Multimodal Evacuation Simulation and Scenario Analysis in Dense Urban Area: A Philadelphia Case Study

Paper No. 15-2186

Fang Yuan, Ph.D., P.E. (corresponding author)
Email: fyuan@dvrpc.org
Phone: 1-215-238-2885
Fax: 1-215-592-9125

Christopher M. Puchalsky, Ph.D.
Email: epuchalsky@dvrpc.org
Phone: 1-215-238-2949
Fax: 1-215-592-9125

Delaware Valley Regional Planning Commission
190 N Independence Mall West
Philadelphia, PA 19106-1520

Word Count: 5,715
Figure Count: 7
Total Word Count: 7,465

Original Manuscript Submitted: 07.20.2014
Revised Manuscript Submitted: 11.13.2014
ABSTRACT

Simulation is an effective tool for estimating evacuation times, identifying system bottlenecks, and evaluating traffic management strategies under a variety of operational and behavioral assumptions. This paper presents the development of a multimodal simulation model for modeling evacuation activities in Center City Philadelphia. The model applied a dynamic sequential assignment method to simulate the movement and interactions of pedestrians, private vehicles, and buses, while considering the variation of evacuation demand and network conditions during evacuation operations. It was applied to perform scenario analysis and provide inputs to update current evacuation plans. This paper shares the experience and findings from the Philadelphia study in modeling multimodal evacuations in dense urban areas.

Keywords:

Emergency evacuation, scenario analysis, simulation, multimodal operations
1. INTRODUCTION

A great challenge presented at a mass evacuation is that transportation supply is often insufficient to handle the unusual surge in travel demand. In dense urban areas, roadway capacity and vehicle mobility are further impacted by the interactions of pedestrian and vehicle flows during an evacuation operation. Travel behavior in emergency situations is also difficult to predict with regard to mode and route choice. To support emergency preparedness and evacuation planning, it is critical to estimate evacuation times, identify system bottlenecks, and evaluate traffic management strategies under a variety of operational and behavioral assumptions. Simulation is a viable tool to perform desired scenario analysis and communicate system resiliency and planning needs to various stakeholders.

In the literature, a variety of simulation techniques have been applied to evacuation modeling. A few paper (1, 2, 3, 4) provided comprehensive review of evacuation simulation models. Traditionally, evacuation research has been focused on vehicle evacuations (i.e., people driving out of a harm’s way) in cases of hurricanes (5, 6, 7) or accidents at nuclear power plants (8, 9). Recently, researchers have started to investigate pedestrian evacuation behaviors and model scenarios such as walking out from a transit center (10), stadium complexes (11, 12), or a downtown area (13). Relatively limited research dealt with multimodal evacuations in dense urban areas. Hossam and Baher (14) developed an optimization model for the evacuation of the City of Toronto using multiple modes including vehicular traffic, rapid transit and mass-transit shuttle buses. The model first coordinates evacuation scheduling, route choice, and destination choice for vehicular traffic and then optimizes the routing and scheduling of mass-transit vehicles. Zhang and Chang (15) presented an integrated model to produce the optimal distribution of vehicle and pedestrian flows with the capacity to account for the interdependent relations between pedestrian and vehicle flows at some conversion locations and the conflicts at intersections. It was applied to an evacuation around a stadium area. Liu et al. (16) studied a corridor-based evacuation of Washington, D.C., assuming an attack on Union Station and evacuating six surrounding traffic analysis zones. The proposed GIS-based model considered both pedestrian and bus operations in corridor planning. Meschini and Gentile (17) presented the application of a within-day dynamic traffic assignment (DTA) model to simulate ordinary, evacuation and emergency scenarios for downtown Vancouver in preparation of the Winter Olympic Games. The macroscopic vehicle DTA model was modified to present the pedestrian flow. Different types of car-pedestrian interactions were also considered in the model. All in all, research and simulation methods for multimodal evacuations are relatively limited in terms of the amount and level of multimodal interactions being considered and the efficiency for large scale (or demand) applications.

