Locating Emergency Response Facilities in the Metrorail System: A Decision Support Tool

Elizabeth R. Ottinger, Alejandro F. Medina Mora, Kaveena A. Patel, Islay R. Van Dusen, and Erica Gralla
Department of Engineering Management and Systems Engineering, the George Washington University

***Abstract*— Large public transportation systems, like that of the Washington Metropolitan Area Transit Authority (WMATA), must appropriately locate response personnel to respond quickly to emergencies throughout the Metrorail system. This is particularly challenging in sprawling and congested metropolitan areas like Washington, DC. The aim of this project is to support the WMATA Office of Emergency Preparedness (OEP) in determining appropriate geographic locations for response personnel with reduced response times to all areas of the Metrorail system. To that end, we developed a simulation model that evaluates response times to emergencies at WMATA Metrorail stations. The model relies on historical data of WMATA emergency incidents to generate probability distributions of incidents, and queries Google Maps application programming interface (API) using Python to provide responder travel times that account for the traffic at that time of day. The user inputs the proposed responder locations (one or several bases) and the tool outputs the response times to a set of emergencies. Resulting response times are then analyzed, visualized, and compared across scenarios, using response time distributions and geographic heat maps, to show response times for the system overall as well as specific stations or geographic areas. In collaboration with the WMATA OEP, we evaluate several scenarios involving moving their current OEP base to a more central location and/or allocating response personnel to different geographic areas. Based on these results, we recommend better locations for WMATA response personnel, which could improve response times by up to 27 minutes or 67% throughout the Metrorail system. While these results are specific to WMATA, the tool could be easily adapted to other public transit systems to support decisions on the location of emergency response personnel.**

I. Introduction

A. Problem Statement

The Washington Metropolitan Area Transit Authority (WMATA) operates a large subway system, and responds to approximately 215 emergency incidents per month. This "metro" system spans the District of Columbia, Maryland, and Virginia (DMV) area. Currently, WMATA's entire Office of Emergency Preparedness (OEP) team is stationed in Landover, Maryland, at the very end of the orange line, at the eastern edge of the transit system. This makes it difficult to travel to emergency scenes quickly, especially considering OEP travels to most incidents using surface level vehicles. It is important that WMATA OEP personnel arrive on scene quickly, in order to mitigate and resolve the emergency. While the transit police may arrive more quickly, OEP is better trained to manage a large variety of incidents. WMATA aims to decrease the travel times to emergencies through improving the base locations of OEP personnel. Our purpose is to create a tool that aids WMATA in identifying optimal locations to base OEP personnel to accomplish their goal.

B. Background

The OEP is a specialized subteam within WMATA which is trained to respond and handle all incidents that occur. When an incident occurs, the station manager is notified by a customer or victim, the station manager contacts the Rail Operations Control Center (ROCC), and subsequently ROCC activates the appropriate personnel to be dispatched to the scene. ROCC is in control of the exhaust fans, railway power, and communication between different sectors of the transit system. The purpose of ROCC is to ensure the safety of all passengers of the DMV transit system and to maintain Metrorail schedules. Additionally, there is always an OEP employee in the ROCC situation room to dispatch the rest of the team whenever an incident occurs. WMATA personnel can only respond to emergencies within their jurisdiction of 100 meters from both sides of the railway. Considering the vast area that WMATA has to respond to when an incident occurs, it is a challenge for OEP personnel to respond quickly to incidents throughout the entire Metrorail system.

In 2015, there was an incident at the L'Enfant Plaza Metrorail station at which smoke from a small fire on the railway was blown into a Metrorail car full of passengers [1]. When the fans to direct smoke away from the train cars were switched on, they were positioned in a way that pushed smoke into the cars instead. Unfortunately, this led to one casualty and many passengers being sent to the hospital. The smoke incident emphasizes the importance of having properly trained responders on scene.

C. Literature Review

The team reviewed literature that developed models for facility and employee location in urban settings, using geographical models and queuing systems [2]. Considering that paths of emergency response vehicles account for traffic routes, which are different from linear distances to an incident location, geographic information systems (GIS) provide value in terms of finding accurate response times. One example of this is the study conducted by Fukushima and Moriya [3], where GPS was used to collect data on response times of fire station dispatches; thus, it accounted for traffic factors such as changing of optimal travel routes and traffic rules, which is applicable to WMATA response teams.

