Developing a Walk-Out Evacuation Plan for Washington, DC
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The DC Walk-Out Evacuation Plan was developed to facilitate the pedestrian aspects of an evacuation of Washington, DC. To reflect the highest volumes of pedestrian evacuees, the project concentrated on a worst case scenario in which the entire city must be evacuated while regular transit service is not functioning. The study team developed a behavior model to forecast the number of people that would evacuate as pedestrians, where they would go and the routes that they would use to get there. This paper describes the methodology used to develop the model and its underlying assumptions. While specifically tailored to Washington, DC, the methodology can be modified for other areas where walking will be a major mode of evacuation.

1. Evacuation Structure

The DC Department of Transportation (DDOT) initiated this project as a supplement to their previous work in emergency evacuation planning. The DC Emergency Management Agency (EMA) identified 14 possible threats to the District which could affect numerous locations within the city at any time of the day or night. Because the threats to the area are so varied and so many potential targets exist, this project was based around a non-specific event occurring at an undefined location. The only details that were assumed about the scenario was that the whole District will need to be evacuated and that regular scheduled transit service (including Metrorail, Metrobus, VRE and MARC trains) will not be available during the evacuation. DDOT and the project team realized that the likelihood of a full-city evacuation is fairly low; therefore the results of the plan are scalable and can be used to facilitate a partial evacuation. To accomplish this, the city was divided into five sub-areas using easily recognizable geopolitical boundaries which made it possible to model and analyze an evacuation of any of these individual sub-areas in an emergency scenario with more localized effects.

As part of the District Response Plan, DDOT’s Emergency Transportation Annex (ETA) provided the structural outline for how all types of evacuations in DC should be organized. The ETA established the roles of various governmental bodies in case of an evacuation and established and analyzed a series of vehicular evacuation routes throughout the District, primarily for traffic operations and emergency response management. The ETA also established a series of transfer points around the District at which buses would transport evacuees out of the city to a series of collection areas located around the National Capitol Region (NCR).

Each transfer point would be served by one or two evacuation bus routes, transporting evacuees to a limited number of collection areas. These transfer points, collection areas and their associated bus routes were the structure upon which planning efforts were based. Therefore, pedestrians had the option of either walking to one of the designated Transfer Points inside of the city; walking directly to one of the collection areas outside of the city; or – for people who live outside of the city - walking directly to their homes. The ETA did not address accommodation and transportation for evacuees once they reach the collection areas. The project utilized these collection areas (in addition to people’s homes) as the end point for their evacuation route.
2. Model Structure

A model was developed so that it accurately represented the evacuation structure that was developed in the ETA while still following the traditional four-step method as closely as possible. Several small modifications were made to this standard structure to reflect the structure of the pedestrian evacuation, including joining the distribution and mode choice steps into a single, simultaneous choice model. Trip generation was not performed using the standard methodology, and instead was developed by applying current population trends to land use and population forecast data. This section discusses the models, assumptions and methods used for the trip generation, trip distribution, mode choice and assignment steps of the travel forecasting process in this study. Figure 1 illustrates the structure of this model.

2.1. Pedestrian Trip Generation

The trip generation step of the traditional four-step model was expanded to include an element of mode choice. This study focused on the evacuation of those who will evacuate without the use of a private car; these evacuees are seen as pedestrians whether or not they make use of DDOT’s emergency bus routes because they will have to walk to a transfer point or to their homes.

The total number of people evacuating from the district can be estimated by using census data and the Metropolitan Washington Council of Governments (MWCOG) travel forecasting model. The first step is to define the evacuating population in terms of their:

- Total Volume;
- Composition – activity type at the time of the evacuation and where they live;
- Distribution – where in the city are they located at the time of the evacuation; and
- Mode of Arrival – how they arrived at their location at the start of the evacuation.

These four attributes were used to determine which evacuees were likely to drive (or be driven) out of the city and which would be left to evacuate by foot.

