

Traffic Simulation Modeling for an Urban Chemical Disaster: Emergency Evacuation Development and Case Study

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ABSTRACT

In the post 9/11 era, emergency evacuation in large metropolitan areas has become a subject of national attention. The purpose of this paper was to simulate an emergency response to evacuation procedure in the downtown Baltimore, Maryland area. Proposed traffic modeling for simulating the response to emergency evacuation procedure in the case of a chemical disaster was designed to determine the most efficient response procedure. Using an integrated M&S framework, this paper seeks to describe the design of the Urban Chemical Disaster simulation. Included are the engineering considerations that led to the simulation flow structure using real-time and faster than real-time components. Components of chemical dispersion, chemical concentrations and wind transport media, chemical release rates, and sensing command/control simulations, are contributing factors to traffic flow manipulation. These manipulations will provide an effective emergency evacuation response method which could be used in the near future. A number of methodologies were posited by the research group to learn which could effectively mitigate a potential bioterrorist attack. Lessons learned in the collaboration along with feasible alternatives are discussed in further detail.

Keywords: Chemical disaster, micro-simulation, emergency evacuation

1. INTRODUCTION

The potential for terrorist attack in larger cities in the United States is a real threat because these cities generally represent numerous "soft" targets. It is therefore imperative to provide the maximum safety measures to the people residing in these high-risk areas. A high-risk area is defined as one wherein levels of risk are based on elements including critical industry, railroads, population and other factors. According to researchers (Piegorisch, et al., 2007), large cities meet this criterion and converge to a "benchmark vulnerability metric." Accordingly, the development of safe and efficient evacuation procedure during emergency situation is of paramount importance.

Some of the major issues associated with bringing safety and security to people is the mass transit of said people. Emergency preparedness, then relates how, if an emergency attack situation occurs, localities will respond to a situation where a mass exodus must be conducted in a timely manner. According to the Department of Homeland Security (DHS), much of the 2008 budgetary allowances will be contributed for just this situation (U.S. DHS 2004, and DHS 2008). Priority focuses on the protection of the infrastructure, as there is a defined link between transport of goods and services, and people and the U.S. economy. As the U.S. government does not own the most critical infrastructure elements (i.e. bridges, power facilities, dams, etc.) it falls within the responsibilities of the DHS to accommodate and work with private sectors, state and local authorities and the like, to enhance the protection of human lives in the case of an unexpected attack.

1.1 PROBLEM STATEMENT

In the city of Baltimore Maryland, there exist many features that would make it a marketable target for suspected terror attacks. As of 2006 the city's population was 640,961 and the Baltimore Metropolitan area was comprised of 2,668,056 residents. Part of the Baltimore-Washington Metropolitan area, the city is the largest in Maryland and the fourth largest on the east coast of the United States. It is comprised of seaports, and situated closely to

major mid-western markets, and the trends for infrastructure growth and an ever-growing professional population will continue into the foreseeable future (Baltimore, 2008, and BMC, 2008).

The development of an integrated modeling and simulation framework to determine the effects of intervention and evaluate the long-term consequence of response-strategy was used as a basis model for this simulation (Coolahan et al., 2007). Figure 1 represents the design concept used for an urban chemical disaster simulation used by Coolahan et. al., 2007. It includes real-time and non-real-time components used during execution. The area consists of two major exit passageways: at Fayette and President Streets, US highway 83 leading north out of the city and along Conway street and a block from Camden Yards to US highway 395 at the southwest corner of the city to US highway 295 toward the south (see figure 1). The amalgamation of the two conditions, namely, the easily transportable chlorine gas containers, and the easy-to-get-to delivery system in the downtown area of Baltimore, MD poses an interesting scenario. What if there was a terrorist threat that employed Baltimore's transit lines and natural weather conditions to transmit harmful gasses to the entire downtown area 2.3 km by 2.3 km (1.43 miles by 1.43 miles)? As a chemical explosion would generate from the southern area, during a southwest wind event, the southern exit would close off any evacuation routes causing major traffic delays toward the north. Based on the above history of chlorine gas it will take 3-4 hours for chlorine gas to permeate the city's substructure and could render persons in contact with said gas incapacitated (Parr, et al., 2007, and Liu et al., 2006).