Additionally, research has shown that scenario analysis is crucial in forecasting the outcomes of certain situations [4]. Scenario-based analysis is done before conducting sensitivity analysis to determine the base-case, best-case, and worst-case scenarios. Subsequently, sensitivity analysis is applied to one of these scenarios. While scenario analysis is commonly used for forecasting financial markets, it can also be applied to measure other uncertainties like environmental impacts. One study identified the optimal scenario for creating a more sustainable environment [5]. The method is now being used to model emergency situations to determine the best outcomes [6]. More emergencies occur daily with the rising use of the metro system. In order to prepare for these emergencies, researchers used scenario analysis to allocate emergency resources in Metrorail systems [7]. The team built on the methods utilized in this literature to analyze and approach the unique challenges of the Washington Metrorail system.

D. *Significance*

In 2022, the Metrorail was used approximately 200,000 times, marking a 65% ridership increase from the previous year [8]. During the height of the COVID-19 pandemic, ridership decreased significantly from 2019 to 2022, when most commuters were under a work-from-home order. Ridership is currently increasing as more individuals return to their commutes, utilizing the Metrorail to travel to school and jobs throughout the DMV area [8]. Furthermore, there is an increased risk of incidents occurring throughout the system. As ridership continues to rise, it is important to ensure safety to Metrorail customers and provide them with quick treatment if they do suffer the misfortune of being involved in an emergency while riding the Metrorail.

The Metrorail system involves inherently dangerous components such as high voltage rails, as well as physical hazards. A wide range of incidents occur in the Metrorail system, such as obstructions in the roadway, fires, derailments, and a variety of human hazards. There are several organizations that respond to emergency incidents, including Metro Transit Police Department (MTPD) and fire, police, and EMT departments from across the DMV. OEP personnel respond to all incidents that are not handled exclusively by law enforcement personnel. The OEP serves as the connection between the emergency situation, other responders, the ROCC office, and the conductors who control the tracks and the trains. OEP personnel want to reduce response times so that ROCC does not have to continue to call on MTPD to respond to every incident. It is critical that an OEP responder arrives at each emergency scene as quickly as possible to eliminate any further health and safety threats and to minimize delays to the Metrorail train schedules. The safety of riders and the proper function of the system are of the highest priority to WMATA.

E. *Scope and Limitations*

The scope of the project focuses on minimizing OEP response times to incidents within the Metrorail system. WMATA manages two public transportation systems: Metrorail and Metrobus. While the OEP responds to incidents occurring in both transit systems, each utilizes separate command centers. Additionally, the Metrorail has greater daily ridership than the Metrobus, and a large majority of the incidents within WMATA jurisdiction occur on the Metrorail system. For these reasons, the project focuses on incidents occurring within the Metrorail system.

Various types of incidents occur in the Metrorail system, and their different natures call for different responses. For example, an active shooter situation or robbery are classified as law enforcement focused. These types of incidents are not included within the scope of this project. MTPD are better trained and equipped to handle these situations, so an OEP responder would not be dispatched to respond to such incidents. For instances that require responses from both MTPD and OEP, ideally an OEP agent would arrive first at the scene due to their knowledge of stations and ROCC operations. Severity of incidents is not directly assessed as OEP wants to reduce their response time to any incidents where their response is required.

Regarding geographic scope, the decision support tool considers emergencies occurring anywhere within the Metrorail system. If the system is ever expanded with new lines, the simulation framework developed in this project can be extended throughout the network once an incident database becomes available for these areas.

II. Project Goal and Research Questions

The project goal is to produce a decision support tool which assesses OEP response times to emergency scenes using simulation and scenario analysis, drawing on incident data from WMATA, and Python and GIS tools, to represent current and potential locations for the OEP, environmental factors such as traffic and time of day, and emergency transportation policies.

To deliver effective results to OEP and set them up for success in achieving efficient response time, three main research questions must be answered:

1. What are the projected response times of an OEP responder to emergencies at WMATA Metrorail stations?
2. How should OEP responders be geographically distributed to reduce the response times of OEP responders?
3. How do the time of day, traffic conditions, and transportation policies affect these results?

Reimagining the geographical placement of OEP responders will help WMATA respond to emergencies more efficiently.

III. Methodology

To meet this goal, ArcGIS software, Python, and a Google Maps API were employed to create a simulation that produces response times to a set of incidents given OEP responder location. This allows for comparison of multiple

OEP responder location scenarios, to assist WMATA as it considers whether to employ additional or alternate OEP base locations.