The number of people that are in the District is largely dependent on the time of day and the day of the week. Employees, students, shoppers and tourists are all likely to be in the city at different times, so the volume and composition of the evacuating population can vary considerably. To account for this variation, scenarios were developed for weekday daytime and nighttime emergencies. The process and parameters used for trip generation can be found in Figure 2.

For this study, people were divided into several groups based on the location of their home and the purpose of their trip in the city. The three location-based population groups were residents (those who live inside the District), non-residents (those who live outside the District but inside the NCR) and visitors (those who live outside of the region). The purpose-based population groups adhere to the standard trip categories used in travel forecasting: work, non-work and other. A separate plan will address the evacuation of students. Additionally, DC residents could be located in their homes at the time of an emergency.
The MWCOG Round 7 Cooperative Forecasts were used to estimate the expected population and employment levels in the region in the 2010 planning year. The MWCOG forecasting model was used to determine the portion of these jobs that would be filled by DC residents and residents of neighboring jurisdictions. The four attributes listed above (i.e. mode of arrival, location, etc) were determined by using census data and the MWCOG Household Travel Survey\(^1\). Residents were assumed to be at work (Box #6), school, home (Box #4), a shopping/other location (Box #7) or outside the District (Box #2). Those at a pre-school, elementary or high school or a location outside of the District are not considered in this study (Box #5). Non-residents in the District were assumed to either be at work (Box #13) or a shopping/other location (Box #14). Information about visitors was provided by the Washington Convention and Tourism Corporation which estimates the number of visitors in the District during an average day. For the daytime scenario, MWCOG trip tables were used to determine how visitors are distributed around the city. During a nighttime incident, visitors were distributed proportionally across the District based on the number of hotel rooms in each (TAZ).

In total, 852,000 evacuees (48% residents, 11% visitors and 41% non-residents) are expected during a daytime scenario while 698,000 (84% residents, 13% visitors and 3% non-residents) are expected during a nighttime scenario. These numbers represent the total number of trips that will be generated during an evacuation situation.

In this study, only two modes are available for evacuees (private vehicle and walking). Assumptions were made about the percentage of total evacuees that would drive or be driven out of the District based on their place of residence, trip purpose and mode of arrival. Residents were assumed to go to their homes first in order to gather their families and belongings. Because regular transit service is assumed to be out of service during the evacuation, all those residents who arrived at their original location (work or shopping location) by transit, bicycle or on foot will walk to their homes. For those residents who arrived by car the portion that will walk home is based on trip purpose and mode of arrival, as follows:

- Drivers at work: 80% drive home
- Passengers at work: 20% are driven home
- Drivers or passengers at non-work locations: 100% drive or are driven home

Due to a high percentage of DC households without access to a vehicle (37%) and the likelihood that some vehicles will be unavailable, it is assumed that only 60% of all DC residents will evacuate their homes in a private vehicle, resulting in 164,000 pedestrian trips generated by DC residents in a daytime evacuation and 233,000 in a nighttime evacuation (Box #8). The same walk-percentage assumptions are applied to non-residents, which yields 186,000 pedestrian trips generated by non-residents during the daytime scenario and 3,000 during the nighttime scenario (Box #15). No reliable mode of arrival data is available for visitors, so the assumption that 40% of visitors will evacuate in a private automobile was used. This assumption resulted in 56,000 pedestrian trips generated by visitors in the daytime scenario and 55,000 in the nighttime scenario (Box #10). The total number of pedestrian trips generated in a daytime evacuation scenario is 406,000 and 291,000 for a nighttime scenario.

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2.2. **Trip Distribution and Mode Choice**

The second step in the four-step forecasting process is to distribute the 406,000 daytime trips and 291,000 nighttime trips across the possible destinations. The assumed goal of each evacuee is to leave the District and reach either their homes (applies to non-residents only) or a staffed collection area where support services will be available, as quickly as possible. The evacuation structure developed by DDOT in the ETA provides only two modes of reaching a collection area: by walking directly to the collection area or by walking to a transfer point and riding a bus. Only one or two collection areas can be reached from each transfer point, limiting the number of destination-mode combinations that are possible. Where the goal is simply to reach a collection area, evacuees are equally likely to select any of the available options. Because the destination end of many trips is undefined, the traditional distribution method is ineffective. Based on the small number of choices available, it is possible to model both the choice of destination and the choice of mode simultaneously as a logit-based discrete choice model.