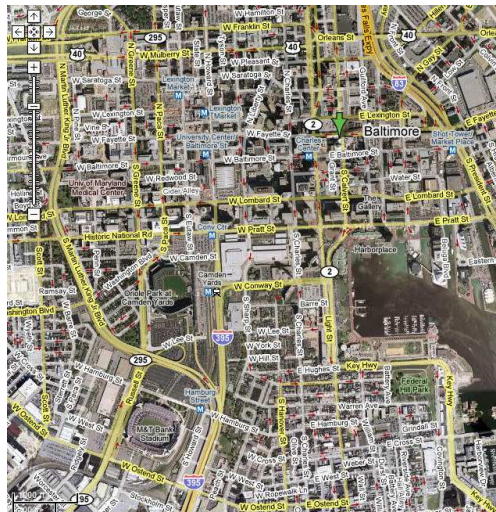


Figure 1: Scenario Location in Downtown Baltimore (Coolahan et al., 2007)

This event would be catastrophic because there would be no early warning signs, as in the case of nuclear or natural disasters. In effect, the safe delivery of people and goods would depend on the systems implemented by competent government officials. The goals of this project are to assess the emergency evacuation models proposed and to develop an ultimate emergency evacuation protocol for the downtown Baltimore, MD area for the protection of lives.

2. LITERATURE REVIEW

The definition of an evacuation as stipulated by the Department of Homeland Security (U.S. DHS, 2004) is “an organized, phased, and supervised withdrawal, dispersal, or removal of civilians from dangerous or potentially dangerous areas, and their reception and care in safe areas.” With regard to emergency evacuation it is further surmised by “an organized, phased, and supervised withdrawal, dispersal, or removal of civilians from areas affected by a situation that poses an immediate threat to human life or serious damage to property, and their reception and care in safe areas.”

Therefore emergency management plans must be incorporated into a city's framework to manage people to their destinations. According to Hwang (9) this plan involves a set of measurements that minimize damages and losses due to natural and other disasters. A management evacuation plan is one where the "the set of measures to fully control departure times, destinations and routes of civilians from areas effected by a situation that poses an immediate threat to human life or serious damage to property".

It is important to note that the timeline in which the evacuation process starts can be relatively short. As many agencies (state, federal, etc.) must mitigate items of response, the time in which an evacuation is carried out remains a key factor to saving lives. Hwang, in 1986 conceived four steps of emergency management: mitigation, preparedness, response, and recovery. As such, the decision making entity, whoever it may be, must make a decision prior to the emergency based on estimations of proximity of emergency and the time it would take to vacate safely. These entities must then deliberate on the margin of time they have to evacuate: an early decision would mean that organization of such is not extremely critical and the evacuation could be superfluous, while a late decision would mean the organization of evacuation is vital to prevent casualties (Zuilekom, 2007).

Unexpected emergencies can occur and therefore must be planned out as well. There is a closeness of time needed between the decision to evacuate and the onset of the emergency situation. They must take place approximately at the same moment.

3. NETWORK ANALYSIS

3.1 SIMULATION

This study uses AIMSUN NG version 5.1.4 (AIMSUN, 2006), a micro-simulation software program that incorporates traffic models and real-time scenarios and fuses static and dynamic approaches within a single milieu. A Transportation Analysis Zone (TAZ) is an area delineated by local and/or governmental transportation officials for use in tabulating traffic-related data (Liu et al., 2006). This delineated area consisting of census blocks are useful for tabulation of data relating to journey-to-work and place-of-work statistics but for the purposes of this research they are useful for configuring an origin-destination matrix based on the specific exit node closest to them. In 1998 a new zone structure was defined by the Baltimore Metropolitan Council and configured 1,151 zones for the Baltimore region. These zones are determined based on socio-economic homogeneity of each area according to census statistics.