A. *Assessment of the Current Situation*

WMATA stakeholders provided historical incident occurrence data from the period April 2021 to March 2023. Analysis of historical emergency incidents throughout the Metrorail system was performed to establish an understanding of incident occurrence. A geographic assessment of historical incident data shows where incidents occur more frequently throughout the system, and where no incidents have been recorded: see Fig. 1.

B. *Scenario Development*

To begin, an exploratory data analysis was conducted to identify candidate locations for OEP placement. From this analysis, stakeholders from WMATA identified twelve facilities, seen in Fig. 2 and Table I, for use as potential locations for OEP personnel. These twelve locations, as well as all pair and triple combinations of the twelve, were used as candidate scenarios for the OEP to be compared through the use of travel time simulations. Providing WMATA with suggestions for multiple OEP stations allows them to cover more of the Metrorail system efficiently, giving them a chance to respond to incidents at opposite ends of Metrorail lines without having to cross the metropolitan area by surface vehicle. While providing the most effective recommendation for the fastest response times is the team's primary goal, stationing personnel at more than one location may be too costly and put a strain on OEP resources. Therefore, top recommendations for a single station, a pair of stations, and three stations will be analyzed and provided.

C. *Travel Time Calculation and Scenario Analysis*

To compare candidate locations, travel times from the twelve candidate locations to a set of simulated incidents were generated. The simulated incidents were created using locations, times, and dates from two years worth of Metrorail OEP data. Results are reported for the entire set of historical incidents, but a bootstrap analysis using subsets of the entire dataset was conducted to assess the accuracy of the estimates from these data (described below).

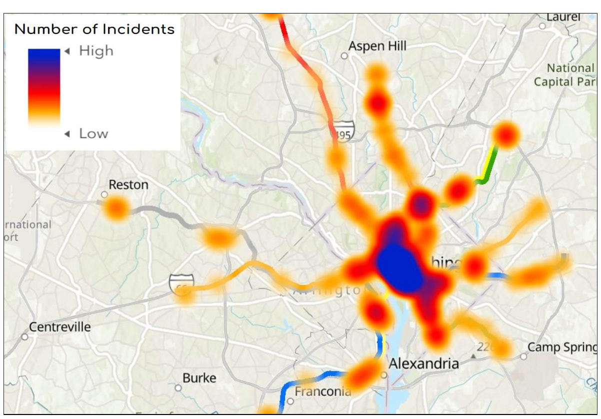

Figure 1. *Heat map of Metrorail incident counts in the District of Columbia, Maryland, and Virginia area. Blue indicates a high number of incidents and red and yellow show a low number of incidents.*

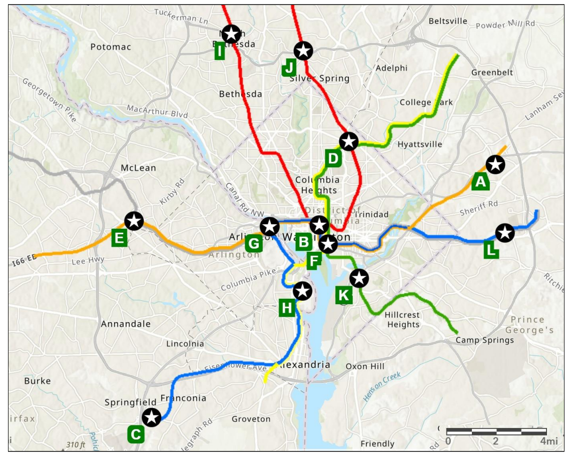

Figure 2. *Map of Metrorail lines and the twelve possible stations for locating OEP personnel. Corresponding facility names can be found in Table I.*

TABLE I: CANDIDATE FACILITIES KEY, WITH FIG. 2.

Possible OEP Stations	
Station Key	***Facility Name***
A	Carmen Turner Facility Complex
B	Metro Center
C	MTPD Harry Davis Jr Headquarters
D	MTPD Marlon F. Morales Headquarters
E	MTPD Trailer, West Falls Church
F	L'Enfant Plaza Headquarters
G	Rosslyn
H	Ronald Reagan Washington National Airport
I	Grosvenor-Strathmore
J	Forest Glen
K	Anacostia
L	MTPD Retrofit, Morgan Blvd

Travel times from each of the twelve candidate OEP locations to each of the 97 Metrorail stations were obtained for four times of day during two days of the week to establish a travel time matrix. Travel times were computed using Python to access the Google Maps API. This process produced a matrix of travel times for each combination of time, day, incident location, and OEP station.