This paper presents the development of a best-of-practice, multimodal evacuation simulation model for the Center City Philadelphia. The model applied a dynamic sequential assignment method to simulate the movement and interactions of pedestrians, private vehicles, and buses, while considering the variation of evacuation demand and network conditions during evacuation operations. It was applied to simulate hypothetical emergency scenarios and evaluate potential traffic management strategies that improve system resiliency. This paper is intended to share and extend the experience and findings from the Philadelphia study to a general discussion of the
2. MODEL DESIGN

Hosting more than 262,000 salaried jobs and 87,000 residents, Center City Philadelphia is the largest employment center in the region and the third largest residential downtown in the U.S. To support evacuation planning, a simulation model was developed by the Delaware Valley Regional Planning Commission (DVRPC), the Metropolitan Planning Organization for the nine-county, two-state area, in cooperation with the City of Philadelphia.

The Center City model is based on DVRPC’s regional travel forecasting model (a traditional four-step model implemented on the VISUM platform), enhanced with intersection details and pedestrian components in the Center City area. The Center City model employs DTA (as compared to static assignment used in the regional model) to simulate vehicle and pedestrian flows during evacuations. With static assignment, which describes a link’s congestion properties using volume-delay functions, it is difficult to accurately estimate evacuation times, as flow can pass through the network even if the volume exceeds the capacity of a road or intersection. DTA is effective in modeling the formation and propagation of congestion in the network with regard to capacity constraints. It is also more efficient (in terms of run time) for simulating the entire Center City network and full evacuation demand (as compared to microsimulation models).

2.1 Multimodal Network

Transportation supply of all modes in Center City was modeled at a great level of detail. The model includes a multimodal network that consists of a highway network, a public transit network, and walkways for pedestrians. The highway network was extracted from the regional model and enhanced with intersection details to include lane allocation, turn bay, traffic control and signal timing plan for accurate capacity estimation. Vehicle loading to the highway network was refined to represent the real-world locations of parking facilities. A detailed public transit network was also carried over from the regional model, including route alignment, stop locations, and service schedules based on the General Transit Feed Specification (GTFS) data (18). Lastly, pedestrian components were added, including pedestrian sidewalks, underground walking facilities, and connections to pedestrian sources and sinks (i.e., buildings, transit stations, and parking facilities).

2.2 Demand Modeling

Demand estimation, specifically temporal variation and mode shift at evacuations, is often overlooked in many simulation models. The anticipated evacuation time, congestion level, bottleneck locations and the effectiveness of proposed traffic control strategies all depend on the demand level. In this study, the four-step demand forecasting procedure used in the regional model was augmented with a feedback loop and a scenario design procedure for modeling scenario-specific evacuation demand including demand variation. Figure 1 shows the proposed modeling procedure.
For a given emergency scenario (in terms of emergency type, time of day and impacted area), a decision needs to be made first between evacuation versus other emergency response plan (e.g., shelter in place). If evacuation is necessary, potential evacuees in the area can be estimated based on a variety of data such as population, employment, tourists and building occupants. For a no advance notice emergency scenario, if there is no damage on transportation infrastructure, it is reasonable to assume that people will try to go back home (or in that direction) by the same mode as they entered the area. If one transportation system is out of service, initial assumptions can be made on mode shift in response to the change of transportation network or service conditions. With the initial demand assumptions, the model can run and evaluate the accessibility and performance of individual transportation systems or modes (e.g., walk versus take bus to a specific destination). The potential mode shift was then re-estimated based on projected highway congestion and overcrowding or delay on transit services. Without an empirical method to study mode choice specific to Philadelphia and specific scenarios, the potential mode shift and its impact may be best analyzed in a scenario design and planning fashion. A plausible range of mode shift may be estimated based on survey data or the regional model (by estimating transit population within a walkable distance from the evacuation area and then assuming a partial or complete mode shift of that group). This iterative simulation and scenario analysis procedure could provide a more robust evaluation of system performance and effectiveness of evacuation plans in accordance with uncertainty in evacuation operations.
2.2.1 Temporal Variation

