Comparison of Transportation Disruptive Events in the Washington, D.C. Area and Traffic and Demand Management Strategies

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16. Abstract

Preparing for every possible disruption scenario is impossible. The overall goal of this study was to begin to better understand the similarities and differences between extraordinary disruptive events and more common incidents so that agencies can identify traffic management strategies and resources that can be applied in multiple settings as well as the limits of those strategies in the different settings. A 2009 MetroRail train collision, an earthquake (2011), and a tipped-over boom truck (2012) in the Washington, DC area provide the context for this study. This study compares and contrasts the impacts of these three major events with the more common vehicle collisions in terms of demand changes, network performance, and the applicability of traffic mitigation strategies. The data for the comparison come from rail and bus ridership, freeway detectors, and probe vehicles. Mesoscopic simulation is used to simulate the events that yield congestion and test strategies.

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1 Introduction

A wide range of disruptions affect the transportation system – from "fender benders" to transit strikes [1] to bridge collapses [2, 3] or closures [4] to natural and man-made disasters. Preparing for every possibility and permutation is impossible. A more practical approach is to recognize similarities and differences among event types so that agencies can identify traffic management strategies and resources that can be applied in multiple settings as well as the limits of those strategies in the different settings.

This study's overall goal was to begin to better understand the similarities and differences between extraordinary disruptive events and more common incidents and the traffic mitigation strategies that are effective in these situations. Three major events affecting the Washington, DC metropolitan area's transportation system in the last decade provided the context for this study. These events are a 2009 Metrorail train collision, an earthquake (2011), and a tipped-over boom truck (2012). The magnitudes and sources of these incidents are different from the more common vehicle collisions. This study compares and contrasts the impacts of these three major events with the more common vehicle collisions in terms of demand changes, network performance, and the applicability of traffic mitigation strategies. The associated objectives include (1) identifying similarities and differences among the major incidents and more common incidents; (2) determining the network performance under major incident and disruptive event conditions; (3) determining the network performance under more common incident conditions; and (4) identifying and evaluating traffic mitigation strategies for applicability to the different event conditions. The study's outcomes will help departments of transportation plan for unusual events of different types and evaluate the benefits of implementing traffic mitigation strategies in the different scenarios.

The remainder of this report is divided into five portions. Section 2 provides background on the events. Section 3 outlines the data used in the analysis. Section 4 describes the methodology. Results are provided, discussed, and compared in Section 5. Finally, Section 6 provides a summary, conclusions, and suggestions for future directions.

2 Background

The events in this study all occurred in the afternoon or evening, which helps limit the variability for the network configuration and operations (e.g., signal timing).

2.1 2009 Metrorail Crash

On Monday, June 22, 2009 at 4:58 p.m., two southbound MetroRail Red Line trains crashed; a moving train collided with a train stopped ahead of it [5, 6]. This crash was the deadliest in the transit system history, wherein the train operator and eight passengers were killed and 80 were injured [5-8]. A malfunctioning electronic circuit contributed to the collision near the Fort Totten station in northeast Washington, DC [6, 7]. Service continued on two separate segments of the red line on either side of the accident site. Red Line service was delayed and free shuttle bus services helped Red Line customers get around the incident. Riders were informed about the accident through media and recommendations were to avoid the Red Line as much as possible and switch to the Green Line or MetroBus services.

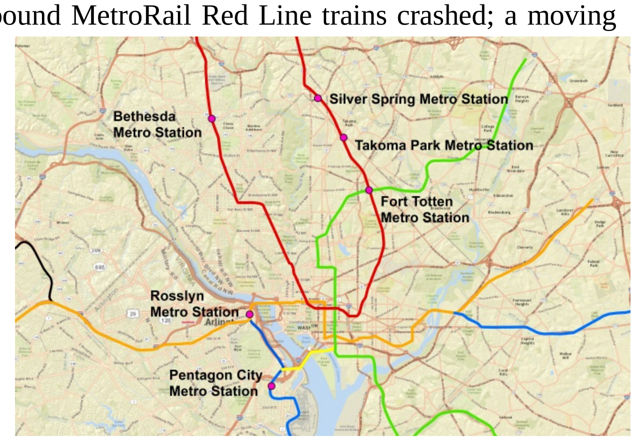

Figure 1 MetroRail Collision Setting – Just North of the Fort Totten Metro Station

The track between the Takoma and Fort Totten MetroRail stations (see Figure 1) reopened on June 27, 2009. However, the speeds were limited to 35 mph on the Red Line until July 2^{nd} and even lower through the investigation site. On July 3^{rd} (11 days after the crash), speed restrictions were lifted except between the Takoma and Fort Totten stations. With slower speeds, fewer trains were operating.

2.2 2011 Earthquake

On August 23, 2011, a 5.8-magnitude earthquake hit central Virginia at 1:51 p.m. EDT near Mineral, VA [9-15]. The earthquake was felt in the Washington, DC area as well as a large part of the east coast. This earthquake was considered the most powerful to hit Virginia in over 100 years with an intensity of VII (very strong) based on the Mercalli intensity scale. Four aftershocks of magnitudes 2.8, 2.2, 4.2 and 3.4 [16, 17] occurred within 12 hours. A 2.5-magnitude shock occurred just after midnight on August 25, followed at 1:08 a.m. EDT by the strongest, a magnitude 4.5 aftershock that woke many residents in the Washington, DC area [10, 11]. Although this earthquake was recorded as the second biggest earthquake to hit Virginia, no deaths or serious injuries were reported [10, 13, 14]. However, effects were seen at two landmarks in Washington: the Washington Monument and the National Cathedral. The Park Service closed all monuments and memorials on the National Mall [18]. Some buildings were evacuated and employees were released early.

2.3 2012 Boom Truck Incident on Route 267

On Tuesday, March 13, 2012, around 4:00 p.m. a boom truck working on the Dulles Corridor MetroRail Project tipped over and blocked the two right lanes of the eastbound Dulles Toll Road (VA-267) east of Tysons Corner. The incident was located between the Margarity Road and Idlywood Road bridges as shown in Figure 2. The clearance time for this incident was 1 hours 53 mins. This segment of the Dulles Toll Road has a bus lane that is open to bus traffic during the p.m. peak period. Viewing news images [19], vehicles were able to use this lane to travel around the boom that blocked the two regular travel lanes.

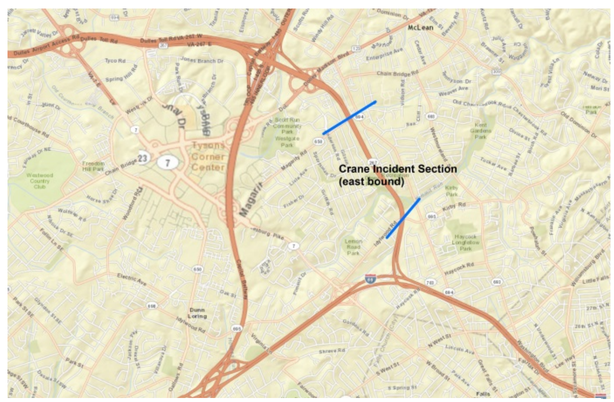

Figure 2 Boom Truck Incident Location

3 Data

The data used in the analyses varied to some degree according to the type of event, as shown in Table 1.

Table 1 Data Sources Used for Each Event

Event	Freeway Detectors	Inrix	Transit Ridership	Simulation
Metrorail Crash	X		X	X
Earthquake		X		X
Crane		X		X
“Normal” incident		X		X

3.1 Freeway Detector Count Data

Freeway detector data provide vehicle volumes based on inductive loop detector technology and are collected by departments of transportation. For the analysis of the MetroRail crash’s impact on freeway traffic, detector data were obtained for I-66 in Northern Virginia and I-270, I-495, and I-95 in Maryland, at locations shown in Figure 3 and Figure 4.

The I-66 freeway count dataset used in the analysis was gathered for the summers of 2008, 2009, 2010, and 2011. The section of I-66 used in the analysis began at Exit 47 (west near Manassas) and ended at Exit 75 (east near Washington, DC). The total number of detectors was 372, covering both westbound and eastbound directions. Each detector measures the vehicle volume every minute for a specific lane at a certain station. The data used in this analysis were aggregated into 15-minute increments.

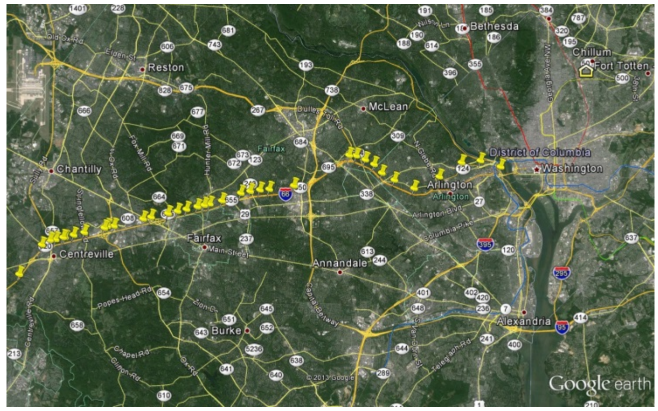

Figure 3 Detector Locations on I-66

I-66 data were accessed from a research database using the Structured Query Language (SQL) Server to obtain the data. Then, MATLAB code was written and used to manipulate the data. First, the data were filtered based on travel direction (westbound and eastbound). Then, the volume of each lane at each station or location was summed into a station volume count. The data from any inaccurate detector status indications were excluded for the whole station for the aggregated 15-minute time period. Finally, the valid station counts were aggregated over a 3-hour period (4:00-7:00 p.m.), representing the evening peak vehicle counts for a given day.

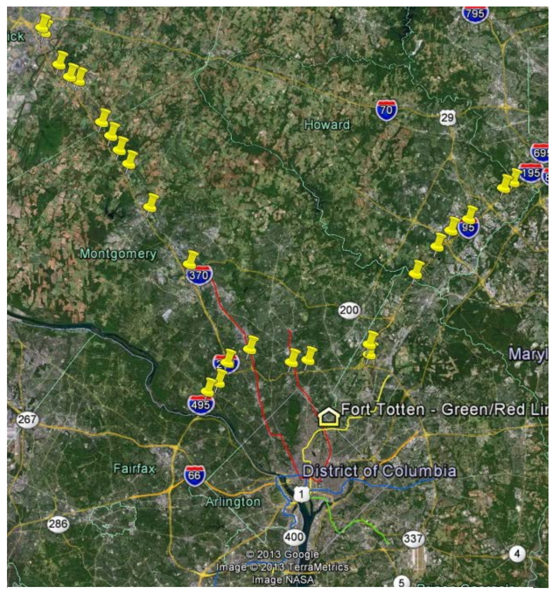

Figure 4 Detector Locations on I-270, I-494, I-95

The second freeway count dataset used in the analysis was from the Maryland State Coordinated Highways Action Response Team (CHART) collected in 2008, 2009, and 2010. Of the 25 total detector stations, 12 were located on I-270, six on I-495, and seven on I-95. To process the raw data, they were imported from the raw text format into Excel, and then grouped by Interstate (I-270, I-495, or I-95). The stations were coded based on the Interstate they belong to, where each ID starts with the Interstate number, 270, 495, or 95. In each group, the stations were given a serial number with an order based on their spatial distribution followed by a number indicating the direction (1, 2, 3, and 4 for northbound, southbound, outer loop, and inner loop, respectively). A MATLAB code was used to filter the data to exclude weekend counts. Then, the 5-minute interval volume counts were summed for each day from 4:00 to 7:00 p.m.

3.2 Transit Ridership Data

With the MetroRail system receiving the primary impact of the MetroRail crash event, mode shifts were possible but may have been within the transit system as well as the road system. The transit ridership data consisted of MetroRail ridership data and bus ridership from two providers (MetroBus and RideOn). Each of the datasets had limitations in the desired analysis.

Aggregate MetroRail ridership data, provided by the Washington Metropolitan Area Transit Authority (WMATA), was available in a daily total for the entire system between January 2004 and May 2013. However, these data did not have a breakdown among the different stations. Another dataset, with a smaller timeframe, provided the average weekday ridership at each Metro station on a monthly basis between 2006 and 2009. The data in this second set contained am, midday, pm, evening, and total ridership.

The bus ridership information was available as average weekday ridership in monthly formats. MetoBus provided ridership data from July 2005 to December 2009. Finally, RideOn provided data from January 2003 to August 2009.

3.3 Inrix

Inrix data are based on probe vehicles and is commercially available. Inrix provides speeds and travel times based on proprietary data fusion algorithms. These data were obtained through VDOT. The data were aggregated into 15 minute increments. For the boom truck incident, "normal" traffic incident, and the earthquake, Inrix data were obtained for the event day and the same day of the week 1 to 3 weeks prior to the event, allowing winter weather disruptions and other incidents to be discarded from the comparison. For the boom truck incident, the dates included February 21, 2012 through March 13, 2012. The dates for the earthquake included August 16, 2011 and August 23, 2011. For the "normal" incident, which occurred on March 31, 2010, the dates included March 17, 24, and 31.

4 Methodology

The assessment methods started with an examination of the available real-world data to determine local impacts. The events that resulted in congestion were then simulated in a meso-scopic context to determine network-wide impacts. Finally, traffic and demand management strategies were tested in the simulation context.

4.1 MetroRail Collision Assessment

Freeway detector counts and transit ridership fed the assessment of the MetroRail collision for potential shifts to personal vehicles (using freeways) and buses. Virginia freeways were considered in this study to account for the potential for fear or safety concerns to play a role in mode choice immediately in the aftermath of a fatal rail accident that received widespread media attention.