Along with single station scenarios all the pair and triple combination scenarios were analyzed. All combinations of two or three locations were simulated, running simulations of 298 scenarios in total. For scenarios in which a set of two or three locations were considered, the location with the lowest average travel time for each incident among the set would be selected to respond to that incident.

D. *Sensitivity Analysis*

Because of uncertainty around surface level travel time throughout the day, sensitivity analysis was conducted. This method ensures that the location scenarios for stationing OEP personnel which performed best in the first simulation also perform well when there is a significant change in the volume of traffic (e.g., if traffic patterns change or if incidents occur mainly at particular times of the day such as rush hour). Similarly, it checks that these scenarios would also be most effective at reducing travel times if policies changed to allow OEP responders to use lights and sirens in response vehicles.

In a heavily populated city with a large number of commuters, surface travel congestion at high traffic times of day can severely affect how long it can take to get from one station to another by road. To simulate increased traffic, the historical incident data was used, but all travel times were calculated during high traffic times of day, both in morning rush hour and during evening rush hour. To simulate the use of lights and sirens on surface response vehicles, the same historical incident data were used, but travel times were computed at 1:00 pm when traffic is light, but there are still cars on the road.

E. Simulation Validation

Several methods were used to validate the accuracy of travel time simulation results. A bootstrap analysis was used in addition to expert elicitation and comparison of simulated results with historical incident response data.

To understand how the distribution of response times depends on the specific sample of incidents, a bootstrap analysis was performed. Fifty samples of 500 incidents were drawn with replacement from the original incident database. Each of the fifty samples was simulated to determine the average response times. In this manner, a distribution of the average response times was computed. The resulting distribution of mean response times was not very wide so the team is confident the results from the entire incident database are a good estimate of the true response times.

Additionally, a dataset of historical response times were provided by WMATA for the period of July 2022 to January 2023 from the current OEP location, the Carmen Turner Facility, to 60 incidents. Travel times were then simulated from the Carmen Turner Facility to each incident, then compared to reported travel times. Unfortunately, the response data reported by stakeholders was too inaccurate for validation, but we were able to alternatively validate our model through the other strategies described in this section.

Finally, regular meetings with stakeholders at the OEP occurred throughout the year to discuss results of each iteration of the simulation. These meetings allowed an OEP expert to verify and validate that the simulation results from the tool were representative of his experience working with WMATA emergency response.

IV. Results

The simulation was run for each of the scenarios using the historical incident data, then using altered datasets as needed for the sensitivity analysis, as described in the methodology. Key results are explored in the following sections.

A. Findings

An initial simulation of travel times from the current OEP location, the Carmen Turner Facility, to historical incidents yields response times as shown in Fig. 3: high (poor) response times to incidents in the downtown area (center), Virginia (west), and northern stations in Maryland (north).

Next, twelve scenarios were simulated, each of which involved stationing OEP personnel at a single facility, in which they could relocate their entire office. These scenarios were considered the most realistic by WMATA stakeholders. In analyzing this simulation and comparing these twelve scenarios, significantly better options emerged than the Carmen Turner Facility, where the office is currently located. L'Enfant Plaza HQ was the single candidate location with the lowest mean, which resulted in a 37.8% reduction in the average travel time.

Based on the combinations of two OEP stations, the pair including L'Enfant Plaza HQ and Forest Glen provide the shortest mean time by reducing travel time on average by 52.6% compared to the current scenario. From Fig. 4, it is evident that average travel times to each station, especially those in downtown, where incidents are more frequent, are reduced from the current scenario at the Carmen Turner Facility, depicted in Fig. 3.

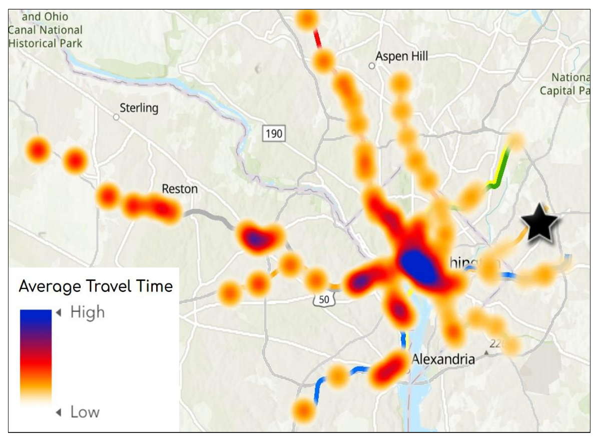

Figure 3. *Heat map of incident response times to emergencies with all responders leaving from Carmen Turner Facility marked by the black star.*