The estimation of potential evacuees is somewhat more complicated than it appears. Maximum daytime population is often the main concern in evacuation planning. The U.S. Census Bureau (19) suggests the commuter-adjusted daytime population, which accounts for population change in daytime due to employment, may be estimated by adding the total workers working in the area to the total residential population and subtracting the total workers living in the area. In Central Business District (CBD) of Philadelphia, which is the core of Center City, the commuter adjusted population is estimated to be about 252,000. The same method can be extended to include the population change in the daytime due to school activities based on the school enrollment and the school-age population. The daytime tourists may also be included based on the recorded number of visitors at tourist attractions. Taking all these into account, the potential maximum daytime population may reach 276,000 within the CBD.

However, in a typical weekday, the actual daytime population is likely to be lower, considering that not all workers commute to the area on a daily basis or are present at the same time. This can also be seen from travel counts. Along all roads crossing the cordon lines around the CBD, DVRPC has regularly collected highway vehicle counts, transit ridership, pedestrian counts, and bicycle counts in weekday conditions. By continuously tracking the cumulative inbound and outbound trips as people entered and left the CBD, the population accumulation within the CBD during the course of a typical weekday can be estimated in Figure 2.

![FIGURE 2 Population Accumulation within Philadelphia CBD by Time of Day](image)

In this figure, the base of accumulation is the nighttime population, which includes the resident population, nighttime workers and nighttime visitors. Within the CBD cordon lines, the resident population is about 60,000, the nighttime population is about 80,000, and the maximum daytime population is likely about 215,000. The maximum daytime population reflected by the cordon line counts is much lower than the potential or “theoretical” maximum daytime population.
estimated previously. The maximum population presented in Figure 2 may be considered as the average daily maximum daytime population.

In this study, scenario-specific evacuation demand was estimated using multiple data sources and calibrated by the cordon line counts. The demand estimation for simulation purposes focuses on the general public at prevailing locations that may be self-evacuated (i.e., workers at work places, residents at home, and visitors at major shopping and tourist attractions). Other person groups such as persons with disabilities and in hospital patients were not simulated (their evacuation time depend on evacuation plans and emergency supply). Furthermore, the daytime population was distinguished between the resident and nonresident population based on Census data and the regional travel model. This distinction allows a more flexible simulation setup with regards to evacuation destination and mode assignments for residents versus nonresidents.

2.2.2 Demand Loading

In the demand modeling process, it is also important to estimate the loading pattern of different modes. This includes the variation in the evacuees' departure time, evacuation time from high-rise buildings, and walking time to transit stations and parking facilities.

In this study, the commonly-used $S$-shaped loading curves were employed to present the variation in individuals' perception, decision and response to different emergency types and evacuation order. It was first applied in loading pedestrian demand. The loading period also varied by zone, depending on the presence of high-rise buildings and the required building evacuation time. The building evacuation time was estimated based on empirical equations and verified by the experience from fire drills. The vehicle loading time will be longer considering the time required to walk to parking facilities and access vehicles. It was estimated from pedestrian simulations. In the model, the loading time for pedestrians was up to 30 minutes for zones with high-rise buildings, and the loading time for vehicles was up to 45 minutes. It should be noted that the loading time can make a great impact on simulation results with regards to observed congestion patterns and evacuation times. Given the high demand level in Center City, the highway network could quickly end in a gridlock situation if the loading patterns were incorrect. Caution should be given when designing the simulation loading curves.