Only a finite number of destination-mode choices are available to pedestrian evacuees including:
- Walk directly to a collection area (nine potential options); and
- Walk to a transfer point and ride a bus to a collection area (29 potential options).

This structure results in a choice set of 38 potential mode-destination combinations for evacuees. Non-residents have the additional option of walking directly to their homes.

Non-residents will make the decision to walk all the way home based on the distance to their homes, according to a curve (developed using the professional judgment of the study team) which is defined so that people who live closer to the city are more likely to walk all the way home. When this curve is applied to the travel patterns resulting from the regional model and the number of pedestrian trips, approximately 39,000 non-residents are projected to walk all the way to their homes during a daytime scenario. Due to the low number of non-residents in the District during a nighttime scenario and the different conditions experienced by pedestrians at night; it was assumed that none of the nighttime evacuees would walk all the way home.

For the remaining pedestrian evacuees (367,000 daytime and 290,000 nighttime), 38 mode-destination options remain, which constitute the choice set for the discrete choice model. (For example, as one option an evacuee can walk to transfer point #6 and take a bus to the King Street Collection area or alternatively can walk directly to the King Street Collection Area). The determining factor in the choice model will be time, indicating that pedestrians will select the option that will transport them to a collection area the fastest. Additionally, it is assumed that pedestrian evacuees are averse to walking long distances, especially during dangerous emergency conditions, and will want to limit their exposure to these risks. Therefore, walking is considered a less desirable option relative to waiting for and riding a bus and is weighted as being 1.5 times more onerous.

For the purposes of this destination choice model, the evacuation for each individual begins at a starting point (home, work, or shopping location) and ends when the pedestrian has reached a collection area. The total evacuation time can be divided into three distinct components, although not all evacuees will experience each:
Figure 2: Trip Generation Model Parameters and Results, 2010 Forecasts

<table>
<thead>
<tr>
<th></th>
<th>Arrival Mode</th>
<th>Evacuation Mode</th>
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<th>Arrival Mode</th>
<th>Evacuation Mode</th>
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<tbody>
<tr>
<td></td>
<td>Transit</td>
<td>Walk</td>
<td>Auto</td>
<td>Transit</td>
<td>Walk</td>
<td>Auto</td>
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<tr>
<td>Students (Pre-12)</td>
<td>100%</td>
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<td>100%</td>
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<td>93,000 people (day)</td>
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<tr>
<td>0 people (night)</td>
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<tr>
<td>Employees</td>
<td>Bike/Ped</td>
<td>100%</td>
<td>0%</td>
<td>Bike/Ped</td>
<td>100%</td>
<td>0%</td>
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<tr>
<td>129,000 people (day)</td>
<td>20%</td>
<td>80%</td>
<td></td>
<td>Driver</td>
<td>0%</td>
<td>100%</td>
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<tr>
<td>7,000 people (night)</td>
<td>80%</td>
<td>20%</td>
<td></td>
<td>Auto Pax</td>
<td>0%</td>
<td>100%</td>
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<tr>
<td></td>
<td>Day Total</td>
<td>94,000</td>
<td>35,000</td>
<td>Day Total</td>
<td>6,000</td>
<td>48,000</td>
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<tr>
<td></td>
<td>Night Total</td>
<td>2,000</td>
<td>5,000</td>
<td>Night Total</td>
<td>1,000</td>
<td>9,000</td>
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<td>Non-Workers</td>
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1. **Walking Time** – amount of time it takes to walk from the starting point to a transfer point (if they decide to take a bus out of the city) or a collection area (if they decide to walk the entire way out of the city).