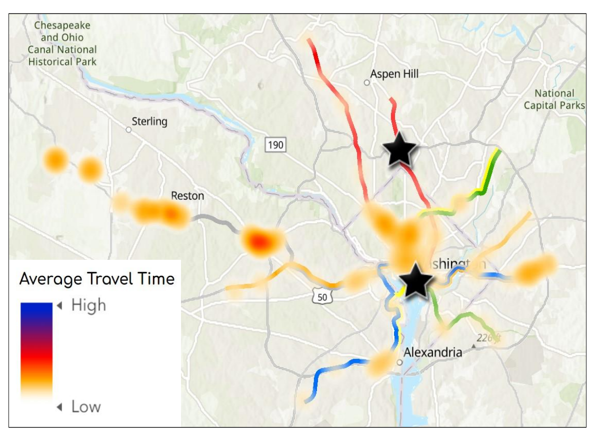

Figure 4. *Heat map of incident response times to emergencies with responders stationed at both L'Enfant HQ (central black star) and Forest Glen (top black star).*

The third set of simulated scenarios included all 298 combinations of singles, pairs, and triplets of OEP locations that could be created using the twelve candidate locations. Fig. 5 visualizes the distribution of travel times for the current location as well as the best single location, best pair of locations, best pair of locations including Carmen Turner Facility, and the best triplet of locations. In any of these various scenarios, the mean is significantly reduced from that of the Carmen Turner Facility, and variability decreases such that there are much smaller right-side tails, indicating a reduced number of incidents with high response times.

The best pairs and triplets of locations reduce the mean and variability even more than that of the L'Enfant Plaza HQ location alone.

It should be noted that simulations of nine different scenarios using triplet locations resulted in an average simulated travel time of between 12 and 13 minutes, but for clarity only one was selected for comparative analysis. If WMATA chooses to expand their OEP to have three locations for personnel, a comparative analysis of the feasibility of adding these locations should be performed, as the travel times are not significantly different.

Based on results of travel time simulation analysis, several different geographical distributions of base locations can be recommended depending on the capacity of WMATA to relocate or add additional OEP locations. The best performance is achieved when employees are stationed at three locations: Forest Glen, L'Enfant Plaza HQ, and Marlon F. Morales MTPD HQ. The scenario of locating OEP responders at all three of these stations resulted in the lowest mean travel time to incidents of all scenarios, and a low variability as well. The resulting mean travel time was reduced by 57.0% from the current single OEP station at Carmen Turner Facility.

In the case that WMATA only has the capacity to relocate their office to a single location, it is recommended they relocate to the L'Enfant Plaza HQ, as this was the scenario that resulted in the lowest mean response time among the single location scenarios. Additionally, if WMATA can expand their office to one location in addition to the Carmen Turner Facility, they should expand to L'Enfant Plaza HQ. If WMATA can relocate their responders to two locations, they should relocate to Forest Glen and L'Enfant Plaza HQ.

B. Sensitivity Analysis

To verify the recommendations will perform well in increased traffic conditions or if responders were permitted to use lights and sirens, sensitivity analysis was conducted. Response times during morning rush hour, evening rush hour, and using lights and sirens, were gathered to ensure that the recommended scenarios performed well if traffic patterns and Metrorail ridership changed significantly. As seen in Table II, the mean response times for the top locations for stationing OEP responders did change when traffic was introduced or when lights and sirens were used, however the best single, best pair, and best triple combinations of stations did not change. In Table II, the most affected station was the current station whose mean jump from 28.47 minutes in baseline traffic conditions to 40.37 minutes in rush hour traffic. This reinforces the idea that the current station is unsuitable and highly affected by external factors. The best pair average response time increased by less than 2 minutes when exposed to rush hour traffic and the time didn't significantly improve when lights and sirens were used. The team's recommendation of stationing OEP responders at two stations, L'Enfant Plaza Headquarters and Forest Glen Facility, does not waver under sensitivity analysis.

C. Bootstrapping

The team conducted a bootstrapping analysis in Python to test the sensitivity to the choice of the set of historical incidents used to create the master dataset. This allowed the team to estimate the variability in the estimated response time means based on the historical set of incidents. The results showed minimal variation, suggesting the model was accurate. As seen in Table II, the 95th percentile for the final simulation model using historical data was minimally different from the 95th percentile using the final simulation with bootstrapped data samples, for every tested traffic period.