Along with loading times, three types of pedestrian demand need to be estimated: walk-to-evacuate pedestrian trips, walk-to-transit pedestrian trips, and walk-to-vehicle pedestrian trips. The latter two types constitute a significant portion of the overall pedestrian volume and present a great impact on vehicle mobility during evacuations. In our case, the transit access walking trips were derived through a skimming process on a loaded pedestrian network, after transit assignment. The parking facility access trips were estimated using a multinomial model considering factors such as walking time to parking zones, driving time to parking zones, parking cost, and parking capacity.

2.3 Multimodal Simulation

To model the interactions between different transportation modes during a no-notice evacuation operation, a sequential simulation approach was proposed, as shown in Figure 3.
For any emergency scenario, walking is always a means to evacuate and pedestrian flow can have a significant impact on vehicle mobility. Even in normal conditions, pedestrian movements on crosswalks may impact vehicle turning movements at intersections. In emergency situations, vehicle movements may be further constrained, considering the surge of pedestrian demand and possible failure of traffic control devices. Arguably, pedestrians always take the right-of-way over vehicles, especially in no-notice evacuation scenarios. Pedestrians may inundate the roadway, reduce vehicle capacity, and slow down vehicles. Therefore, a scenario analysis can start with the pedestrian simulation to establish pedestrian flow and evaluate the impact of the pedestrian flow on the vehicle flow. The vehicle simulation can be followed with the simulation settings (e.g., turn capacity at intersections as well as link capacity and free-flow speed if pedestrian inundation is modeled) updated at each simulation time interval (TI) according to the pedestrian simulation results. On the other hand, intersection traffic control may change during an emergency, and that can also be modeled by applying a time-varying intersection capacity setting to the vehicle simulation.

At the end of pedestrian and vehicle simulations, pedestrian and vehicle evacuation times are obtained along with other performance measures. The transit simulation is conducted last to estimate transit volume and transit evacuation time, using a schedule-based, capacity-constrained assignment method in VISUM (21). It is noted that transit evacuation time would be affected both by the considerable slowdown of on-street transit operations by pedestrian and vehicle
traffic, and by the mis-match of available transit capacity with demand. For the first part, the bus
delay can be estimated based on the experienced vehicle travel time along bus routes from the
vehicle simulation. For the second part, since the maximum evacuation demand in the Center
City case occurs during a trough in transit service between the AM and PM rush periods, this
transit demand-capacity mis-match greatly increases evacuation times, as will be seen later.

2.3.1 Vehicle and Pedestrian Simulations

The Center City model employs the Dynamic User Equilibrium (DUE) model implemented in
VISUM to simulate network flow dynamics during evacuations. Given time-dependent origin-
destination (OD) tables, which represent the loading pattern of vehicles and pedestrians during
an evacuation operation, the DUE model evaluates the time-varying characteristics of links based
on the Lighthill-Whitham-Richards (LWR) traffic flow model, and balances the path flows based
on the experienced travel time. Since the underlying equilibrium assumption is unlikely met in
evacuation situations, the DUE model was not intended to reach or converge to equilibrium
conditions, but was used mainly for evaluating the evolution of network performance under
changing demand and/or network conditions (roadway capacity and traffic control). A desirable
feature of the DUE is that it can take time-varying variables (e.g., free-flow speed and capacity)
as inputs.

In addition, the LWR model was modified to account for the pedestrian capacity on a link and
represent pedestrian flow characteristics, as proposed by Meschini and Gentile (17). Without
changing the current network configuration (a unidirectional node-link network), the link
pedestrian capacity was first set for each direction of a road based on the “right-hand drive”
convention, and a directional capacity was defined considering the longitudinal space required
by a pedestrian (22). Bidirectional pedestrian flows (pedestrians moving in two directions on the
same link) were modeled using an iterative procedure to balance the capacity distribution to the
demand, as proposed in the literature (17).