3.1.1 DESCRIPTION OF NETWORK

There are a total of twenty-two zones that are analyzed for this research and therefore each zone creates a certain number of vehicles to be included on the network. Each zone then corresponds to a specific origin-destination matrix outlined by the researchers as the safest and most feasible solution to evacuate safely. Six destination safe-zones were chosen for mass departure away from the area of attack. These zones were then used to create staged evacuations.

3.1.2 ORIGIN/DESTINATION MATRICES DEFINED

The origin-destination (O/D) matrix is a type of tool that allows for analogous spatial movements. For the purposes of this research, the O/D matrix had only six destinations based on the destination safe-zones mentioned previously. These safe-zones were based on the geometry of the road network. For instance, if exit nodes combine they would only combine to make one exit. The origin in the matrix assumes that during a weekday or a workday the downtown Baltimore area would be approximately four times the normal standard population density. Therefore, when approximating the O/D matrix, each of the six local zones would continually produce vehicular traffic to compensate for evacuation of individual populations.

4. EVACUATION METHODOLOGIES

Six evacuation methodologies (Do Nothing/ Nearest Two Exits, Police Assisted, Staged, Staged with Police Assisted, Contraflow, and Staged Contraflow) are simulated for the purpose of this study. A brief description of each methodology is given below.

A “Do Nothing” approach employs the ‘Two Nearest Exits’ methodology. It is created to simulate the conditions of evacuees fleeing to the nearest exit without any forethought or advance notice. No evacuation strategies are in place and the evacuees of the city are free to choose their route within the available network area. Evacuees fleeing from each zone are split: 50% go to the nearest exit and 50% go to the second nearest exit if the first is unavailable. This is based on the psychological underpinnings of behavioral choice attitudinal modalities wherein a choice to go to one exit or another would be made based on availability of options no matter the type of situational circumstances present (Slovic et al., 1977). Therefore in a supposed panic situation (i.e. chemical attack) one would choose the “two nearest exits” based on accessibility. This methodology was used as a control in this study.

A Police Assisted methodology simulates police officers arriving at critical traffic signals and allowing extended green time for the evacuees. Currently the traffic timing within the city at the time of evacuation is about 1:1 which means that at all corners of a signal there exists the same traffic cycle length. This methodology takes this ratio to 4:1 for evacuation traffic. Also, it takes into account a 10-minute delay from the time of evacuation. This means that if at 12:30 pm the evacuation order is given, the police will not arrive at their designated traffic light until 12:40 pm barring any unusual circumstance. This mimics the current evacuation methodology performed by the City of Baltimore. Based on experience of the researchers, it was surmised that a guided decision employing persons of authority might make evacuation more feasible and possible.

Staged is a common evacuation methodology wherein the city is divided into zones. These zones are then grouped together according to level of proximity to disaster. Those residing in zones that are in the most danger (closest proximity) are evacuated first. All zones in contact with the pre-selected zones that are evacuated first are evacuated second. All other zones that are not directly adjacent to the zones in immediate danger are evacuated first as well. This type of strategy considers staggered evacuation and schedules a series of evacuations between origin nodes and safety destinations. A dynamic network assignment is imposed so as not to overload the network at any one time (Shayti and Mahmassani, 2006) It is hoped that this strategy would provide an organized evacuation route for all directly involved and congestion might be delayed.

Staged with Police Assistant methodology is the Staged concept used along with the police assisted traffic signals. Employing both methodologies potentially ensures that the most expeditious of evacuations strategies be met.

Contraflow is the increase of roadway capacity by the use of employing opposing lanes in addition to the existing paths. It is also known as ‘Lane Reversal’. Contraflow takes into account all lanes of a road (North, South, East, or West) and makes them all flow in one direction. Contraflow has the ability to nearly double the capacity of a particular direction. Additionally contraflow has been used in emergency situations by emergency personnel vehicles to allow expedient movement around a network. In this study, Contraflow is used on streets which allow the maximum capacity in order to effectively evacuate the downtown areas.