2. **Waiting Time** – amount of time spent waiting at a transfer point. Waiting time can be divided into two parts: startup time and queuing wait time. The startup time accounts for the lag time between the call for evacuation and the commencement of bus services at the transfer points. A startup time of three hours is anticipated in the ETA. The capacity of each transfer point is limited by the number of buses available and the loading time; queuing time is caused by congestion at the transfer points. At each transfer point, this is equivalent to the average time a person will have to wait in line for a bus.

3. **Bus Time** – amount of time spent on a bus traveling to a collection area.

Each evacuee’s destination decision is made by comparing the weighted travel times for all of the options. The starting points were aggregated into one of the 319 TAZs in Washington DC and the total weighted time from each TAZ through each destination-mode option is developed. The number of trips made using each destination-mode option is apportioned based on a logistic curve, allocating a higher percentage of trips to the option with a lower weighted total time.

**2.2.1. D.C. Core Model**

Non-residents are likely to want to evacuate towards their homes, instead of being indifferent towards their destination. In the city core, where transfer points are plentiful and closely spaced, it would be possible for non-residents to select a transfer point served by a preferred bus without a significant increase in travel time. For this reason, a separate model was developed in which non-residents evacuating from the core are directed towards the collection area closest to their homes. Using the MWCOG forecasting model, the preferred collection area was determined to be the collection area located closest to home. These evacuees were directed only to transfer points that offer a bus to their preferred collection area, or to that collection area itself in the same manner as the model described in the previous section.

**2.2.2. Additional Collection Areas**

During the course of this study it was recognized that some of the collection areas (e.g. Rockville, Vienna) were not intended as pedestrian destinations and were located so far from the District as to render them almost inaccessible by foot. To more realistically account for people who would walk to localities very close to the District line (e.g. Arlington, Bethesda) and to provide more reasonable walking distances for evacuees, an alternate analysis was performed for the daytime scenario which includes nine additional pedestrian destinations.

The inclusion of these additional collection areas brought the total potential walking destinations to 42 for the main choice model. In the core choice model, each of the additional collection areas was added to the choice set corresponding to the closest DDOT-designated collection area. (i.e. Grosvenor was added as a potential destination for all those headed towards Rockville). The same choice models were applied and the evacuees were redistributed. A similar analysis could be performed for any additional or alternative points around the study area.
2.3. Assignment

Once the origin-destination pairs were established, routes were determined by using a modified version of the MWCOG model for assignment. Modifications to the standard model network include the addition of non-vehicle facilities including pedestrian and bike trails; the deletion of all vehicle-only highway facilities; the removal of one-way restrictions from the road network and; the definition of the speeds on all remaining pedestrian facilities as three miles per hour (4 feet per second). All of the trips generated by pedestrian evacuees are assigned to this network.

Ten walk-out routes were identified as the primary routes based on the results of the pedestrian assignment. For each walk-out route, all parallel facilities were identified and consolidated into corridors to account for the flexibility in route choice available to pedestrians who would be free to use any available pedestrian facility. However, it is expected that the majority of pedestrians will use the designated routes as police, information and support services will be located there.

3. Analysis

This model structure was implemented for daytime and nighttime emergencies in addition to evacuations of individual sub-areas of the District. Using the results of this model this study estimated the volume of evacuees that can be expected at each transfer point and collection area and along each of the walk-out routes. Operational analysis at these points of interest will allow DC EMA to determine how to effectively allocate support resources, identify which collection areas will be overwhelmed and which transfer points to operate during various scenarios. Additional scenarios can be defined and tested using the same model structure.

3.1. Transfer Points and Collection Areas

As previously discussed, the vast majority of pedestrian evacuees will walk to a transfer point or collection area, and only a small portion will walk directly to their homes. The daytime scenario – the scenario with the highest volumes – evacuates over 365,000 pedestrians to the collection areas. Of these, 55% walk first to a transfer point and then ride a bus. Of the remaining 160,000 evacuees, over 65% walk to the two collection areas that are closest to the District. This is consistent with the fact that many of the collection areas are located very far from the District line and require such long walking times that almost no pedestrians are expected to walk directly to them while the close-in collection areas may be overwhelmed if careful attention is not paid to the operations of support services at these locations.