2.3.2 Vehicle and Pedestrian Interactions

Different types of pedestrian-vehicle interactions were modeled via Python scripts to update the
vehicle simulation settings after the pedestrian simulation. First, time-varying vehicle turn
capacities were calculated based on the conflicting pedestrian volume at crosswalks and traffic
control settings. In case of normal signal operations, the through capacity of vehicle traffic is not
affected by pedestrian movements, but the right-turn and left-turn capacities are affected. This
pedestrian impact was calculated following the Highway Capacity Manual (23) methods for
capacity adjustment at signalized intersections, under two situations: 1) the pedestrian adjustment
for right-turn lane groups, and 2) the pedestrian adjustment for left-turn lane groups from a one-
way street. To represent the flow dynamics in a relatively high resolution, pedestrian flows and
their impacts on vehicle flows were evaluated at the 15-minutes interval, and accordingly,
vehicle capacities were updated at the 15-minutes interval during the vehicle simulation.

In case of signal failure, vehicle capacities will be adjusted for all movements. In this case,
signalized intersections may function like all-way stop control, while pedestrians are likely to
cross with a higher priority regardless of vehicles. In this study, a simple but intuitive method was applied to evaluate the impact of signal failure, using the following equation:

\[ C_{veh} = k \times C_{veh}^0 \times (1 - V_{ped}/C_{ped}) \]

where,

- \( C_{veh} \) = new vehicle turn capacity (vph)
- \( C_{veh}^0 \) = initial vehicle turn capacity (vph)
- \( V_{ped} \) = pedestrian flow rate (pph)
- \( C_{ped} \) = pedestrian capacity (pph)
- \( k \) = base reduction factor

The base reduction factor \((k)\) represents the additional delay incurred as traffic control type changed from signalized to all-way stop operations. Without empirical data for validation, the proposed method is not intended for providing a rigid estimation of new intersection capacity and delay in the signal failure condition but rather, a viable tool for evaluating the potential delay on evacuation times. The proposed method may be sufficient for evaluating the relative effectiveness of different traffic management strategies (e.g., how to allocate police officers to direct traffic) under the same capacity assumption.

Furthermore, pedestrian inundation was modeled. Inundation in this context is defined as the overflow of pedestrians from a sidewalk to driveway due to the high pedestrian density on the sidewalk. In this situation, an assumption was made that pedestrians will occupy one vehicle lane if the sidewalk is overcrowded. This was implemented by checking for the critical density on sidewalks, after performing the pedestrian simulation and updating the vehicle capacity and free-flow speed on the inundated links for the sequential vehicle simulation.

3. SCENARIO ANALYSIS

After the model calibration (with regard to demand, simulated volume, and travel time), two hypothetical emergency evacuation scenarios were modeled. The first one is a generic scenario not tied to a specific emergency type. In this case, assuming no damage of transportation infrastructure, a multimodal evacuation of the entire Center City at the peak of daytime population was simulated. The simulation started with assumptions that nonresidents of Center City will evacuate by the same mode and in the direction as they entered Center City in the morning, while residents of Center City will evacuate to the nearest exit outside Center City from their current locations. The second scenario is a regional blackout scenario, which also involves moving a large amount of population. In this case, since the subway and regional rail systems are out of service, nonresidents will drive, walk, or take buses home or to designated transit centers in order to access transit service back to their homes across the region. Furthermore, two potential strategies were evaluated for prioritizing intersection control and enhancing system resiliency in the blackout scenario. Simulating these scenarios provides insights how Center City evacuation functions and answers to a number of critical planning questions posted by the Office of Management with respect to evacuation timeline, transit dependence, emergency vehicle routing, critical infrastructure protection, and emergency supply distribution. Given its
sensitivity, only selected results are discussed in this paper with a focus on analysis methods and 
making recommendations to evacuation planning in general.