4.1.1 Freeway Detector Data

The first step in the analysis involved assessing the freeway volumes for an immediate impact by comparing the traffic volumes from the week just before, the week of, and the week after the crash. A complication was that school was in session the week prior to the crash but not the weeks of or after the crash. Furthermore, the week after the crash had some travel related to the July 4th holiday.

The traffic data analysis was based on the time period from 4:00 pm to 7:00 pm, representing the pm peak period. The analysis considered weekday data from Tuesday, June 16, 2009 to Thursday, July 9, 2009. The processed data were compared on a station-by-station basis for both the east- and westbound directions on I-66 and at all stations in Maryland providing valid data for the specified time period. To aggregate the weekday differences among all stations, we adapted the calculation associated with the mean absolute percentage error (MAPE), shown in equation (1). ***Note that we used this formula not as an error measure, but as a relative difference aggregation measure.*** To distinguish the intent of the measure, we called the measure the ***relative difference aggregation measure*** *(RDAM)*.

$$RDAM = \frac{1}{n}\sum_{i=1}^{n}\left|\frac{x_i - y_i}{x_i}\right| \qquad (1)$$

where

- n is the number of detectors (stations),
- x_i is the vehicle count before the crash, and
- y_i is the vehicle count after the crash.

4.1.2 Transit Ridership Analysis

The transit ridership analysis had three components: (1) daily aggregate MetroRail system ridership, (2) monthly MetroRail ridership at stations, and (3) bus ridership.

To investigate the short-term effect of the MetroRail crash at the system level, ridership for Monday through Thursday was compared to the same weekday for the two weeks before and the two weeks after the crash. The longer-term effect that could have resulted from the crash was also investigated by comparing the ridership across the years. Tuesday, Wednesday, and Thursday of the crash week were compared with the same days in the same time period of the year in 2004 through 2012.

Investigating the spatial effects on MetroRail ridership, we then used the second MetroRail dataset. We graphed the ridership for every station across the years 2006, 2007, 2008, and 2009 to compare 2009 ridership with the previous years. A trend line, based on the 2006, 2007, and 2008 ridership, was drawn for every station, to predict 2009 ridership. To determine the percentage change of 2009 ridership from the predicted value, equation (2) was used:

$$\%\ change = \frac{actual\ 2009\ ridership - predicted\ 2009\ ridership}{predicted\ 2009\ ridership} \qquad (2)$$

Positive values indicated that the 2009 ridership was greater than the predicted ridership, while negative values meant that the 2009 ridership was less than the predicted value.

The bus ridership analysis followed the same approach as the MetroRail ridership analysis, with trend lines to compare actual and predicted ridership values for the accident year. Actual monthly ridership values were also used in the analysis to look for changes in ridership in June relative to May and July.

4.2 Methodology for the Earthquake, Boom Truck, and Freeway Incidents

The local impacts of the earthquake, boom truck incident, and a “normal” freeway incident were assessed through speed profile heat maps based on Inrix data. The creation of the speed profile heat maps involved two steps: (1) constructing a pseudo-linear referencing system using the coordinate pairs of the Inrix stations and (2) computing the speed profile and representing it with a color-coded map.

Linear referencing is a method of storing geographic locations by using relative positions along a measured linear feature. Since Inrix records store the speed of a section of the road, it was necessary to map the Inrix stations using a linear referencing system for visualization. Inrix stations were geo-coded using longitude-latitude coordinates to pinpoint their locations. In addition, along a specific interstate, each station was also associated with a mile marker, which represents the distance to the designated start of the road. This mile marker was used to construct the pseudo-linear referencing system. With the aid of this linear referencing system, the speed at any point along a road could be found.

The heat maps depicted the proportion of the actual speed of the speed limit. Red indicated congestion and blue indicated free flow conditions. The temporal resolution was 15 minutes.

4.3 Simulation

To examine wider-scale impacts of the different events and to test a variety of traffic management strategies, meso-scopic traffic simulation was conducted using DynusT on a previously calibrated network of Northern Virginia with small pieces of Washington, DC and Maryland, as shown in Figure 5. This network consisted of 1,240 zones, 5,665

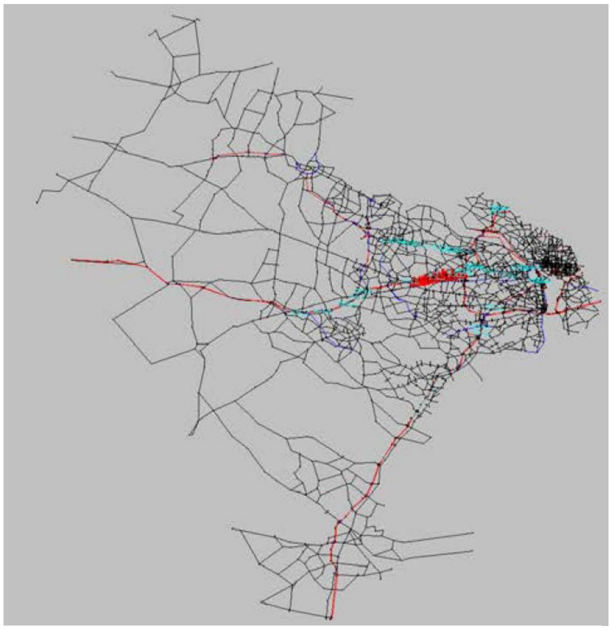

Figure 5 Northern Virginia network used for simulation

nodes, and 12,908 links.

Network-wide measures readily available from DynusT include total and average travel time, stopped time, and distance, as well as the number of vehicles unable to complete their trips in the allotted simulation time.

4.3.1 Demand

The base demand represented the pm peak and evening (3:00 p.m. to 10:00 p.m.) for a total of approximately 4,860,000 vehicles. The first 30 minutes of the simulations were used to load the empty network and were not part of the statistics calculations.

The base demand was organized into origin-destination (OD) matrices of 15-minute increments and was assumed to follow a user equilibrium (UE) routing approach. The UE conditions were determined by running 45 iterations of the routing algorithm. The equilibrium routes were saved for each vehicle for the testing of different strategies.

The base demand was used for the boom truck and regular incident simulations. However, the earthquake occurred earlier in the day and corresponding demand (1:45–3:00 p.m.) was required to maintain the first 30 minutes for loading the empty network. Demand generation starting at 1:45 to 2:15, in 15-minute increments, was assumed to be half of the base demand generated at 3:00. Demand starting at 2:30 and 2:45 was assumed to be 75% of the base demand generated at 3:00. These new demand values were appended to the beginning of the base demand to form an overall demand generation time period of 1:45 to 10:00 p.m. This demand of approximately 5,038,700 vehicles was then run to user equilibrium using 45 iterations to simulate normal conditions.

The demand for the earthquake was then modified based on a series of assumptions. Based on the speed profiles (see results section) and personal experience, employees were assumed to start being released at approximately 2:15 p.m. and generated over approximately 2 hours to account for building evacuations and communication and response delays. Original demand that started at 7:00 p.m. (simulation time 300) or later was assumed to contain a large portion of discretionary trips that could be cancelled; 75% of this demand was cancelled (roughly based on [20]). The original demand that started in the first 75 minutes of the simulation was assumed to remain identical to the UE condition; part of this demand was pre-earthquake and the rest were within a reasonable timeframe of their normal plans. These 183,880 vehicles were assumed to follow their original UE paths. The remaining demand of approximately 4,041,500 vehicles, originally generated between simulation time 75 and 480, was condensed into the 2 hours beginning at simulation time 30 (2:15 p.m.), following a general S-shaped curve associated with evacuation traffic [21]. In the condensed version of the demand, the 15-minute spacing of demand matrices was not maintained. These vehicles were assigned to the network generally using the one-shot setting, which gives each vehicle a good, but not necessarily the best path. Other settings were used according to the strategies considered.

4.3.2 Modeling the Events

The effects of the earthquake were primarily on the demand while the boom truck incident and more "normal" traffic incidents blocked lanes during the pm peak period[1]. The boom truck incident was modeled as a 95% capacity reduction on the appropriate link of the Dulles Toll Road from 4:00-6:00 p.m., corresponding to the incident timing. The 5% capacity allowed use of the bus lane around the boom. A vehicle collision of similar duration was selected for comparison. This incident occurred at 5:30 p.m. on I-66 near Nutley Street (a fairly common location for incidents). This incident blocked a shoulder lane for 50 minutes and took 107 minutes to clear. This incident was modeled as a one-lane reduction for 60 minutes and then 50% of one lane for 45 minutes. Routing for the boom truck and Nutley incidents were based on the regular paths from the UE conditions.

[1] The MetroRail collision was not simulated as there was no direct impact on highway infrastructure and freeway volumes (see Results) did not show a discernable increase that would warrant traffic management strategies.

4.3.3 Strategies for DOTs

Personal correspondence with VDOT engineers in the traffic operations division indicated that they monitored traffic conditions for each of the atypical events and did not find a need to adjust signal timings. Thus, such adjustments were not considered in the simulation. However, this strategy does have a role in other locations or for other types of events, such as those that directly impact arterials. The general strategies considered included capacity-based strategies, speed-based strategies, and information-based strategies.

4.3.3.1 Capacity-Based Strategies

Within the network, for a normal weekday, HOV restrictions and shoulder-lane use are in effect. According to VDOT's webpage http://www.virginiadot.org/travel/hov-novasched.asp, four different HOV segments exist in the study area, with different times of operation for the pm peak period:

- I-395 and I-95 reversible lanes: two separated HOV lanes run from Washington, DC south to Dumfries (30 miles) on weekdays from 3:30 p.m. to 6 p.m.,
- I-66 inside the Capital Beltway (I-495): all (two) lanes are reserved for HOVs westbound from the Theodore Roosevelt Bridge to the Capital Beltway from 4:00 to 6:30 p.m.,
- I-66 outside the Beltway: the left lane is reserved for HOVs westbound from I-495 to Route 234 in Manassas from 3:00 to 7:00 p.m. The westbound shoulder lane (far right lane) is opened to all traffic at 2:00 p.m. and remains open until 8:00 p.m. from the Beltway to the Route 50 interchange, and
- Dulles Toll Road: the left lane is reserved westbound from the main toll plaza to Route 28 from 4:00 p.m. to 6:30 p.m.

In some situations, it may be appropriate to lift the HOV restrictions and allow all vehicles to use the HOV lanes. The shoulder lanes may also be opened at other times of day to increase capacity.

Due to the location of the boom truck incident, neither the shoulder nor HOV strategies were tested. The incident was on the eastbound lanes of the Dulles Toll Road where HOV restrictions were not in effect due to the pm peak timing. Shoulder lanes only operate on I-66, not the Toll Road.

The traffic incident on I-66 blocked the shoulder lane, so this lane could not be opened for additional capacity. However, the strategy of opening the HOV lane upstream of the incident was considered.

With the earthquake scenario temporally condensing the demand significantly for the entire network, both strategies of opening the shoulder lane for the entire simulation period after the earthquake and removing the HOV restrictions were considered. These strategies were tested individually and jointly.

4.3.3.2 Speed-Based Strategies

Based on the idea of variable speed limits, speed limit reductions were considered for the boom truck and Nutley traffic incidents. Lower speeds could result in reduced stopped time in the vicinity of the incident. This strategy was considered for implementation approximately 1 mile upstream of the incidents. Speed reductions were considered between 5 and 15 mph. In the simulation, the speed limits had to be set prior to running the simulation (i.e., they were not dynamic).

4.3.3.3 Information-Based Strategies

Information can help drivers avoid incident impact areas. Information can be widespread throughout the network or localized.

For localized incidents, the variable message sign (VMS) setting is more appropriate than a widespread "en-route" information setting. The VMS may contain congestion warnings or detour information. For the boom truck incident, both were considered at a location prior to the interchange upstream of the incident. The detour corresponded to the one recommended during the actual event. Since the majority of the lanes remained open in the I-66/Nutley incident, only the congestion warnings were considered. The effectiveness of the VMS depends on the number or percentage of drivers responding to the information. This parameter was varied from 20 to 100% for both situations.

The earthquake's effect on demand, on the other hand, led to more widespread congestion. To simulate some travelers receiving information or more correctly predicting actual network conditions, they were assigned according to the user equilibrium setting but with only one iteration (thus true equilibrium was not reached). The others were modeled as having pre-trip information.

4.3.4 Demand-Based Strategies

Demand-based strategies require the cooperation of or entirely depend on the travelers rather than the transportation agencies. For the earthquake scenario, two demand strategies were tested. The first involved pausing the network loading for different amounts of time, giving the vehicles in the network an opportunity to use the network without new vehicles being added to the system for a given amount of time. This strategy was suggested for evacuation conditions by Mahmassani [22]. The second strategy involved carpool improvisation. With the use of social media and services like Uber and Lyft gaining popularity, it is reasonable to consider the possibility that ridesharing, or carpool improvisation, could be used to reduce the vehicular demand.

4.3.4.1 Pausing Demand Loading

To create a pause in the demand loading, demand matrices with all zeros were inserted at the appropriate timings in the overall demand profile. Several loading time periods and gaps were considered. In all of the cases, the demand generated starting from simulation time 0 through 60 remained as the original demand. The start time of the inserted matrix (matrices) of zeros was 15 minutes after the previous matrix and the regular demand resumed 15 minutes after the last matrix of zeros. Table 2 shows the original and paused earthquake demand timing. Gray cells indicate inserted matrices of zeros. For simplicity, only the matrices after time 60 are shown. The case names indicate roughly how many minutes the demand is loaded and how many minutes of zero demand. For example, (30-15) indicates roughly 30 minutes of loading and 15 minutes (1 matrix) of no new vehicles.