Finally, Staged Contraflow employs conceptually the same methods in the Contraflow methodology but differs in that the evacuation order is given in two stages.

5. RESULTS AND DISCUSSION

5.1 RESULTS

The measures of effectiveness (MOE) are used to distinguish and determine relative data concerning the model. Data included are the traffic density, mean speeds, evacuation counts, and traffic flow rates for the purposes of this discussion. These MOE’s were chosen based on their assessment on evacuation and evacuation properties of the network methods used. Results were determined using Microsoft® access compiled data from AIMSUN NG.

Figures 2 through 4 show the comparison of the mean speed at 11:30 AM, 12:00 PM, and 12:30 PM evacuation for each strategy. What these figures show is the mean speed at ten-minute intervals for a four hour evacuation. Contraflow and staged contraflow strategies show a significantly higher mean speed throughout the four hour increment because the vehicles are allowed to occupy the entire network, essentially doubling the network capacity. During staged evacuation (both scenarios), mean speeds are lowered because the second stage are reaching the first stage evacuees. Therefore at three hours into the evacuation procedure, there appears a convergence where a speed drop of 10km/hr (6.2 mph) occurs. As mean speed is a function of density, it approaches a steady state as the capacity on the network is reached for each scenario.

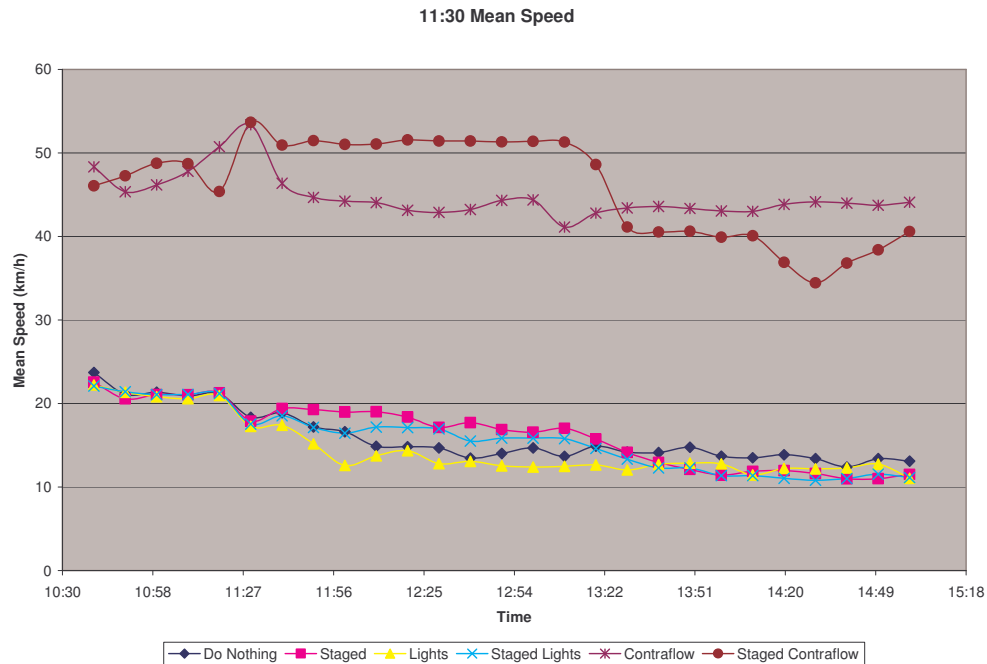


Figure 2: 11:30 AM Mean Speed Comparison

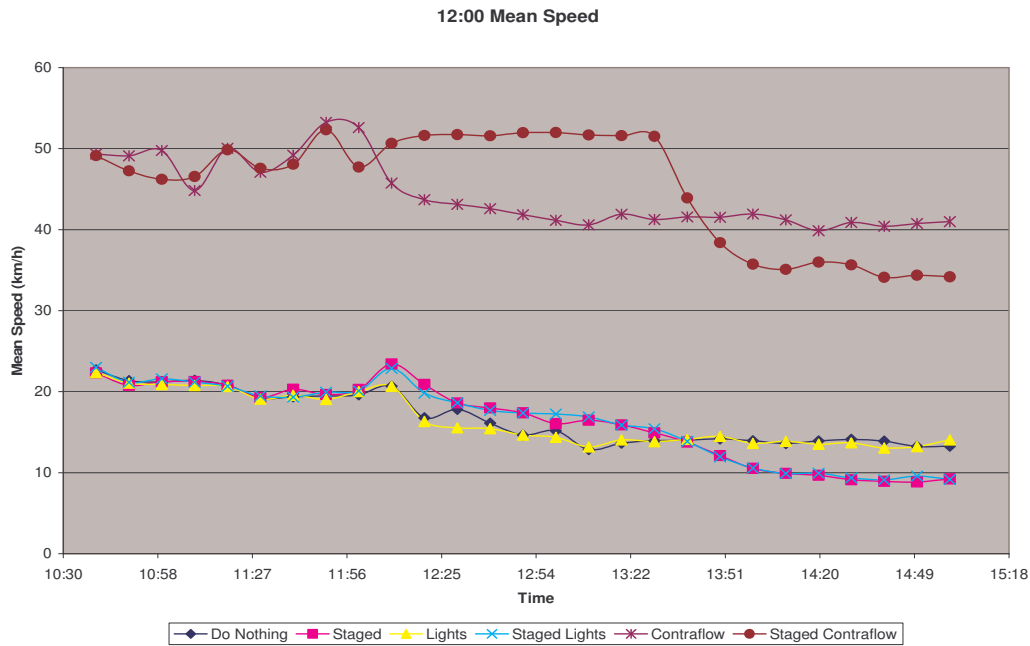


Figure 3: 12:00 PM Mean Speed Comparison

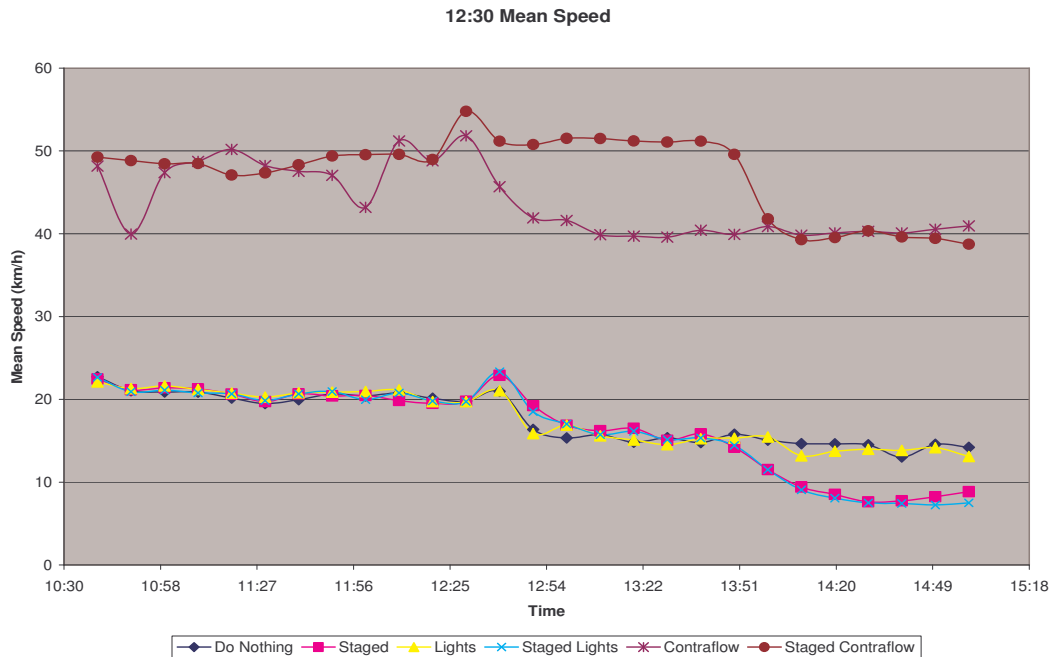


Figure 4: 12:30 PM Mean Speed Comparison

Figures 5 through 7 show vehicle evacuation counts. Vehicle evacuation counts are the most necessary gauge of how effective each evacuation is with regard to the number of lives potentially saved. It is a comparison of each evacuation strategy per time interval. Generally most strategies evacuated between 45%-51% of the cars generated on the network evacuation.