Based on these capacities of each transfer point (given in the ETA) and the expected volumes, the study was able to determine the time it would take to transport all evacuees from each transfer point. Using the assumptions highlighted in this paper, the amount of time estimated to evacuate all pedestrians from each transfer point was from two to four hours. Therefore, the last transfer point would be fully evacuated seven hours after the call for evacuation, and when the buses and drivers will be available to perform other necessary tasks.

3.1.1. Additional Collection Areas

When the nine additional collection areas are added into the model, the number of evacuees seeking bus transportation from a transfer point was reduced significantly. These new pedestrian destinations decrease the pedestrian volume at each transfer point by up to 71%. Overall, the number of evacuees using the transfer points is cut from over 200,000 pedestrians to only
88,000. Consequently, the number of evacuees walking directly to a collection area increases dramatically. The additional collection areas receive all of the increased pedestrian volume; the number of pedestrians walking to one of the original collection areas drops by more than 75%.

### 3.1.2. Other Scenarios

The nighttime and sub-area evacuation scenarios require the evacuation of fewer pedestrians than the full, daytime scenario. Under some conditions, the expected volumes of pedestrians arriving at several of the transfer points and collection areas may be very low. It is therefore important for DC EMA to carefully monitor the volume of evacuating pedestrians to determine which transfer points and collection areas should be made operational during an actual emergency.

### 3.2. Walk-Out Routes

The volumes of pedestrians expected on each sidewalk facility were generated by the assignment results of the forecasting model. The volumes were aggregated across all parallel roads into walk-out corridors. The expected volumes along these corridors were compared to the available capacity of the pedestrian facilities to ascertain where additional pedestrian capacity may be necessary. Locations where conflicts between pedestrians and vehicles could be expected were also noted for traffic control resources.

#### 3.2.1. Sidewalk Capacities

Due to the large volumes of pedestrians that are expected in an emergency situation, the sidewalk facilities may be overloaded creating potentially unsafe conditions; measuring the capacities of the sidewalk facilities was necessary to identify locations where interventions may be necessary to minimize pedestrian and vehicular conflicts. Capacities were measured for a series of cutlines located throughout the District that were designed to allow volumes and capacities along corridors to be compared meaningfully.

For safety reasons, it was determined that the evacuation plan would encourage pedestrian evacuees to use pedestrian-only facilities as much as possible, including both the actual sidewalks and any grass buffer area. At each cutline location, the minimum total width (sidewalk and buffer combined) was measured, with adjustments made where necessary to account for the presence of trees or other landscaping elements. Research by Fruin provides several factors that can be used to convert widths to capacities, depending on the level of crowding expected on the facilities; however the factor recommended by Bolton et al utilizes a flow of 600 people per hour per foot of width. At this capacity, pedestrians are able to select their preferred walking speed and to bypass slower pedestrians. Higher pedestrian densities are certainly possible; however the restriction in movement that occurs often results in the undesirable condition of pedestrians leaving their designated facilities in order to move faster.

DDOT provided the g/c ratios (percent of time that pedestrians can walk in a particular direction) for most of the necessary traffic signals. For each measured location, capacities were reduced by the g/c ratio corresponding to the closest traffic signal to the cutline. This provided the final sidewalk capacities at multiple locations along each of the designated walk-out corridors.

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3.2.2. Corridor Analysis

For each walk-out route, the impacts of using only sidewalks or using the sidewalks and the street facility were analyzed. Initially, the total expected volume was compared with the hourly capacity at several points of interest along each corridor. Where volumes were very high, the capacity was also measured with the vehicular lanes on the walk-out route dedicated to pedestrians. While this would require shutting down a street to vehicular traffic, it can significantly increase the capacity of a corridor.

In order to more accurately compare volumes and capacities, arrivals of pedestrians at two points on each corridor were estimated by half-hour periods and compared with the capacity, as illustrated in Figure 3. This allowed DDOT and the study team to determine where vehicular lanes may need to be dedicated to pedestrians during an evacuation. Due to the lack of parallel facilities, it was determined that the inbound vehicular lanes on some of the District’s bridges would need to be dedicated to pedestrians in order to accommodate the high pedestrian demand.