Table 2 Demand Matrix Timing for the Demand Pausing Strategy

Case	Timing of Demand Matrices															
Orig	68	75	83	90	93	96	100	105	108	111	115	120	128	135	138	141
		144	147	150	152	154	156	158	160	162						
30-15	75	90	97	105	112	115	118	133	148	153	156	159	163	168	176	191
		206	209	212	215	218	221	223	225	227	229	231	233			
30-30	75	90	105	112	120	127	130	133	148	163	178	183	186	189	193	198
		206	221	236	251	254	257	260	263	266	268	270	272	274	276	278
45-15	68	75	90	105	112	115	118	122	127	130	133	137	142	150	165	180
		183	186	189	192	195	197	199	201	203	205	207				
45-30	68	75	90	105	120	127	130	133	137	142	145	148	152	157	165	180
		195	210	213	216	219	222	225	227	229	231	233	235	237		
60-15	68	75	83	90	105	120	123	127	132	135	138	142	147	155	162	165
		168	171	174	177	179	194	209	211	213	215	217				
60-30	68	75	83	90	105	120	135	138	142	147	150	153	157	162	170	177
		180	183	186	189	192	194	209	224	239	241	243	245	247		
75-15	68	75	83	90	93	96	100	105	120	135	138	142	147	155	162	165
		168	171	174	177	179	181	183	185	187	189					
75-30	68	75	83	90	93	96	100	105	120	135	150	153	157	162	170	177
		180	183	186	189	192	194	196	198	200	202	204				
90-15	68	75	83	90	93	96	100	105	108	111	115	120	135	150	157	160
		163	166	169	172	174	176	178	180	182	184					
90-30	68	75	83	90	93	96	100	105	108	111	115	120	135	150	165	172
		175	178	181	184	187	189	191	193	195	197	199				

4.3.4.2 Carpool improvisation

Hypothetical travelers participating in improvised carpooling (ridesharing) ranged from 0-10%. The modeling for this strategy involved selecting the appropriate percentage of personal vehicles operating as HOVs and decreasing the demand matrices by an appropriate fraction. The initial 183,880 vehicles were assumed to not participate in this strategy.

5 Results

The results for each event are presented separately here.

5.1 MetroRail Crash

First, the traffic volume analysis results are presented, followed by the ridership analyses. The particular timing of the crash, between the week of public school ending and the week of a holiday, July 4, added complications to the interpretation of the results.

5.1.1 Freeway Traffic Volumes

In the pm peak, the peak direction is westbound on I-66 and northbound out of the Washington, DC area in Maryland.

5.1.1.1 I-66 Westbound Direction

Figure 6 presents the detector stations on I-66 for the westbound direction. The westernmost MetroRail station along I-66 is the Vienna station, located near detector station 1591 in Figure 6. Thus, only detector stations 1235, 1501, 1591, and 1689 are within the MetroRail service area. Detector 1689 is on an on-ramp fed directly by the Vienna Metro station park-and-ride.

Table 3 summarizes the percentage decrease (represented by a positive value) or increase (represented by a negative value) in counts for the stations for Tuesdays, Wednesdays, and Thursdays between the week before the crash and the crash week and between the week before the crash and the week after the crash. As can be seen from the table, the RDAM value for Tuesdays of the week before the crash and the crash week is only 4, which was the maximum value compared to Wednesdays and Thursdays of the same two weeks. Comparing these RDAM values with those of the week before the crash and the week after the crash, values were similar for Tuesdays and Wednesdays, whereas the RDAM values for Thursdays jumped to 8. However, this jump can be attributed to the fact that this Thursday (July 2nd) fell before the Independence Day holiday and holiday travel likely resulted in lower traffic volumes on that day. Furthermore, some reductions in peak travel in the week of the crash and the week after the crash were expected relative to the week before the crash due to the impact of the public school calendar. Some general summer travel could have begun the week of the crash, since the last day of school was the Friday before the crash. Thus, at the aggregate road level, it was difficult to derive any specific impacts attributable to the crash.

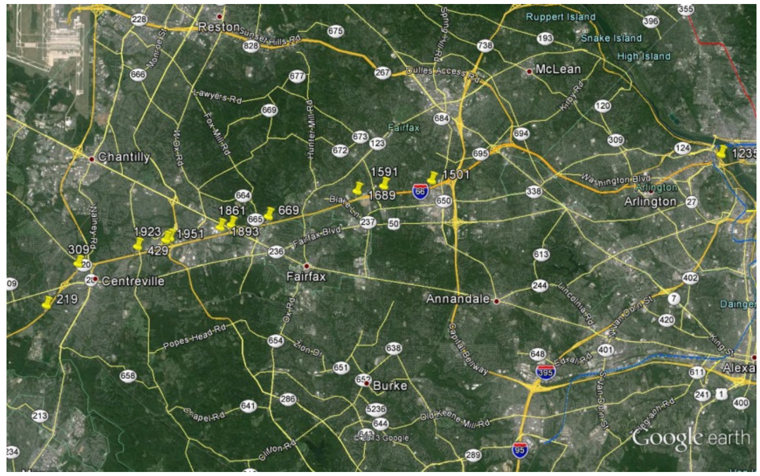

Figure 6: Westbound I-66 Traffic Count Stations

Looking at the detector stations within the MetroRail service area, the results were somewhat mixed but warrant some discussion. Detector 1235 is on an on-ramp close to Washington, DC but during the pm peak, I-66 inside the Beltway is for HOV use only. This ramp saw little change after the crash. The other station IDs (1501, 1591, and 1689) are outside of the HOV restriction area. With the exception of the Thursday before the holiday, these stations were generally among those with the greatest magnitude of changes. The changes generally indicated lower vehicle counts after the crash; possibly, a few people avoided the MetroRail but seasonal effects were also present. Since the volumes were lower, no traffic management strategies were needed.

Table 3: Percentage change in vehicle counts for I-66 westbound in the evening peak

Station ID	Type of Lane(s)	Percentage difference in counts between the week of June 15 (before the accident) and the week of June 22 (week of the accident)				Percentage difference in counts between the week of June 15 (before the accident) and the week of June 29 (after the accident)			
		Tue	Wed	Thu	Average	Tue	Wed	Thu	Average
219	Normal	2.1	1.5	-0.5	**1.0**	-0.3	-2.0	13.2	**3.6**
309	Normal	2.1	0.4	-1.6	**0.3**	0.5	-1.6	10.6	**3.2**
429	Normal	4.4	0.6	1.2	**2.1**	3.4	-3.1	6.0	**2.1**
669	Normal	4.4	3.1	5.8	**4.4**	4.3	-0.1	3.1	**2.4**
1235	On-ramp	1.3	1.5	-0.7	**0.7**	-3.1	-1.9	19.9	**5.0**
1501	Normal	-4.7	1.6	8.5	**1.8**	3.9	6.7	-0.9	**3.2**
1591	Normal	3.7	4.0	7.6	**5.1**	5.6	3.6	-9.1	**0.0**
1689	On-ramp	6.3	4.4	8.9	**6.5**	9.6	6.3	-10.2	**1.9**
1861	Normal	5.5	3.4	4.3	**4.4**	6.3	-0.1	3.9	**3.4**
1893	Normal	3.9	2.4	1.4	**2.6**	4.6	-0.3	4.7	**3.0**
1923	On-ramp	-6.6	1.2	-3.8	**-3.1**	-2.4	-0.6	-10.1	**-4.4**
1951	Normal	3.2	1.6	0.7	**1.8**	4.0	-1.9	5.0	**2.4**
RDAM		**4.02**	**2.14**	**3.75**		**4.01**	**2.35**	**8.06**	

5.1.1.2 I-66 Eastbound Direction

The eastbound direction is the non-peak direction in the evening. Figure 7 presents the locations of the I-66 eastbound detector stations. Only stations 901, 961, and 991 are within the MetroRail service area.

Table 4 presents the changes in the traffic counts and the RDAM values calculated for each weekday's count difference among all stations. Similar to the westbound direction, the Thursday before the July 4 holiday had detectors with the greatest magnitude of change, which could be attributed to holiday travel. The RDAM values ranged from 1.9 to 4.1. The direction of the change (increase or decrease in counts) varied by day of the week and detector. Within the MetroRail service area, the three detectors each had an average change less than 4% in each of the weeks (compared to the week before the crash). The positive sign on this change indicated less traffic after the crash (which could be a seasonal effect), and thus traffic management strategies were not be needed.

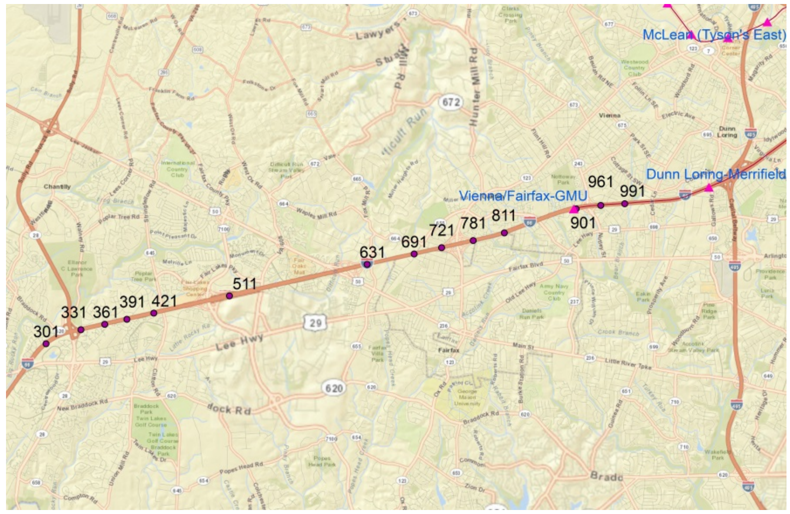

Figure 7: Eastbound I-66 Traffic Count Stations

Table 4: Percentage change in vehicle counts for I-66 eastbound in the evening peak

Station ID	Type of Lane(s)	Percentage difference in counts between the week of June 15 (before the accident) and the week of June 22 (week of the accident)				Percentage difference in counts between the week of June 15 (before the accident) and the week of June 29 (after the accident)			
		Tue	Wed	Thu	Average	Tue	Wed	Thu	Average
301	Normal	-3.5	-6.0	-2.7	**-4.1**	-4.4	0.8	1.9	**-0.6**
331	Normal	-3.8	-8.8	-2.3	**-5.0**	-5.4	-0.2	1.1	**-1.5**
361	Normal	-7.6	-2.3	-2.6	**-4.2**	-3.5	5.0	3.1	**1.5**
391	Normal	-3.0	-4.3	-0.2	**-2.5**	-0.9	3.6	4.6	**2.4**
421	Normal	-3.5	-4.1	1.4	**-2.1**	-1.4	2.5	5.0	**2.0**
511	Normal	-5.7	-6.1	-2.6	**-4.8**	-2.3	2.2	1.6	**0.5**
631	Normal	-4.6	-6.6	1.1	**-3.4**	-0.4	1.7	1.4	**0.9**
691	Normal	-6.7	-8.9	2.9	**-4.2**	-2.3	-4.5	6.3	**-0.2**
721	Normal	0.0	-0.4	8.2	**2.6**	2.1	-0.7	2.8	**1.4**
781	Normal	0.8	1.2	8.2	**3.4**	3.3	1.2	1.4	**2.0**
811	Normal	-2.3	1.3	9.5	**2.8**	3.4	2.1	11.5	**5.7**
901	Normal	-1.5	-0.9	4.4	**0.7**	0.5	-0.2	3.0	**1.1**
961	Normal	0.0	2.2	6.2	**2.8**	3.5	0.6	7.4	**3.9**
991	Normal	-0.4	-2.4	3.8	**0.3**	0.5	-2.0	2.4	**0.3**
1362	Off ramp	-1.8	1.6	5.4	**1.7**	-2.6	2.4	2.3	**0.7**
1385	Normal	0.6	3.2	4.7	**2.8**	-3.0	-1.0	-4.4	**-2.8**
1387	On ramp	-1.6	2.4	3.4	**1.4**	1.4	2.1	10.4	**4.6**
1390	Normal	0.4	3.1	2.7	**2.1**	-2.7	2.0	-3.0	**-1.2**
RDAM		**2.7**	**3.6**	**4.0**		**2.4**	**1.9**	**4.1**	

5.1.1.3 Maryland Traffic Data

Similar to the I-66 data analysis, the data from I-270, I-95, and I-495 were investigated for the week of June 15th (before the crash) and the crash week of June 22nd as well as the week of June 29th after the crash. Originally, 25 locations were in the Maryland data with some of the detector stations having bi-directional data, which resulted in a total of 44 detector stations. The data were filtered for the weeks of interest for the evening peak time period from 4:00 p.m. to 7:00 p.m. Any detector with missing values during this 3-hour period was excluded for that day. After the filtering, only five detector stations had valid counts from 4:00 p.m. to 7:00 p.m. during those three weeks. Figure 8 presents the locations of the detectors: four of the five detectors were on I-270, only one was on I-95, and none were on I-495. These detectors were fairly far north of the MetroRail service area (RedLine shown in Figure 8), making it difficult to attribute changes directly to the MetroRail crash.