3.1 Evacuation Time

Evacuation time is the most commonly used measure of effectiveness for evacuation planning. The time required to evacuate 100% of the population (i.e., network clearance time) is seldom attainable in reality; the time required to evacuate 95% of the total population is a more practical and meaningful measure to represent the overall evacuation timeline. Further, the evacuation process by transportation mode (i.e., walk, car, bus, subway, light rail and heavy rail) can be described by evacuation curves, which represent the cumulative percentage of evacuees cleared from the evacuation area as a function of time. Figure 4 represents the evacuation curves associated with each transportation mode used for evacuation in the first scenario. For example, the “walk” evacuation curve represents the time required for those who were assumed to evacuate by walking to walk out of Center City, while the “bus” evacuation curve includes the time required for evacuees walking to bus stop, waiting for bus, and riding out of Center City.

![Figure 4: Evacuation Curves by Mode if No Damage on Transportation System](image)

The evacuation times for car and pedestrian (walking) were directly available from the simulation model. The sensitivity of these evacuation times were analyzed with respect to capacity assumptions, simulation settings, and loading times. Overall, the results appeared to be consistent in terms of the timeline to evacuate the majority of the evacuees (the network clearance time is more sensitive). On the other hand, the transit evacuation time was estimated by first evaluating evacuation demand versus transit supply (the service frequency at noon, which is the peak of person accumulation in Center City and the onset of the evacuation in the first scenario). If there is no delay in transit service (i.e., transit vehicles could arrive in Center City on time, make turns, and drive out of Center City with normal runtime), the transit supply may be sufficient to accommodate the evacuation demand within three hours. In Figure 4, the
evacuation time for Regional Rail and PATCO appears to be the longest, which in fact shows the
mis-match of the off-peak transit capacity with the peak daytime population. The evacuation
time could be significantly reduced if the operation of the heavy rail system is able to adapt to a
higher service frequency in response to the emergency conditions. As such, the bus evacuation
time and delay may be more of a concern. Based on the change of car travel time in simulations,
the delay on bus run time was estimated and included in the estimated bus evacuation time.

Figure 5 shows the estimated average bus delay outside Center City by direction. The delay on a
bus route was estimated by the difference between the car runtime along the bus route and the
scheduled bus runtime. The longest bus delay appears along the eastbound bus routes from
Center City Philadelphia to New Jersey via the Ben Franklin Bridge. Therefore, potential
mitigation strategies may consider improving traffic control along bus routes in that direction or
detouring buses entering New Jersey to other bridges. The bus routing strategy may be designed
by examining the network congestion pattern.

![Figure 5 Delay of Bus Travel Time during Evacuation](image)

3.2 Transit Dependence

Mass transit system plays an important role in many dense urban areas. In Philadelphia, about
50% of nonresidents rely on mass transit system for commuting to Center City on a daily basis.
In case of emergency evacuations, the conditions and effectiveness of mass transit operations
may be the key of the entire evacuation process. From the planning perspective, it is critical to
understand how partial or complete shutdown of various modes of mass transit would affect
evacuation time. Accordingly, emergency response plans may be developed and prioritized to
improve transit system resiliency.

To evaluate transit dependence, first a ball-park evaluation of transit system importance can be
made based on the estimated demand split on individual transit systems versus supply from the
first scenario. Then scenario analysis can be conducted to evaluate how the partial or complete
shutdown of a specific transit system would affect evacuation time. The blackout scenario is a
good (and realistic) example out of all permutations. In the blackout scenario, while the subway
and regional rail systems are assumed to be out of service, bus service will continue with limited
service due to congestion. Nonresidents who commute by subway and regional rail now need to
detour to designated transfer centers outside Center City to access transit services back home
across the rest of the region. Figure 6 shows the evacuation curves in the blackout scenario.

In this scenario, the pedestrian evacuation time was least impacted by the blackout, and
expectedly the vehicle evacuation time increased due to intersection delay when signals failed.
In reality, the pedestrian and vehicle evacuation time may be even longer, since some transit
riders may walk, carpool, or wait to be picked up by families and friends instead of waiting for
transit service. The mode shift may increase the congestion level on the street network and
consequently increase the vehicle and pedestrian evacuation times. However, the major
challenge in this case is that the bus capacity is far below the transit demand (due to a
combination of a low midday transit capacity and a large demand shift between sub-transit
modes), resulting in an unacceptable long evacuation time.