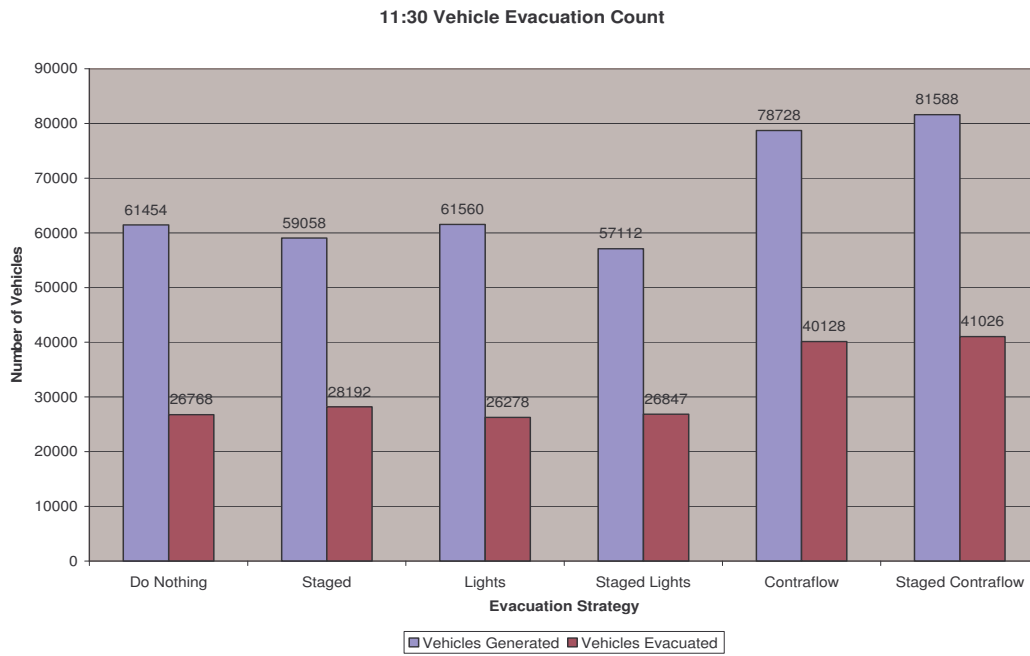


Figure 5: 11:30 AM Vehicle Evacuation Count

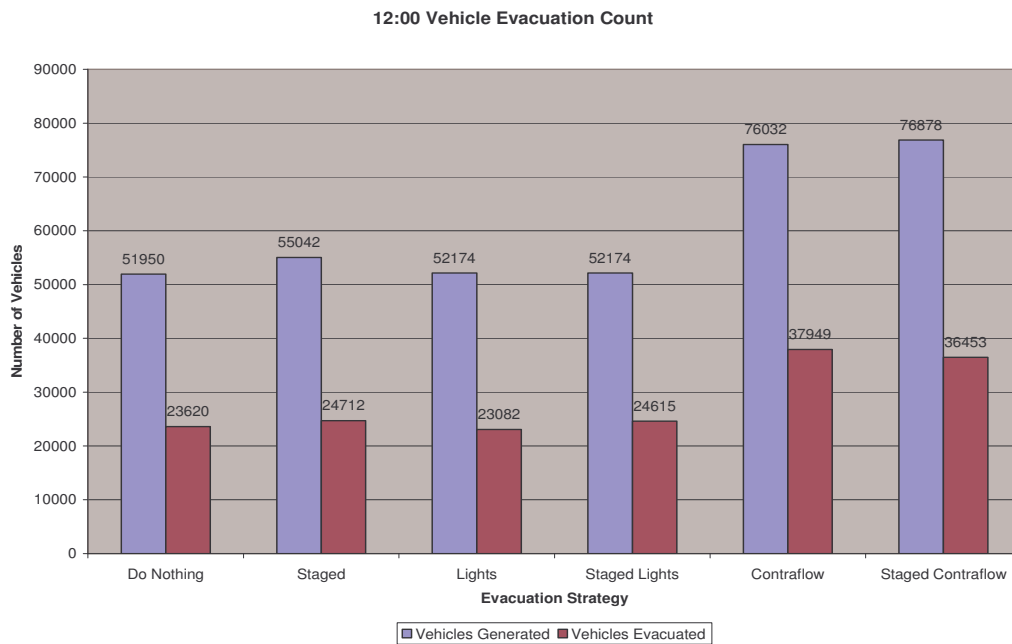


Figure 6: 12:00 PM Vehicle Evacuation Count

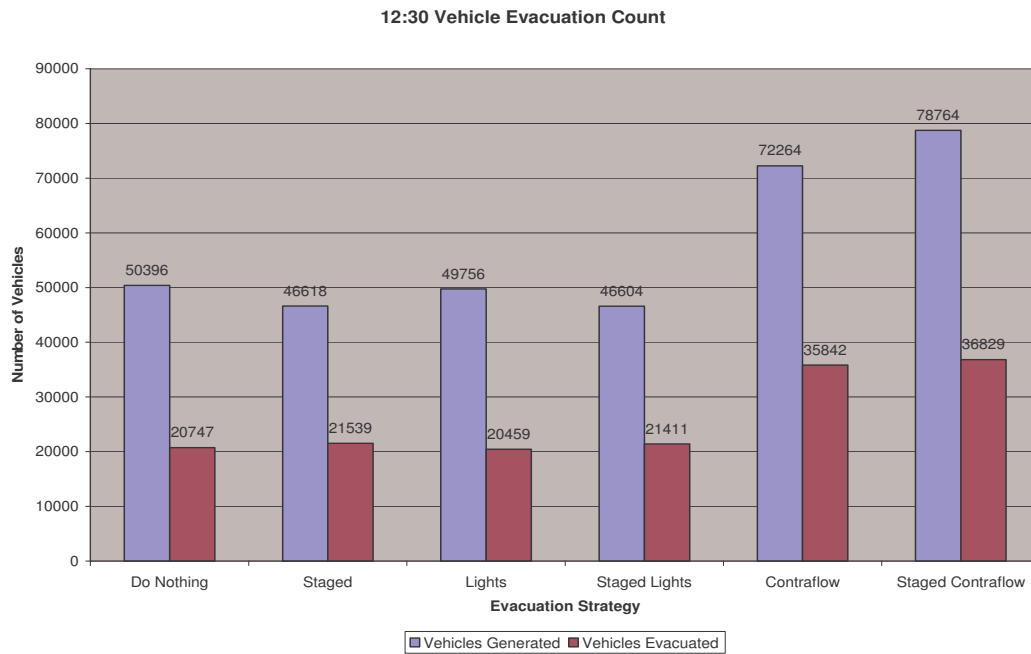


Figure 7: 12:30 PM Vehicle Evacuation Count

5.2 NETWORK DISCUSSION

Figures 2 through 4 where mean speed on the network is compared, shows interesting details about the supposed psychological comfort of the evacuees. Evacuee perception of the road network environment is essential and can be quantified by the level of service detected on the exiting roads. This is in direct proportion to mean speeds evaluated. It is therefore advisable for a road network to maintain higher speeds when an evacuation occurs. When lower speeds or even complete stoppage on the queue occurs, there is potential for vehicular abandonment. If this occurs, queue and delay times become affected as well as severely decreasing lane capacities (by as much as half). It is the equivalent of having a car accident in the lane. The strategies employing contraflow methodology resulting in higher mean speeds and decreased congestion would be less likely to have persons on the network abandon their vehicles. Other strategies resulting in lower mean speed would not be advisable for a complete evacuation.