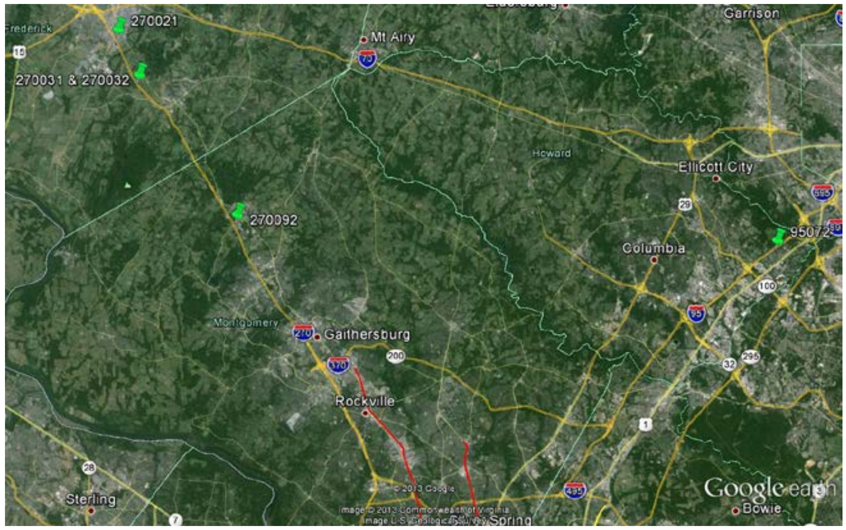

Figure 8 Locations of the Five Maryland Detectors

Table 5 summarizes the relative difference aggregation measure and percentage change in counts for the five valid detector stations between the week before the crash and the crash week, and between the week before the crash and the two weeks after the crash. (The last week was included since the results of the previous weeks were highly variable.)

Table 5: Percentage change in vehicle counts in Maryland

Station ID	Percentage difference in counts between the week of June 15 (before the accident) and the week of June 22 (week of the accident)				Percentage difference in counts between the week of June 15 (before the accident) and the week of June 29 (after the accident)				Percentage difference in counts between the week of June 15 (before the accident) and the week of July 6 (after the accident)			
	Tue	**Wed**	**Thu**	**Avg.**	**Tue**	**Wed**	**Thu**	**Avg.**	**Tue**	**Wed**	**Thu**	**Avg.**
95072	5.7	9.5	3.6	**6.3**	-10.7	1.3	-15.9	**-8.4**	8.2	7.2	10.9	**8.8**
270021	-3.9	-4.9	-3.2	**-4.0**	-10.5	-14.9	-31.0	**-18.8**	10.2	-2.6	-1.2	**2.1**
270031	-7.9	-10.7	-4.0	**-7.5**	-16.6	-23.3	-43.1	**-27.7**	9.0	-7.6	-1.4	**0.0**
270032	-0.4	-11.3	-0.3	**-4.0**	-6.6	-12.4	-27.8	**-15.6**	-0.9	-10.1	-1.3	**-4.1**
270092	-4.3	-9.8	-3.8	**-6.0**	-10.9	-19.3	-44.2	**-24.8**	-3.8	-8.3	-1.1	**-4.4**
RDAM	**4.4**	**9.3**	**3.0**		**11.1**	**14.2**	**32.4**		**6.5**	**7.2**	**3.2**	

As can be seen from Table 5, the RDAM values for the week of the crash were lower than the week after the crash but more aligned with the values for the second week after the accident. The Thursday of the week of June 29 had the largest magnitude of change, again likely attributable to holiday travel. The I-95 detector had lower volumes in the first week while the detectors on I-270 had higher volumes compared to the week before the MetroRail crash. In Figure 8, the I-95 detector is closer to Baltimore, MD than to Washington, DC and could represent a simple seasonal effect. The detector on I-270 closest to the service area was 270092, which consistently showed higher values than the week before the crash. However, the actual difference in vehicles was not very high, as the counts, averaged over Tuesday, Wednesday, and Thursday, at this location for the three-hour time period ranged between approximately 3,000 and approximately 3,500 vehicles, which is fairly light for a freeway during the peak and do not require traffic management strategies. (Note: the I-66 volumes were considerably higher.)

5.1.2 MetroRail Daily Total Ridership

The MetroRail system was anticipated to experience a larger impact than the freeways, due to the fact that the MetroRail system was directly impacted. The Red Line was split into two disconnected pieces for approximately one week.

The short-term effect of the MetroRail crash was examined using the aggregate daily ridership counts. As shown in Figure 9, ridership for Monday through Thursday of the crash week was compared to the corresponding weekdays for the two weeks before and the two weeks after the crash. The immediate effect of the crash was observed on Tuesday, the day after the crash, where the total MetroRail ridership dropped by 12.3% compared to Tuesday of the week before the crash. On the other hand, the ridership on the Monday of the week of the crash only dropped by 5.1% from the Monday one week before the crash. The drop in ridership on Monday was smaller, which can be attributed to the crash time (4:58 p.m.) and hence the effect was only observed during the evening hours. Some of the ridership drop was likely due to a seasonal change (schools out on the week of the crash and thereafter), as suggested by lower volumes on the week of July 6th. Holiday travel related to July 4th could have contributed to the ridership on Wednesday and Thursday of the week of June 29 being lower than the adjacent weeks and Monday, July 6 being the lowest ridership.

The day after the crash had an obvious drop in total ridership. However, ridership rebounded quickly (Wednesday) to approximately seasonal levels. Perhaps MetroRail riders sought other travel options or cancelled trips, anticipating MetroRail delays the day after the crash. Transit strategies and possible use of alternate stations may have drawn riders back to the system later in the week.

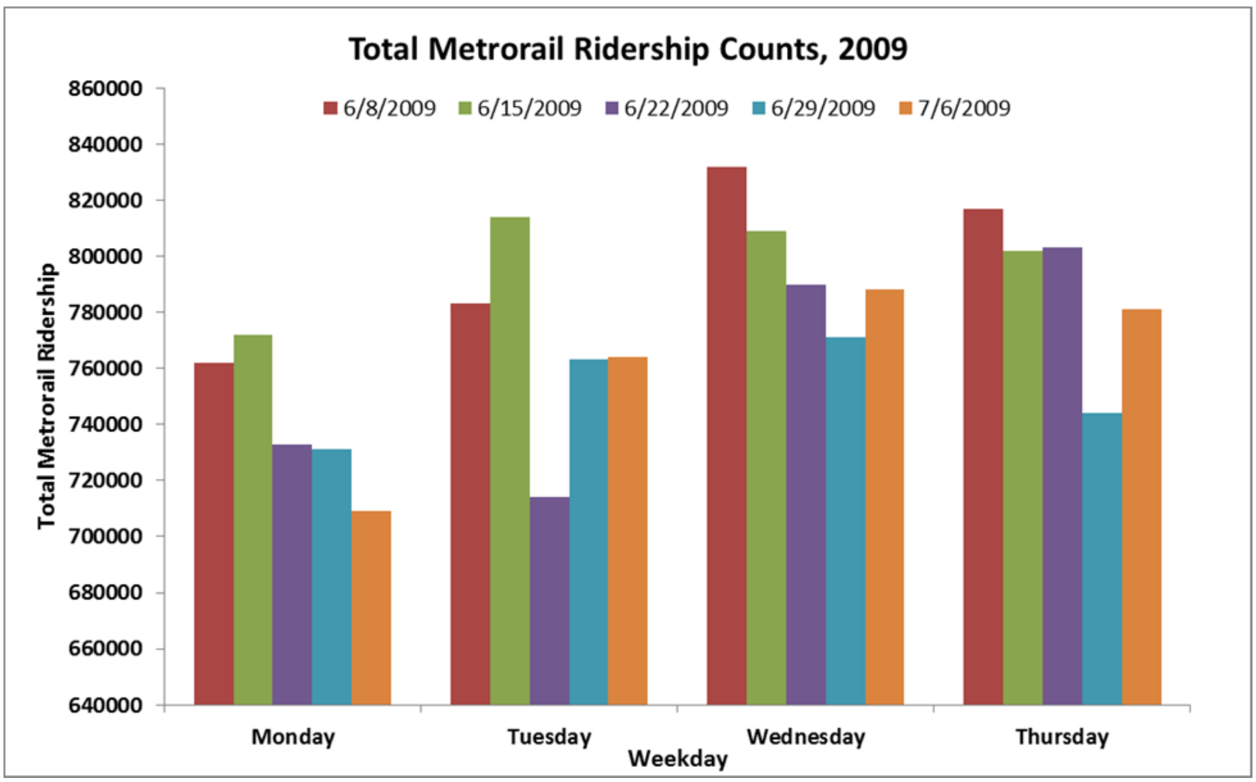

Figure 9: Total Metrorail Ridership for the Weeks of June 8, 2009 – July 6, 2009

To help control for the seasonal effect, we also compared total ridership for Tuesday, Wednesday, and Thursday of the crash week across years, using data from the third week of June for the years 2004-2012. Figure 10 shows the comparison. Despite the general decrease in ridership on this week from 2008 to 2009, the Tuesday after the crash in 2009 had the lowest ridership since 2004. Ridership in 2010 was comparable to that of 2008, with the exception of Wednesday, June 23, 2010. On this date, a Washington

Nationals baseball game and a musical concert were held. In 2011 and 2012, the ridership totals were also higher than in 2009, further supporting only a short-term effect of the crash on ridership.

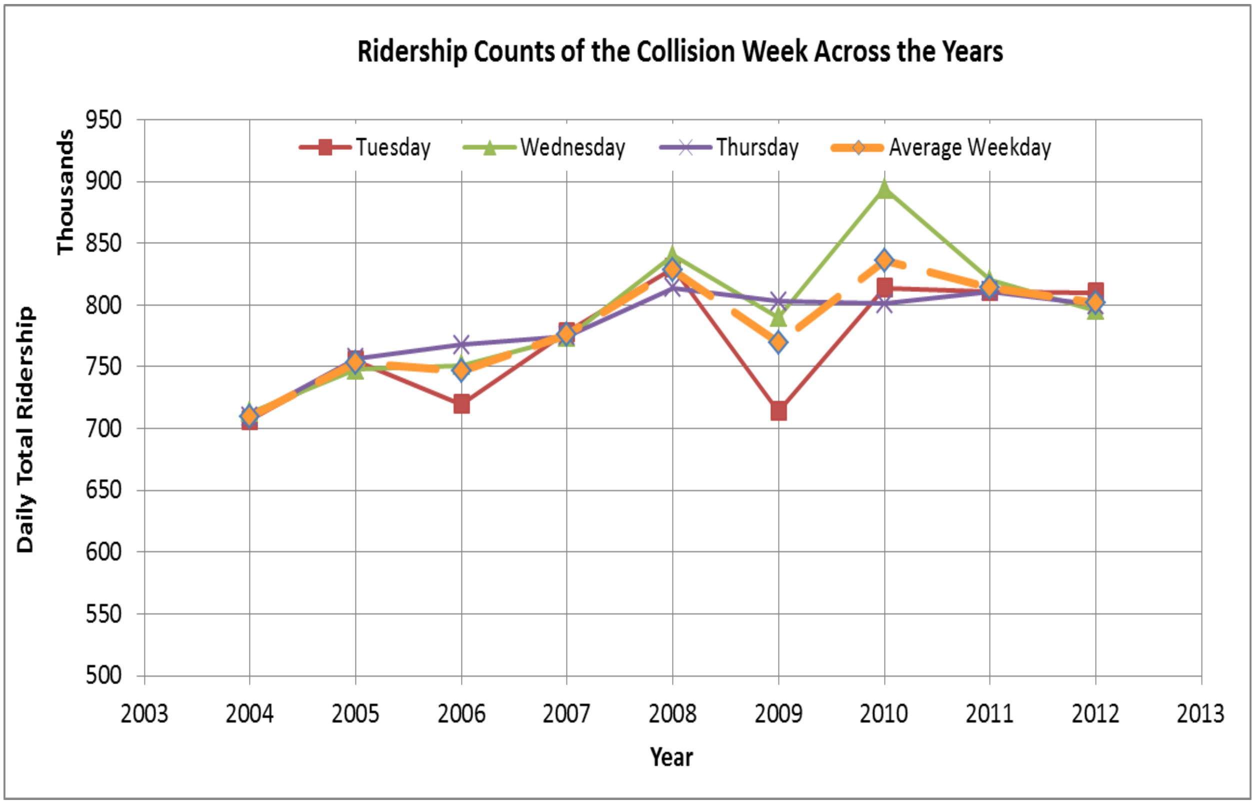

Figure 10: Comparison of total MetroRail ridership in the third week of June across the years

5.1.3 MetroRail Monthly Ridership by Station

To investigate the crash's effect on the monthly MetroRail ridership per metro station, the actual June 2009 ridership was compared to predicted June 2009 ridership. The prediction was based on a trend line drawn from June 2006, 2007, and 2008 data. Figure 11 presents the percent change (equation 2) for every station in the MetroRail system. A negative change means that the actual value was less than predicted. The percent change was grouped into four categories: (1) exceeding the predicted value (blue); (2) small decrease – between 0 and -5% (green); (3) medium decrease – between -5 and -10% (yellow); and large decrease – values less than -10% (red).

As shown in Figure 11, most of the stations had a small decrease from the predicted value (green) or a medium decrease (yellow). Within Washington, DC, several increases over the predicted value (blue) were found. The least frequently occurring category was the large decrease (red). A clear geographic area on the east leg of the Red Line consistently fell into this category. These five stations (Glenmont, Wheaton, Forest Glen, Silver Spring, and Takoma) are north of the crash location and are the stations that were temporarily disconnected from the rest of the rail system until June 27, 2009. The next station (Fort Totten) showed an increase in ridership, which may have been due to travelers selecting this station to access the system rather than one of the disconnected stations, where a bus would have been needed to avoid the closed track.