On the demand side, potential mode shift was considered in this scenario, assuming that certain
percentages of transit users will walk home if it is possible. On the supply side, transit
evacuation time was estimated considering only bus routes that provide direct service from
Center City to the transfer centers. While people may take alternative buses that require transfers
or walk to the transfer centers, the transit supply is still significantly lower than the potential
evacuation demand. Furthermore, when taking into consideration the congestion along the bus
routes, the bus evacuation times would be even longer. The simulation suggests that evacuee
collection points should be designed with a closer proximity to Center City to ease the access and
transport of people to their homes.
3.3 Intersection Control Priority

In the event of mass traffic control system failure, intersection control priority (i.e., which intersections should be prioritized for the initial deployment of police officers, given limited resource) is an important planning question. Even if signals remain functional, controlling critical intersections could be advantageous to smooth evacuation flow (overriding midday signal timings that may not favor evacuation operations) and ensure safety (against conflicting movements of pedestrians and vehicles from minor approaches). In Center City Philadelphia, since all signalized intersections operate with pre-timed timing plans, implementing emergency intersection control would be practically necessary and more effective.

There are two potential approaches to prioritize intersection control. One approach is to focus on routes or route segments that carry high vehicle traffic. All intersections along these routes or route segments may need to be controlled as early as possible. The concern is that traffic breakdown at one intersection of a high-volume route may cause the breakdown of upstream intersections and a gridlock condition. The other approach is to focus on critical high-volume intersections, which may be selected based on a combination of factors including the total amount of evacuation traffic to pass through, the directional split of the vehicle volume (i.e., the conflicting level of the vehicle movements), and the pedestrian volume. Figure 7 compares the effectiveness of these two approaches in prioritizing intersection control.

![Evacuation Curves by Traffic Control Scenarios](image)

**FIGURE 7 Evacuation Curves by Traffic Control Scenarios**

For intersections selected for initial police control, their capacities were assumed to be restored to the original capacity. Police control was established in an incremental manner (deployment sequence depends on the intersection or route ranking), while the total number of intersections to be controlled was subject to the constraint of staff capacity. In this case, the police capacity in Center City was only sufficient to control a small portion of signalized intersections in a no-notice evacuation scenario. Both approaches appeared to reduce the delay and mitigate the
impact of signal control failure to some extent. On the other hand, two approaches did not present a lot of difference in terms of evacuation time, since many critical intersections were identified by both approaches. In reality, it may be a more complicated problem and a good research topic with regard to the selection criteria and control sequence.

4. CONCLUSION AND RECOMMENDATIONS

This paper presents the development of a multimodal simulation model for modeling evacuation activities in Center City Philadelphia. The simulation model provides extended capacity in scenario analysis to account for the variation in evacuation demand, the changing network and traffic control conditions, and the interactions of pedestrians, vehicles, and buses during an evacuation operation. The scenario analysis provides answers to a variety of planning questions including but not limited to evacuation timeline, effect of mass transit closures, emergency vehicle routing, critical infrastructure protection, and emergency supply distribution. Simulation results including visualization also help communicate system resiliency and identified planning needs to various stakeholders including local emergency management agency, police department, and transit operators.

The model structure and simulation procedures proposed in this study are transferable to other locales and applicable to modeling a wide range of no-notice evacuation scenarios. Different software may be also used for simulating the multimodal evacuations in this modeling framework depending on the characteristics of the modeling area (e.g., size, demand level, and traffic composition) and the purpose of study. In addition, the simulation results show that factors such as demand variation, mode shift, loading pattern, and pedestrian-vehicle interactions all have a great impact on evacuation time. Based on findings from this study, the authors recommend that future studies pay greater attention on these factors in evacuation modeling and scenario design.

REFERENCES