3.2.3. Emergency Management

The technical modeling aspects of this study were used as the basis for DC to begin emergency management planning for a pedestrian evacuation. As such, part of this study required analysis of the walk-out routes from the perspective of resource management and emergency response. Each pedestrian walk-out route was analyzed for:

- Locations for potential pedestrian support areas along the route;
- Potential conflicts with vehicular evacuation routes where traffic control support will be important to maintaining both pedestrian and vehicular flows; and
- Signalized intersection where signal timing will need to be adjusted in order to accommodate the pedestrian flows out of the city.

Determining the locations where these resources would have the maximum effect was made significantly easier through the use of a travel forecasting model that allowed the study team to predict where high volumes of pedestrians should be expected.

4. Conclusions and Further Research

As pedestrian evacuation planning on a citywide scale has little precedent this study uses an innovative approach to emergency planning that merges the travel forecasting methods employed in transportation planning with emergency management planning. While the plan is scenario-independent, it is scalable to disaggregate the impact generated by each of the sub-areas of the city. In addition, the pedestrian evacuation is assessed during two weekday time periods: midday when the commuter/visitor population in the city is maximized (with the largest number of people at their desks) and during the night when the resident population is maximized (with the

![Figure 3: Volumes and Capacities along a walk-out Corridor](image-url)
largest number of people in their beds). Subsequent plans should focus on specific threats, such as highly vulnerable locations and events using the same data and methodology.

The overall methodology provided reasonable, usable results that can be easily modified or scaled to match any potential scenario. These results can readily be used as the basis for emergency management planning and resource management. Significant research is still needed in this area, but the basic tools for pedestrian evacuation planning can be taken almost directly from the traditional transportation forecasting process. One drawback of the study was that there is limited data regarding pedestrian behavior during an evacuation in a major urban area.

Trip generation proves to be one of the more difficult steps in forecasting a pedestrian evacuation. Determining the full number of evacuees is possible using available data, however there is little data that can be used to determine what portion of evacuees will evacuate as pedestrians. Comprehensive data regarding pedestrian behavior during an emergency is limited due to the small number of pedestrian evacuations that have occurred. Therefore, much of the available information is based on anecdotal evidence from the terrorist attacks of September 11, 2001 and the New York City blackout of 2003. Further, this type of behavior is likely to vary between cities, the type of emergency, the amount of advanced warning provided and the likelihood of damage to the vehicle if left behind.

The model used for trip distribution and mode choice is straightforward to use, implement and update. Many types of changes can be tested using this model including the addition of new potential destinations; changing the assumptions about the total number of trips and; conducting sensitivity analysis on several of the assumptions on which the discrete choice model was based (including the length of the startup time, average bus speed and the time weighting factors). While this model is representative of the evacuation structure developed by DDOT and DC EMA, it can be modified to match the evacuation structure in use in other urban areas.

The travel forecasting methodology used in this study assumes that evacuees will be aware of evacuation plans in advance. If the structure of a planned evacuation is not made clear in advance to residents, employees and visitors in the region, then it is unlikely that they will make the choices and the trips forecasted in this study. Therefore, distribution of information is a key element in ensuring the fast, efficient and safe evacuation of pedestrians from Washington, DC.

The primary focus of this study was on pedestrians; however DDOT must balance the competing needs of all modes of evacuation. During an actual emergency, the identified walk-out routes and corridors should be monitored closely by DDOT and DC EMA to determine what actions are necessary.

The District of Columbia presents unique challenges for evacuation planning due to the significant number of agencies that claim jurisdiction in the city. There are multiple police forces operating within DC, in addition to several military installations. Coordination with the state governments and local governments of the surrounding areas is essential in order to ensure safety for all of the evacuees. It is also unlikely that any emergency requiring a full city evacuation would only affect the District without requiring at least a partial evacuation of the surrounding areas.