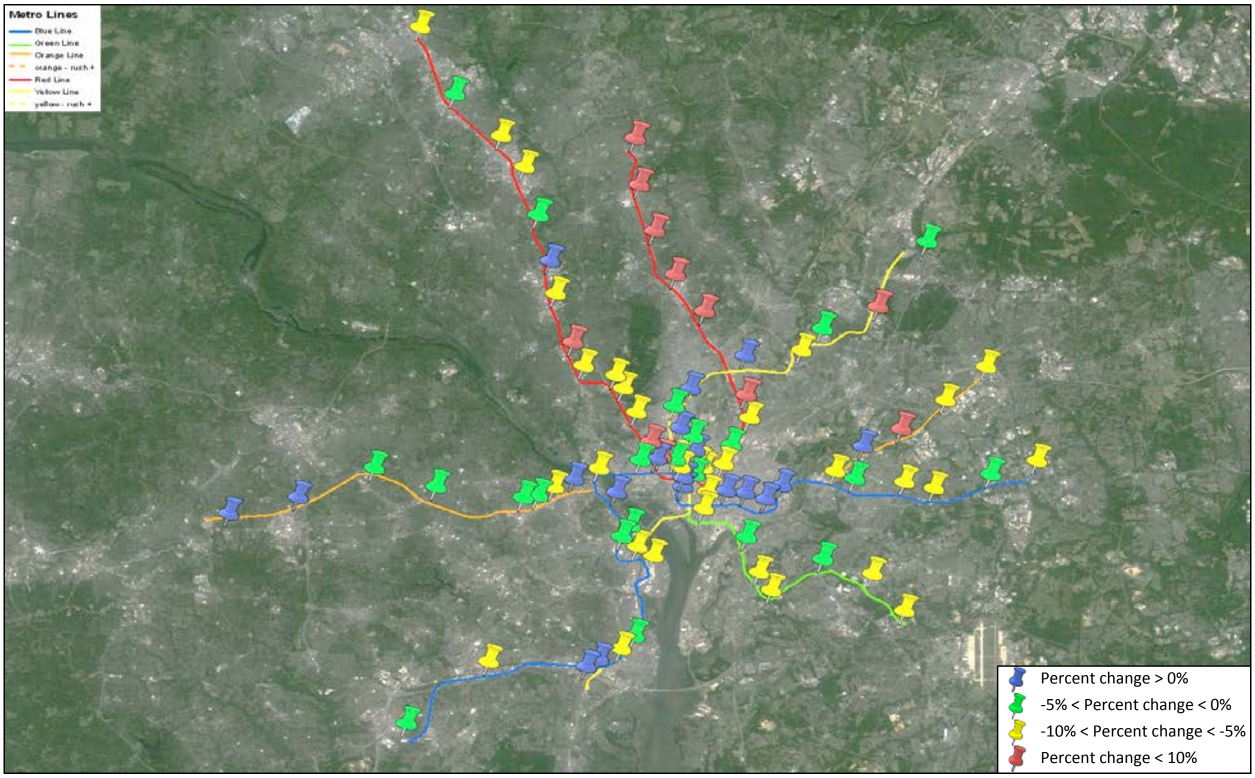

Figure 11: Spatial change of actual metro ridership from predicted 2009 values for all stations

5.1.4 Bus Ridership

Table 6 presents the average weekday percent change of rail and bus ridership in June 2009 from the predicted 2009 ridership for the most affected stations (north of Fort Totten on the east part of the Red Line) and the Fort Totten station. For each Metro station in Table 6, the corresponding MetroBus connections and RideOn bus routes were selected. Ridership values from bus lines that have connections at the most affected Metro stations were summed at each Metro station for Metrobus and RideOn[2]. The total bus ridership was lower for each of the MetroRail stations from the trend associated with the 2006-2008 data. This result was anticipated since travelers likely would have preferred to skip the disrupted section of the MetroRail system if they had alternatives available. Thus, it is likely that at least a portion of the bus ridership decrease in June 2009 from the previous years' trend was due to the integration with the disrupted MetroRail system.

The percent change in bus ridership was lower in magnitude than that of the rail. This could have been attributed to (1) rail stations being accessed by more modes of transportation than just bus, (2) bus routes serving other origins/destinations, and (3) some bus routes serving multiple rail stations.

Table 6: June Rail and Bus Ridership Average Weekday Percent Change for the Most Affected Metro Stations

MetroRail Station	Rail Ridership			Bus Ridership	
	Entry	Exit	Average	MetroBus	RideOn
Glenmont	-17.2%	-19.9%	**-18.6%**	-6.3%	-4.7%
Wheaton	-12.7%	-14.9%	**-13.8%**	-12.3%	-3.7%
Forest Glen	-16.3%	-20.4%	**-18.3%**	-10.1%	-8.2%
Silver Spring	-25.6%	-29.2%	**-27.4%**	-5.2%	-6.1%
Takoma	-17.6%	-20.5%	**-19.0%**	-1.9%	-5.2%
Fort Totten	1.3%	2.5%	**1.9%**	-8.3%	NA

[2] Bus ridership data account for the entire line rather than a particular stop.

The MetroBus routes serving the vicinity of the affected Metro stations on the east leg of the Red Line, as shown in Figure 12, were also analyzed. Any MetroBus route that ran parallel to or passed through the east leg or that could transport people from/to any Metro station to/from the vicinity were included in this analysis. Each MetroBus line color in Figure 12 was based on the average weekday percentage change for June 2009 based on the predicted trend, summarized in Table 7.

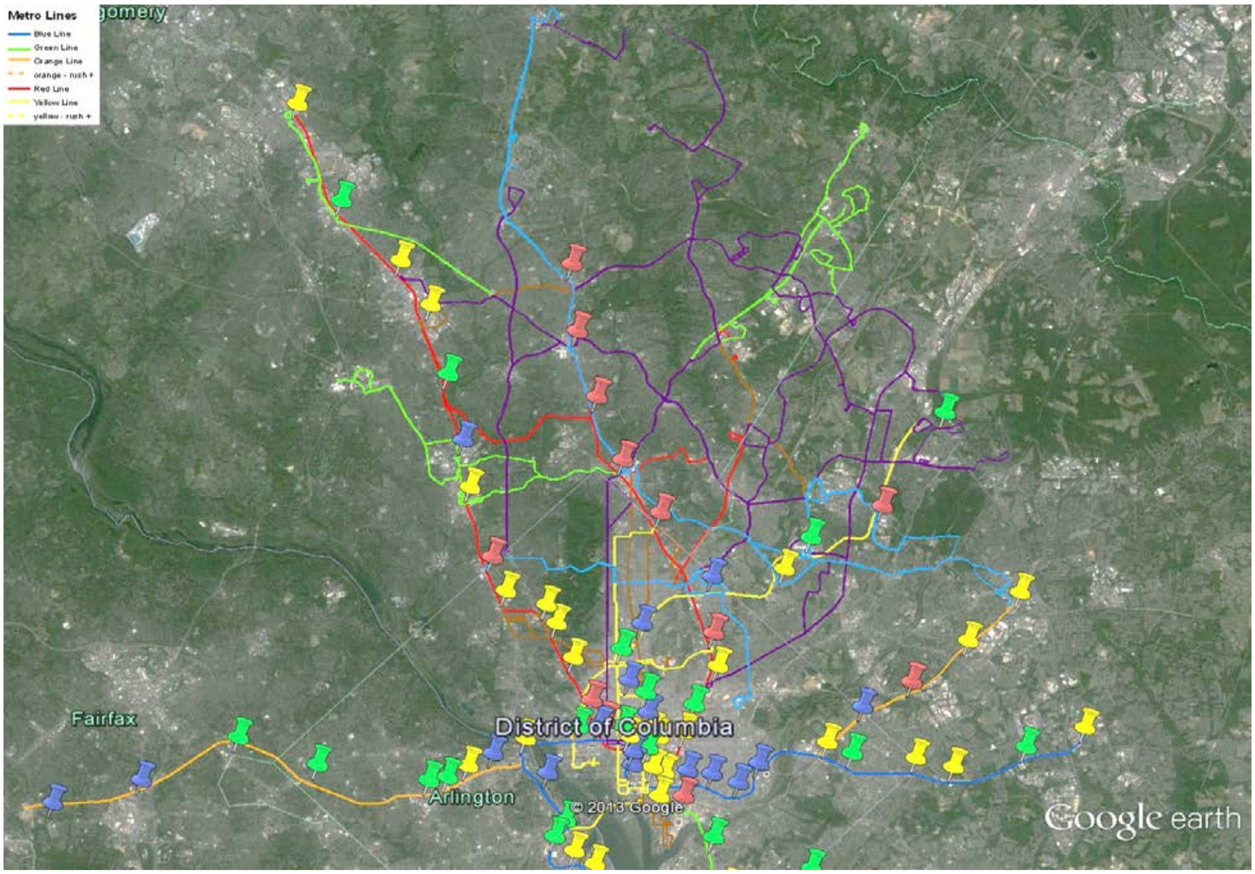

Figure 12: Metrobus lines that serve the affected vicinity

Table 7 presents the average weekday percentage change in April, May, June, and July of 2009 compared to the corresponding 2009 predicted ridership. The results were classified into six categories:

- Brown represented a 5 - 10% increase in June 2009 ridership from the predicted value,
- Yellow represented a 0 - 5% decrease in June 2009 ridership from the predicted value,
- Blue represented a 5 - 10% decrease in June 2009 ridership from the predicted value,
- Green represented a 10 - 15% decrease in June 2009 ridership from the predicted value,
- Purple represented a 15 - 20% decrease in June 2009 ridership from the predicted value, and
- Red represented a 20 - 35% decrease in June 2009 ridership from the predicted value.

MetroBus routes 62 and C8 showed increases in June 2009 ridership of 10% and 7.1%, respectively, over the predicted value. However, comparing the percentage change (observed to predicted) of June with April and May, the magnitude of the increase was lower than in April and May. For July, Route 62's magnitude of increase approached that of May. In terms of actual average weekday ridership, June had the lowest value for Route 62 and nearly the lowest for route C8 (only 3 more riders than May). For Route C8, July had a negative percent change in ridership (compared to the predicted value) and generally had a decreasing trend in the magnitude of the difference between the observed and predicted value from April through July.

Table 7: Average weekday ridership and percentage change (observed to predicted) in 2009 for the MetroBus routes serving the surrounding vicinity

MetroBus Route	April	Observed April 2009 Ridership	May	Observed May 2009 Ridership	June	Observed June 2009 Ridership	July	Observed July 2009 Ridership
62	16.2%	3,499	21.4%	3,621	10.0%	3,397	20.5%	3,472
70, 71	1.3%	11,295	8.8%	12,533	12.1%	12,426	17.8%	12,605
H2, H3, H4	6.2%	7,203	3.0%	6,743	9.8%	6,968	-5.1%	6,870
K2	-8.8%	522	1.6%	550	7.2%	357	-1.5%	268
C8	19.3%	2,091	16.7%	2,052	7.1%	2,055	-11.4%	2,393
52, 53, 54	-0.3%	13,690	7.8%	13,723	-4.7%	13,221	-7.1%	13,613
H1	6.1%	595	-0.3%	553	-4.5%	593	-9.4%	611
E2, E3, E4	-4.3%	6,326	-5.9%	6,231	-7.0%	6,059	-12.0%	6,209
F4, F6	-9.1%	7,503	-6.7%	7,512	-6.1%	7,522	-15.0%	7,579
Y5, Y7, Y8, Y9	-6.5%	6,593	-8.0%	6,773	-9.7%	6,783	7.2%	7,572
J1, J2, J3	-8.9%	5,513	-11.0%	5,839	-11.1%	5,695	-13.2%	5,819
Q2	-2.9%	9,491	-14.4%	8,955	-10.3%	9,416	-15.7%	NA
Z6	-14.1%	1,708	-6.1%	2,227	-11.7%	2,244	-0.7%	2,514
Z8	-2.5%	3,419	-11.6%	3,254	-14.5%	3,338	-28.4%	3,093
Z11, Z13	-7.7%	915	-8.1%	1,009	-14.6%	951	7.3%	1,031
L7, L8	-14.3%	2,480	-17.6%	2,469	-18.6%	2,389	-13.7%	2,829
R1, R2, R5	-10.0%	3,520	-2.7%	3,835	-15.2%	3,727	3.3%	3,834
Z2	-9.9%	1,862	1.6%	1,840	-16.8%	1,590	-27.8%	1,268
S2, S4	-12.5%	12,542	-15.2%	12,215	-15.9%	12,707	-7.2%	13,764
81, 82, 83, 86	-6.3%	4,500	-9.1%	4,599	-19.0%	4,761	-2.4%	5,157
C2, C4	-20.6%	12,036	-18.2%	12,533	-15.1%	12,582	-23.0%	11,803
C7, C9	-4.5%	374	-5.9%	432	-15.7%	379	NA	NA
J4	-13.0%	964	-14.0%	985	-20.8%	943	-23.4%	930
J5	-10.1%	377	-25.9%	334	-33.3%	283	-52.0%	320
K6	-21.3%	5,386	-19.2%	5,691	-20.4%	5,783	-7.9%	6,063

On the other hand, MetroBus routes (70, 71), (H2, H3, H4), and (K2) had increased ridership changes (actual to predicted) in June with magnitudes greater than those of April and May. Route (70, 71) had a consistently increasing trend in percentage change from April through July, so the June increase must be considered within this overall trend and may not be associated with the MetroRail crash, despite connecting the Silver Spring MetroRail station with other stations south of the crash and within the District. The actual average weekday ridership for June was lower than May or July's but higher than April's. Routes (H2, H3, H4) and (K2) had a peak increase over the predicted values in June with decreases from the predicted value in July. Route (H2, H3, H4) appeared to have a generally decreasing trend (April, May, and July) that was interrupted by June. The actual average weekday ridership was highest in June. This route connected the east and west legs of the MetroRail Red Line south of the Fort Totten station on the east leg; possibly some passengers switched from rail to bus. The peak increase in percent change for the (K2) route in June may be attributable to riders using this bus route to avoid the disrupted portion of the MetroRail line, since this bus route connected the Takoma Park station (first one north of the incident) with the Fort Totten station (just south of the incident). Although the actual average weekday ridership for June was lower than April and May, it was higher than July. Figure 13 shows these MetroBus routes in the context of the MetroRail stations.