Staged strategies are of interest here (Figures 5 through 7) because the network reaches capacity at later points in time improving overall network flow. They do however reflect a concern that once stages reach each other there is heavy congestion. Density on the road network is perceived as traffic congestion representing a poor level of service. Density increases as flow times are limited. Regardless of which strategy is used, the traffic density is ultimately dependant on the lane geometry of the network. Contraflow produces more vehicles but has less density over all other strategies because more lane geometry is available.

Vehicles generated are a function of the entire network capacity where vehicles evacuated is a function of exit capacity – the sum of all vehicles on all roads exiting the network (Figures 12 through 14). Congestion on the network increases as later evacuation times are given. Each of the previous analyses showed the comparisons to one another but the vehicle evacuation counts showed the actual numbers of compromised vehicles on the network compared to escapees. Contraflow results in approximately 15,000 more vehicles evacuated based on the increase in size of exit capacity. There appears to be a 2500-3500 drop in vehicles evacuated between each evacuation order – as time passes between evacuation orders the number of potential casualties increases. This happens because evacuation time is limited.

6. CONCLUSIONS

The police assisted methodology starts with many assumptions, the most prevalent being the fact that the police will arrive at their respective traffic signals in a certain time despite existing traffic delays and an orderly flow of traffic. The staged evacuation strategy does not take into account the possibility of pre-existing conditions. An evacuation that would employ this strategy requires that directions are followed explicitly. Contraflow takes a lot of preparation, time, and trained personnel. The problem with contraflow remains that once a direction is chosen one must precede in the direction that contraflow designates without chance of redirection.

The present strategies used are police assisted traffic control at pre-defined intersections. While this is a useful strategy for control and flow of traffic, it puts the police personnel in a potentially precarious situation. According to data found, there exists only a marginal difference between related strategies. A “do-nothing” strategy versus a “police-assisted” strategy has been shown not to improve the network evacuation strategy because of the length of time spent in the traffic queue. Both prove to leave more vehicles in the network because queue times in signalized pre-timed controllers are distributed throughout the network and while the presence of police personnel may be necessary, the simulation surmises that the same pre-timing will take place. It is therefore recommended that these two strategies not be used for evacuation of said network.

During staging of the network, the area has been divided into three zones – where the zones in closest proximity to the emergency point will be evacuated first. Those zones adjacent to the ‘danger’ zone would then be evacuated next and so on until all zones in the area of interest would be cleared. The two scenarios conceived were a simple staging strategy and then paired with pre-timed controllers. The problem developed here was saturation of the network. As shown in the traffic density diagrams, within a half-hour of evacuation, there appears exponential growth, and lag time because available network capacity reaches saturation. Meanwhile, staged evacuation optimizes network capacity because particular zones are allowed full capacity of the entire network. This is a viable solution except that with a limited number of exit points, at the point of exit each subsequent stage reaches the previous stage and traffic congestion inevitably occurs not allowing complete evacuation of the network constituents. Therefore staged evacuation along with controlled staged evacuation strategy does not prove to be a practical solution and the researchers do not suggest they be used.

Contraflow is a strategy that nearly doubles the amount of network capacity in one direction. It does not allow multiple directional traffic but does provide a clear way out should the need arise. The strategy requires much planning but proves to be the most effective for large scale quick evacuation. This is proven in figures showing mean speed where during earlier evacuations the mean speed was between 15 km/h (9.32 mph) but during later evacuations (12:30 PM) there was a mean speed average of approximately 40km/h (24.85 mph). Because mean speed is shown to be consistent, the researchers conclude that the relative delay time is positively affected.

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