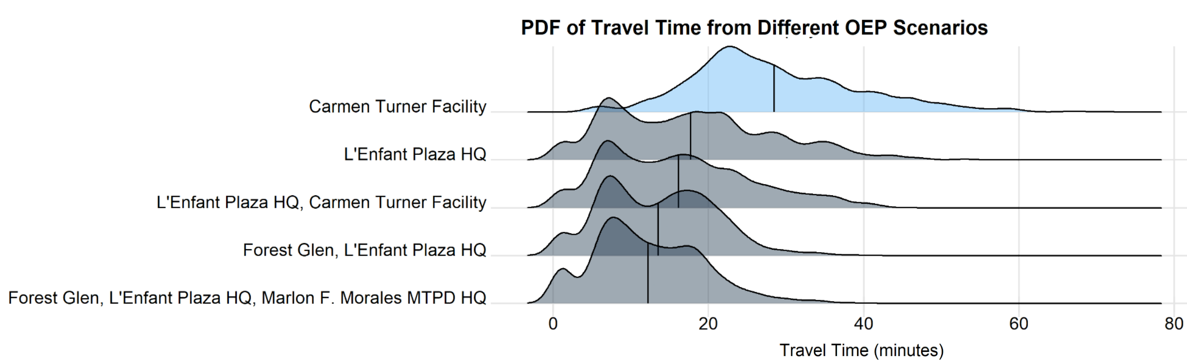

Figure 5. *Probability density function of simulated travel times for various location scenarios to each incident in historical incident dataset. Mean travel times of each scenario displayed by a vertical line.*

Table II: Sensitivity Analysis Response Time Data In Minutes.

		Response Time Statistics with Sensitivities											
		Baseline Traffic Response Times			*Bootstrap Samples*	*Rush Hour Response Times*			*Bootstrap Samples*	*Lights & Sirens Response Times*			*Bootstrap Samples*
Scenario	**Stations**	*Mean*	*95th percentile*	*Standard Deviation*	*Mean*	*Mean*	*95th percentile*	*Standard Deviation*	*Mean*	*Mean*	*95th percentile*	*Standard Deviation*	*Mean*
Current	A	28.5	49.0	10.8	28.4	40.4	60.0	12.9	40.2	27.9	45.0	8.6	27.9
Best Single	F	17.7	36.0	10.4	17.7	18.9	40.0	11.3	19.0	17.3	33.0	9.8	17.4
Current & Best Single	A & F	16.1	34.0	9.3	16.1	18.1	39.0	11.1	18.2	15.7	32.0	8.6	15.8
Best Pair	F & J	13.5	25.0	7.1	13.5	14.7	28.0	7.9	14.7	13.5	23.0	6.8	13.5
Best Triple	J & D & F	12.2	25.0	7.0	12.3	13.4	28.0	7.9	13.4	12.2	23.0	6.8	12.3

V. Conclusion

A variety of scenarios for selecting locations for the WMATA OEP were simulated, analyzed, and compared in this project. The results show that, by relocating or expanding their OEP to include an office at the L'Enfant Plaza HQ or expanding to one of the recommended combinations of locations, the OEP can reduce their mean travel time during rush hour traffic conditions by up to 27 minutes or 67% for emergency response to incidents that occur within the Metrorail system. With faster OEP response times, the overall response to an emergency will be managed earlier by trained personnel, ensuring a more appropriate and efficient response to emergencies.

This decision support tool can be expanded to examine OEP responses to incidents that occur within the WMATA Metrobus system or other DC transit options as well. Additionally, the tool can be easily adapted for other subway systems or public transportation systems in cities across the globe to assist these programs in geographically organizing their emergency response departments. Further analysis of historical incident reports could be explored to account for other sensitivities not accounted for in this project. More detailed analysis and incorporation of more data could lead to exploration of other methods of response transportation for the OEP or other response team organizations as well.

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Author Information

Elizabeth Ottinger, Student, EMSE Department, George Washington University. Alejandro Medina Mora, Student, EMSE Department, George Washington University. Kaveena Patel, Student, EMSE Department, George Washington University. Islay Van Dusen, Student, EMSE Department, George Washington University. Erica Gralla, Professor, EMSE Department, George Washington University.