All of the other bus routes had lower ridership that predicted for June 2009. Many of these, including (H1), (E2, E3, E4), (J1, J2, J3), (Z8), (S2, S4), (J4), (J5), and (C7, C9) were within the general trends and/or magnitudes of percent change associated with the other months. Routes (H1), (E2, E3, E4), (J1, J2, J3), (S2, S4), (J4), and (J5) had lower actual average ridership in June than July and (E2, E3, E4), (J1, J2, J3), (J4), and (J5) had both June and July actual ridership lower than in May, suggesting seasonal effects. Route (Z8) had higher actual average ridership in June than in May and July but lower than in

April. Route (Z8) connected a few park-and-rides to the Silver Spring MetroRail station and the lower July ridership may have been a seasonal effect. For routes (52, 53, 54) and (L7, L8), the actual average ridership in June was the lowest of the four months. Routes (F4, F6), (Y5, Y7, Y8, Y9), (Z6), (81, 82, 83, 86), and (K6) had actual average riderships that followed an increasing trend from April through July so there was no clear effect of the crash on ridership. Routes (Z11, Z13) and (R1, R2, R5) fluctuated in both actual average ridership and percentage change from predicted ridership. Actual average ridership for (Z2) followed a general decreasing trend across the four months. Finally, route (C2, C4) followed an increasing trend in actual average ridership until July, which was the lowest of the four months. This route also serves the University of Maryland, which has fewer students in July than in April and May.

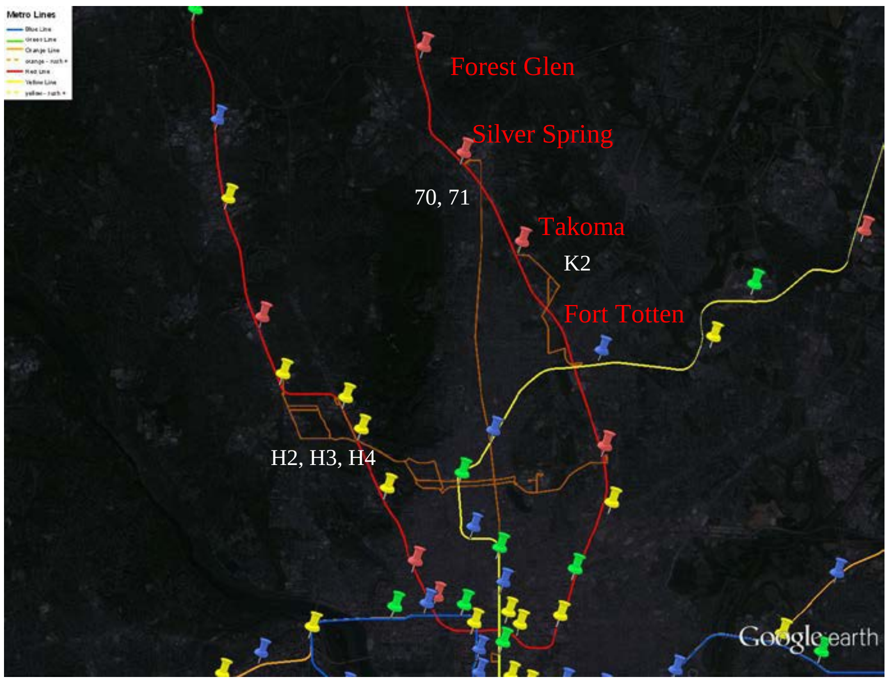

Figure 13: MetroBus lines that have increased ridership in June 2009 compared to the predicted ridership

5.2 Boom Truck Incident

To eliminate the potential impact of demand fluctuation, three Tuesdays prior to the incident date (March 13, 2012) served as a baseline for comparison. Figure 14 shows the speed dynamics on February 21, 2012 and Figure 15 shows those for the incident day. The boom truck accident caused severe congestion near the incident section on VA-267. The speed was around 10% of the speed limit. The reason the speed was not 0 was the presence of the bus lane that could be used to avoid the portion that had fallen on the road. Despite the fact that the incident location was near the VA-267 interchanges with other major roads like VA-7 and I-66, there was no obvious impact of the incident upon these roads. However, delays in bus service were experienced by riders connecting at the West Falls Church Metro Station. The local effects of the boom truck accident appeared to be similar to severe vehicle crashes that block multiple lanes of a high-speed road/freeway.

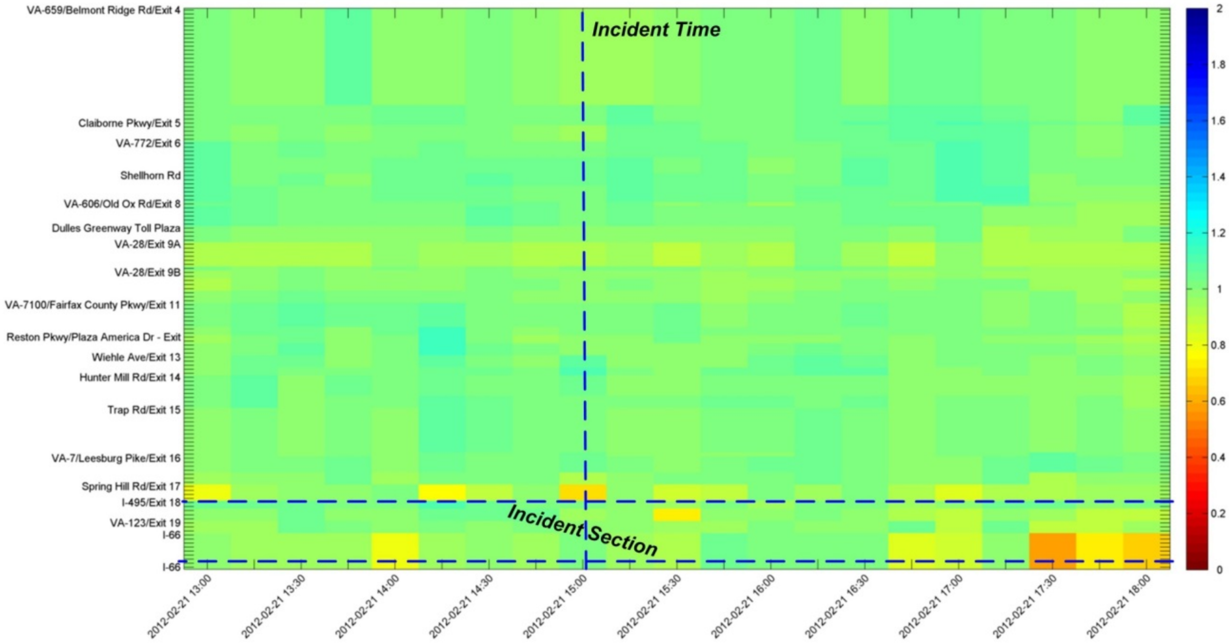

Figure 14 VA267 East on 2012/02/21 13:00 to 2012/02/21 18:00

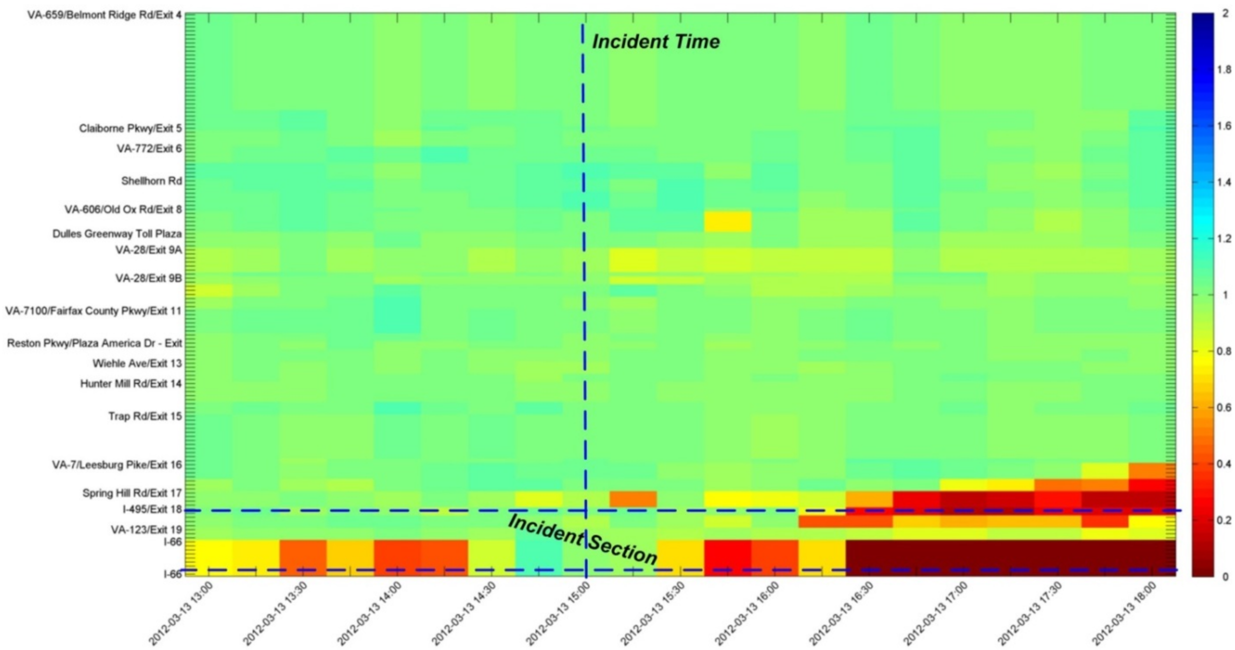

Figure 15 Speed Profile of VA267 East on 2012/03/13 13:00 to 2012/03/13 18:00

5.3 Earthquake

The earthquake was felt in a large part of the East Coast. Many federal government agencies, public schools, and private companies allowed their employees to leave work early. This shifted demand corresponded to a shifted congestion pattern. Figure 16 and Figure 17 show the speed profiles of I-66 West from 13:00 to 20:00 on August 16, 2011 and August 23, 2011, respectively. The congestion occurred earlier on the earthquake day than usual. Between the exits for Sycamore Street and US-29, this shifted congestion was particularly obvious, possibly due to the early release of employees. A similar pattern was observed for I-395 South, as shown in Figure 18 and Figure 19. This was expected, since I-395 South is one of the major corridors for federal empolyees to leave Washington, DC.

The congestion shift was not as obvious for I-95 South, as shown in Figure 20 and Figure 21. However, the congestion on the earthquake day expanded to a longer section compared to that on August 16, 2011.

The impact of the earthquake was different from that of the boom truck accident. The earthquake's impact was primarily manifested in the congestion shift. Specifically, the congestion occurred earlier than usual and the congestion occurred at more locations on I-95 South. The main reason for the difference of impact between the boom truck accident and the earthquake lay in the difference of the incident nature. The boom truck accident resulted in capacity reduction on a major road (VA-267), which led to localized congestion. In comparison, the earthquake caused demand changes, which shifted congestion network-wide.

