considered in the evacuation scenario. These evacuees are loaded to the origins that are located within the city, based on different loading durations and are moving towards destinations outside of the city. Vehicular traffic dynamics is evaluated based on Network Fundamental Diagram. It is shown that in short loading durations (e.g. 2 or 4 hours) just some portion of evacuees can finish the evacuation process because of the gridlock phenomenon. Main findings of this paper consist of:

1. Simulation results confirm the minimum differences between maximum production of the network in loading and recovery phases.
2. Results show a clear decrease in average network speed in higher standard deviation of densities.

These results could help in developing more efficient emergency evacuation plan for Tehran.

Future research directions include optimization of route guidance in evacuation procedure based on NFD. Also, the effect of different loading structures on Tehran NFD needs to be studied further.

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