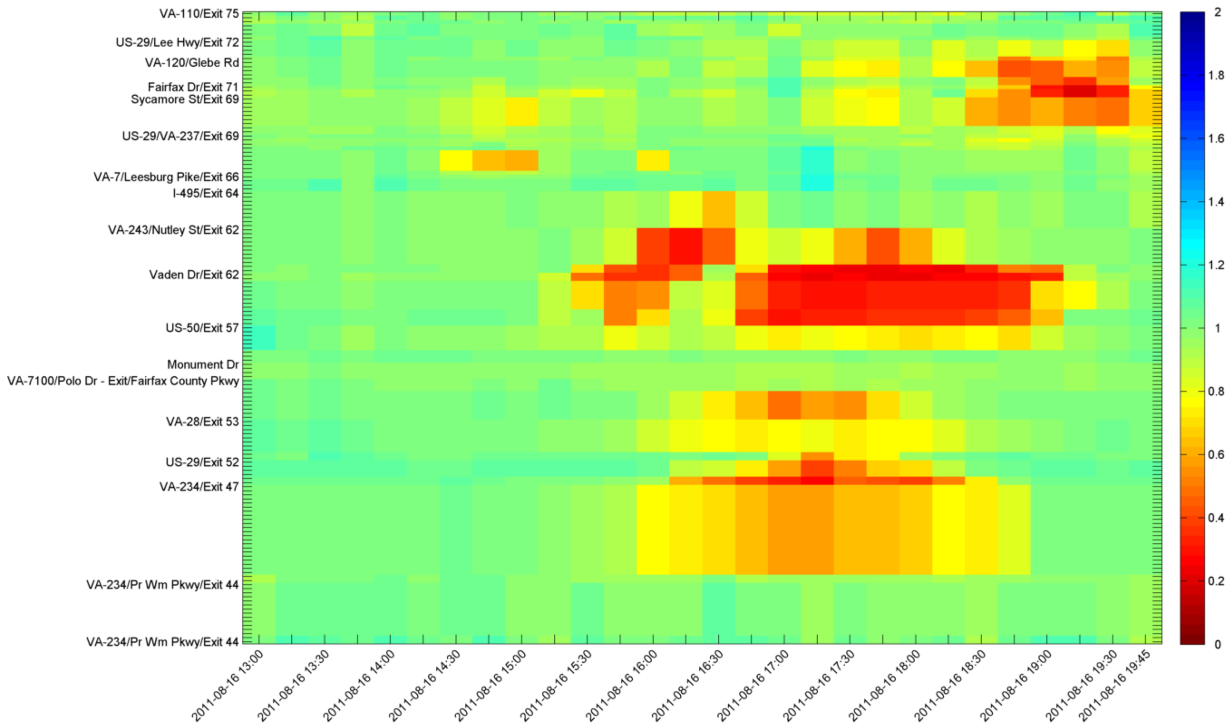

Figure 16 Speed Profile of I-66 West on 2011/08/16 13:00 to 2011/08/16 20:00

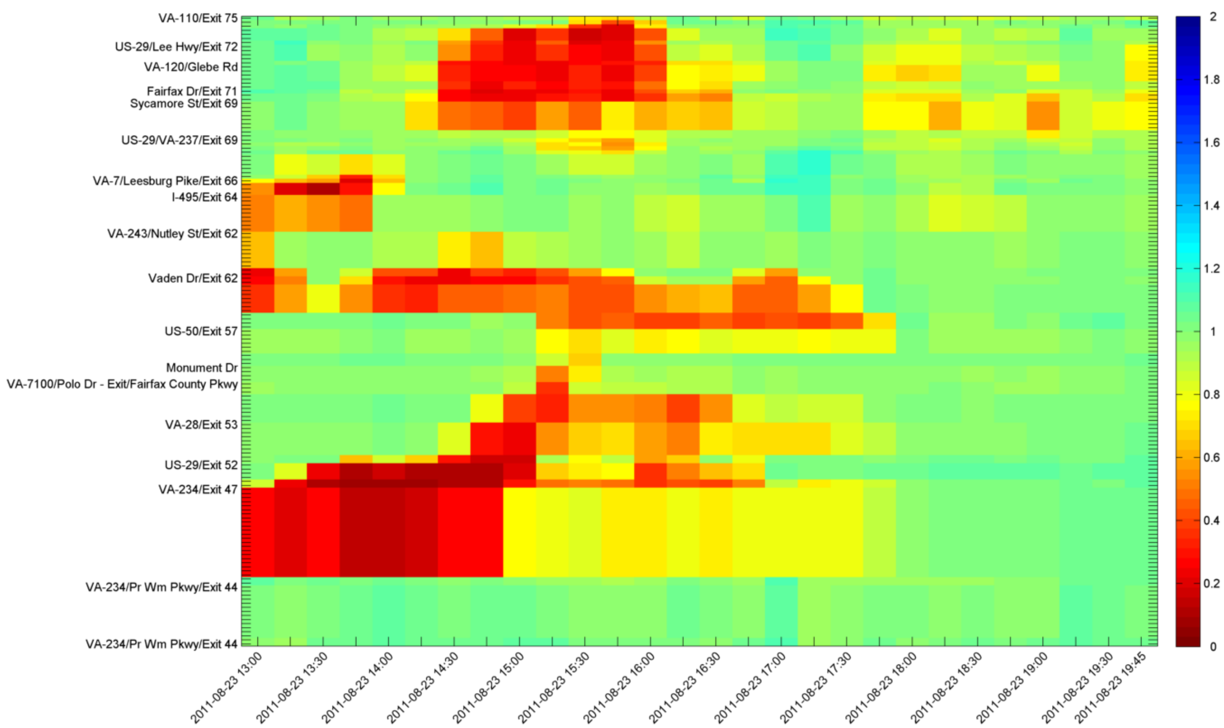

Figure 17 Speed Profile of I-66 West on 2011/08/23 13:00 to 2011/08/23 20:00

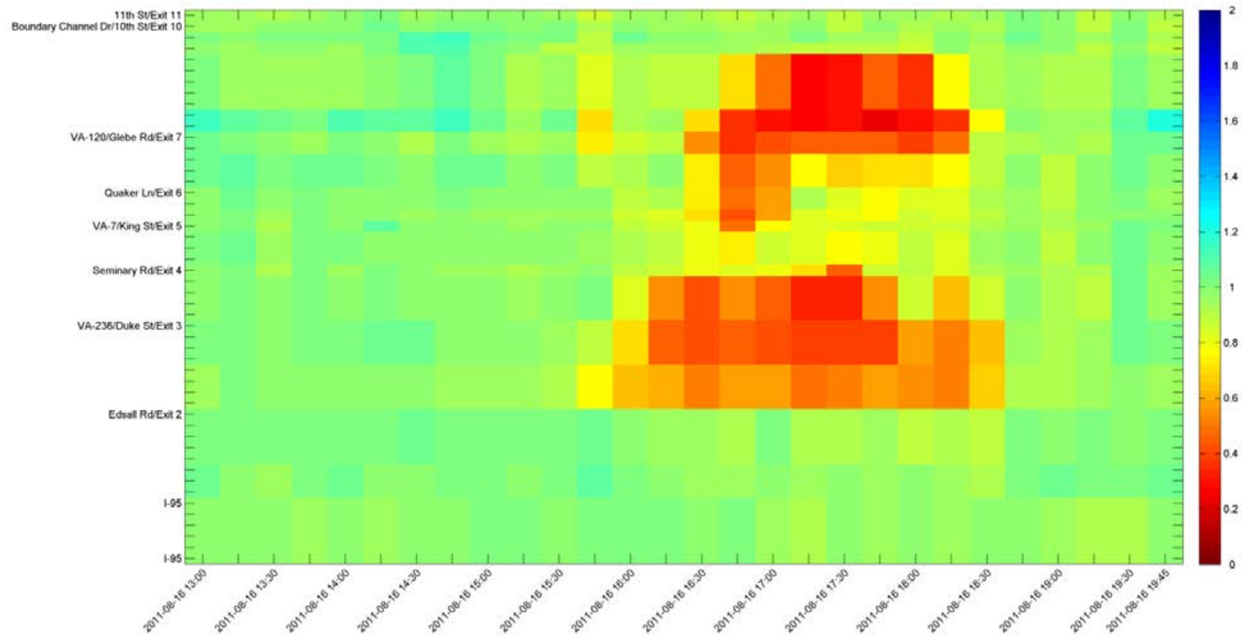

Figure 18 Speed Profile of I-395 South on 2011/08/16 13:00 to 2011/08/16 20:00

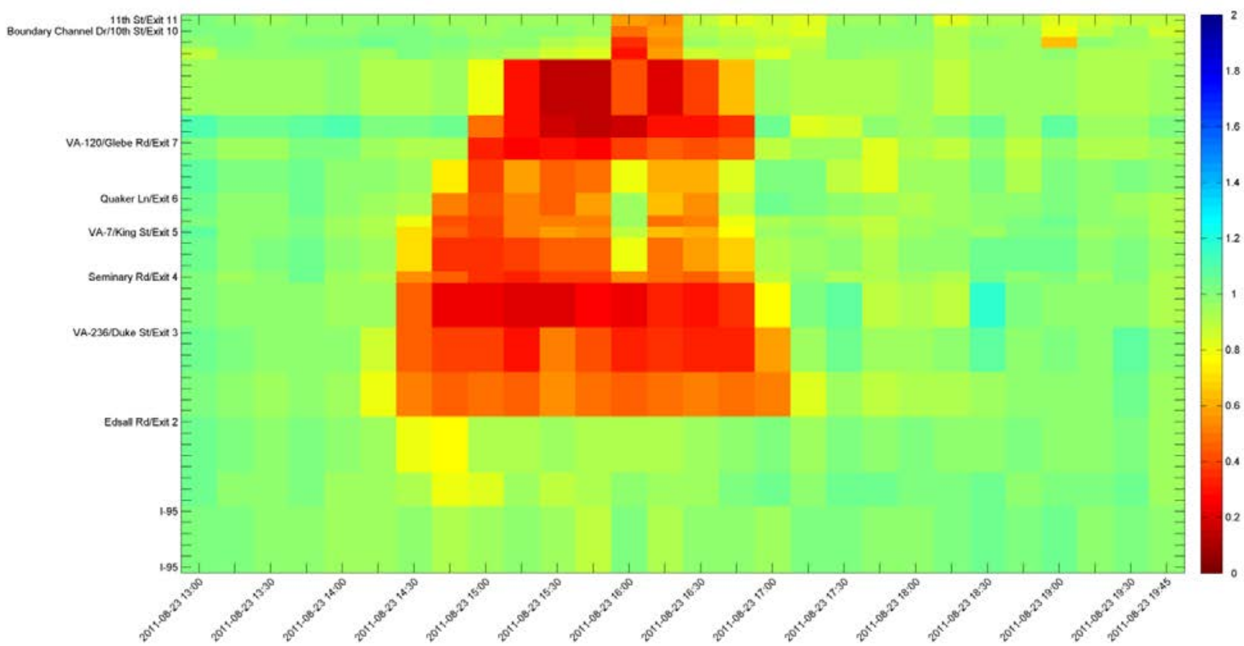

Figure 19 Speed Profile of I-395 South on 2011/08/23 13:00 to 2011/08/23 20:00

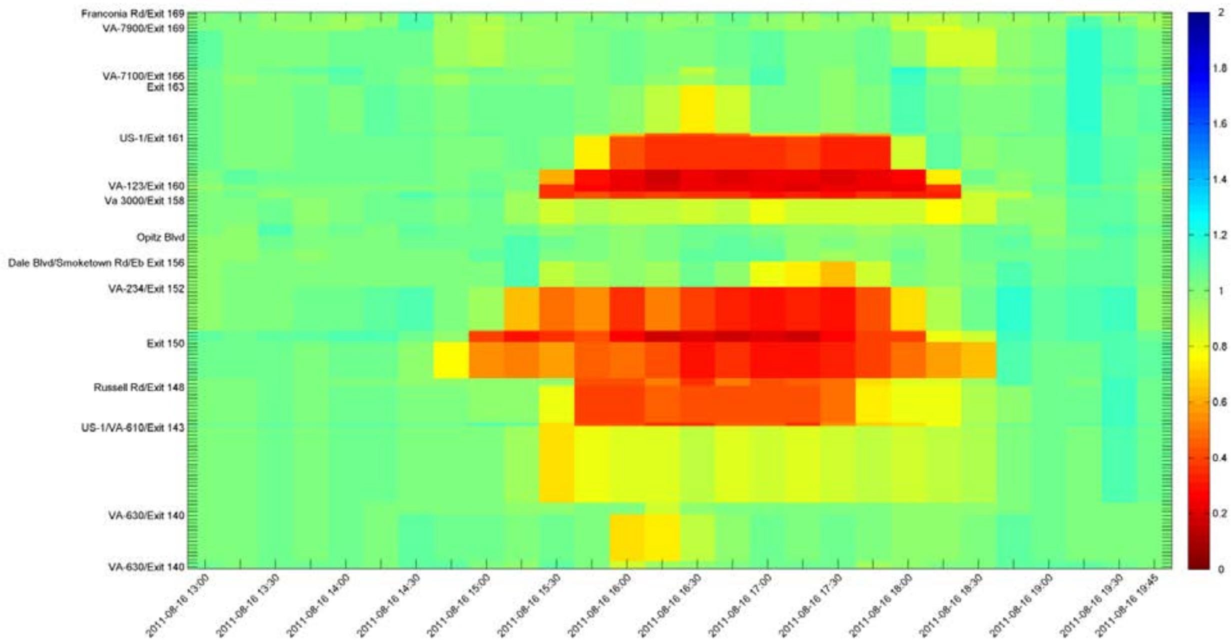

Figure 20 Speed Profile of I-95 South on 2011/08/16 13:00 to 2011/08/16 20:00

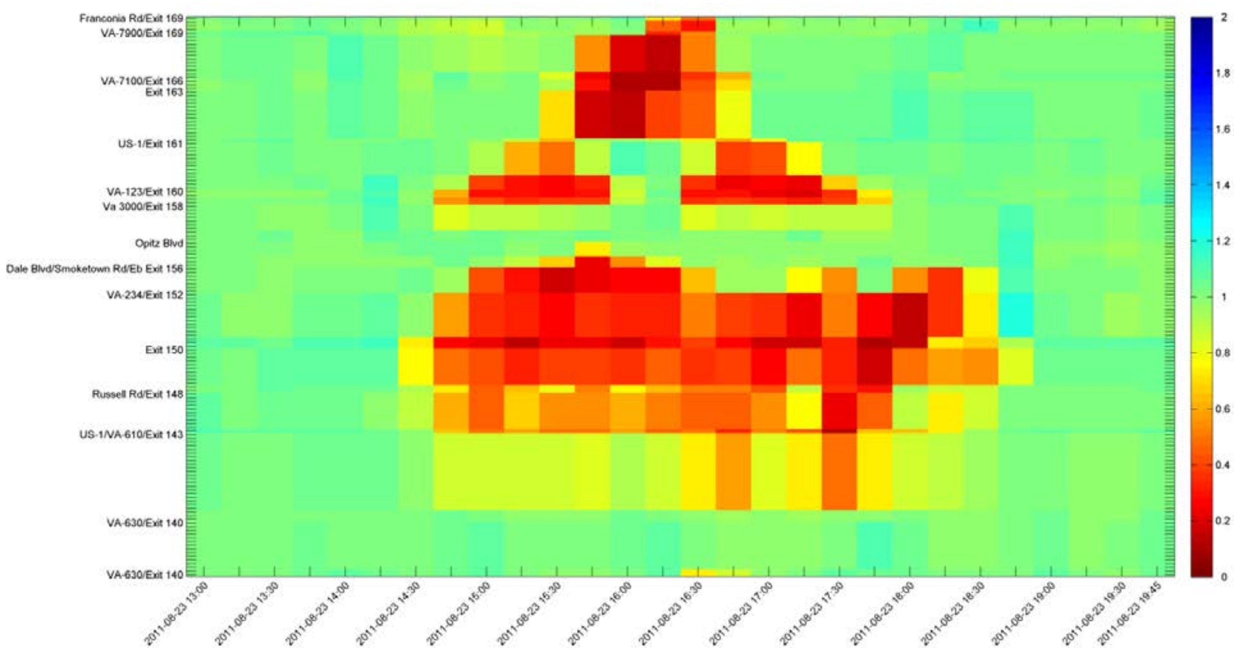

Figure 21 Speed Profile of I-95 South on 2011/08/23 13:00 to 2011/08/23 20:00

5.4 Impact of the Regular Incident

The regular incident used for comparison against the earthquake and the boom truck accident was an accident that involved a disabled vehicle on I-66 West near Nutley Street (Exit 62). The incident occurred at 5:32 p.m. on March 31, 2010 with a clearance time of 1 hour 47 minutes, with a closed shoulder lane for about 50 minutes. The days for comparison were two Wednesdays prior to the incident, namely March 24, 2010 and March 17, 2010. The effect of the incident was not obvious mainly because the afternoon-peak congestion was already serious. The conditions are visualized in Figure 22 and Figure 23.

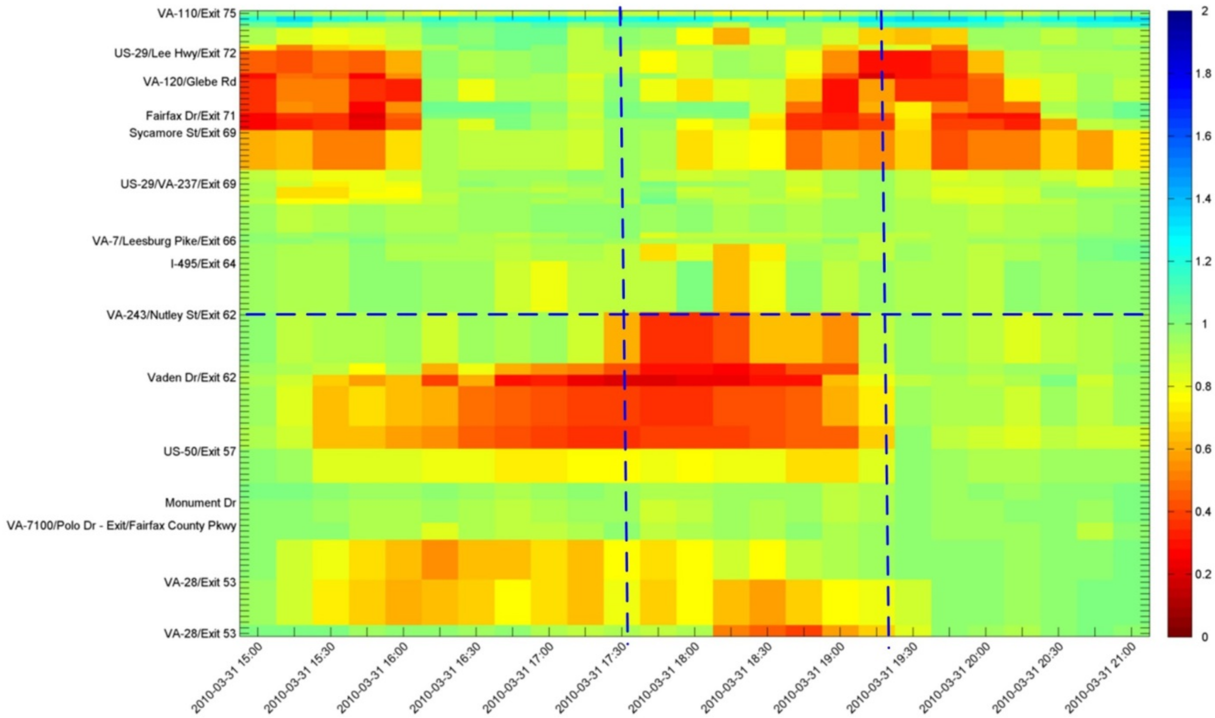

Figure 22 Speed Profile of I-66 West on 2010/03/31 15:00 to 2010/03/31 21:00

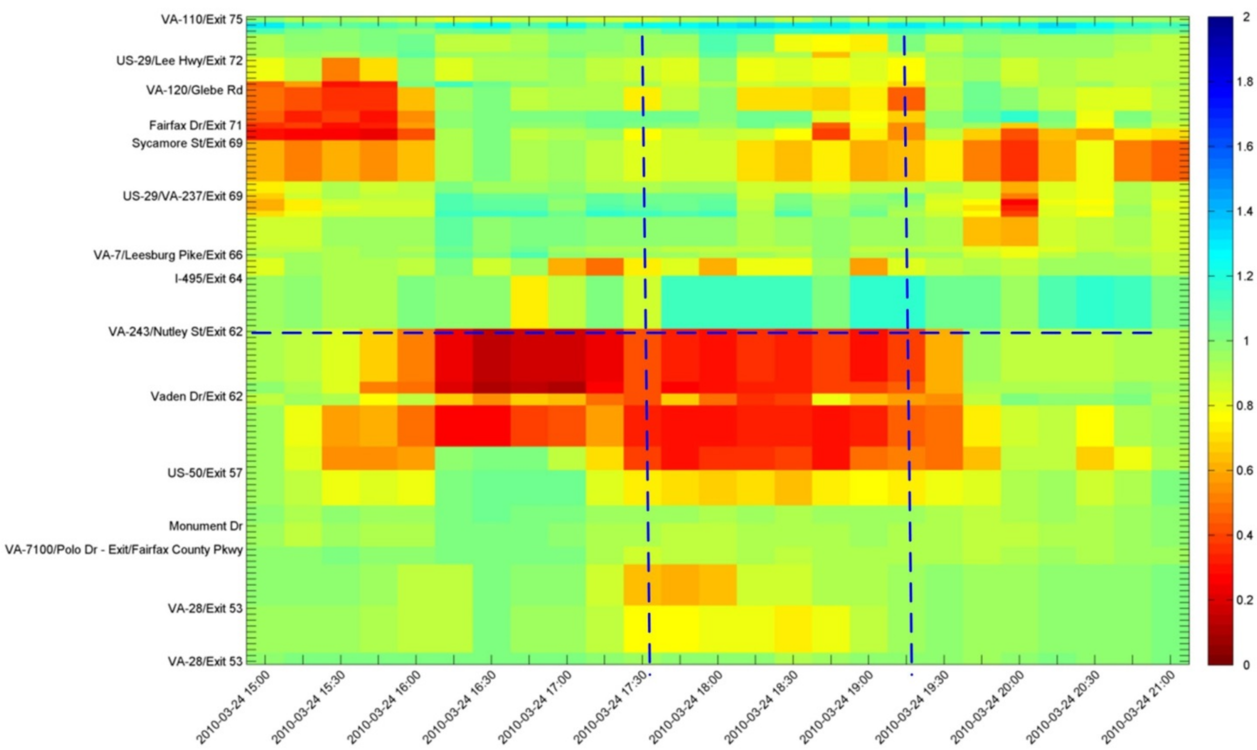

Figure 23 Speed Profile of I-66 West on 2010/03/24 15:00 to 2010/03/24 21:00

5.5 Simulation Results

Table 8 and Table 9 present the network-level results of the simulation of different strategies for the disruptive events. Italicized values indicate an improvement over the "do-nothing" ("no-strategy") option.

The boom truck[3] and I-66/Nutley incidents occurred at different times during the pm peak, at 4:00 (near the beginning) and at 5:30 (near the middle) and in different directions, non-peak and peak, respectively.

As previously discussed in Section 4, no capacity-based strategies were applicable to the boom truck incident. For the I-66 incident, opening the HOV lane to regular traffic was not beneficial in the simulation context. This could partially be attributed to the way the lane was modeled, with limited points to transfer between the HOV and general purpose lanes. While this modeling approach could be improved for situations where the two lane types are continuously adjacent, the result could transfer to separated HOV facilities. Drivers who shift to the HOV facilities would have different, potentially longer routes and merging at the access and egress points may induce congestion and lengthen travel times at different segments of the network. Another consideration for this strategy is the utilization of the HOV facilities. If they are normally heavily utilized, adding traffic could cause congestion on these facilities as well as the main lanes, requiring a careful balance across the two facilities, especially when using aggregate measures of effectiveness.

The simulation results indicated that speed adjustments need to be carefully implemented. Reducing the speed too much (e.g., 15 mph here) increases both stopped time and average travel time. However, lower speed reductions (e.g., 5-10 mph for the boom truck incident) can reduce stopped time, and in some situations, the overall average travel time. Speed reductions are not always effective[4] for reducing travel time. If volumes are high and congestion is such that traffic is already traveling below the speed limit, reducing the speed limit may have a safety consideration but may not be effective at reducing travel time. If volumes are low or the incident is such that the number of lanes available is adequate to accommodate the vehicles at a high speed safely, reducing the speed limit will not improve travel times.

Information-based strategies can reduce travel and stopped time for any event type, as shown in Table 8 and Table 9. However, the type of information and the response rate affect the aggregate performance. Mandatory detours can cause congestion at exit ramps, as in the case of the boom truck incident, and increase average travel times. If traffic signals exist at or near exit ramps associated with the detour, they may need to be re-timed based on the increased traffic. For widespread events, such as the earthquake with associated high demand, network-wide information is needed rather than isolated locations. Generally, when more people have network-wide information and better anticipate traffic conditions (as in the UE and pre-trip information combination cases in Table 9), network performance improves in terms of average travel and stop times and more drivers complete their trips in a given timeframe[5].

When an event, such as the earthquake, causes a demand surge, demand-based strategies that reduce the number of vehicles overall or space the loading of vehicles over time can improve the network performance more than capacity-based strategies. Improvised carpools (ridesharing) are one way to reduce the vehicular demand. Social media and personal contacts as well as ridesharing services can be used to implement this strategy. Even if only 1% of the travelers choose to carpool, improvements were seen. Pausing the network loading, even for small increments of time (e.g., 15 minutes), reduced

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[3] Traffic resulting from the boom truck incident involved an approximate 1-mile queue, which was similarly found in the simulation.

[4] The ineffectiveness for the I-66 speed reduction cases may have been due to a simulation modeling issue. The speed limits were set at the beginning of the simulation, so vehicles traveling on the roadway prior to the incident also had to slow down, affecting the overall travel times.

[5] The results for 70% UE and 30% pre-trip information are outside of the general trend but consistent over multiple simulation runs. No clear explanation is available.

congestion and travel time, improving network performance. For any given loading period, a longer pause (30 minutes) improved network conditions more than the shorter pause (15 minutes).

However, trade-offs between the loading and gap length exist. The 30-30 strategy yielded the best performance while the 90-15 strategy was the worst. The strategies with loading lengths between these did not have a generalizable trend. For instance, strategy 60-15 generated lower average travel times than the 45-15 strategy. To further investigate the effects of the demand pausing strategies, Figure 24 shows the percent of vehicles loaded or exiting the network by a given time. Although the 30-30 strategy had the lowest travel time, it had the least number of vehicles exiting the network by a given time, suggesting that the limiting factor for this case was the demand loading rather than the network. For loading periods greater than 45 minutes, the exit curve seemed smoother and to less reflect the shape of the loading curve, suggesting that the network was saturated and the network was the limiting factor to network clearance. All of the strategies seemed to converge at 90% network clearance.

Table 8 Simulation Results for the Boom Truck and I-66 Incidents

Strategy		**Average travel time (min)**	**Average stop time (min)**	**Average trip distance (mi)**	**Num. of vehicles not completing their trips**	**% not completing their trips**
Baseline UE Conditions		21.981	8.853	7.957	318	0.01%
		Boom Truck Incident				
No strategy		**22.258**	**9.155**	**7.958**	**318**	**0.01%**
Reduce speed	5 mph	*22.258*	*9.150*	7.958	318	0.01%
	10 mph	22.259	*9.153*	7.957	318	0.01%
	15 mph	22.265	9.157	7.957	318	0.01%
VMS: mandatory detour		22.586	9.381	7.955	3167	0.07%
VMS: congestion warning (response)	20%	*22.255*	*9.150*	7.958	318	0.01%
	40%	*22.256*	*9.149*	7.957	318	0.01%
	60%	22.259	*9.153*	7.958	318	0.01%
	80%	*22.248*	*9.142*	7.958	318	0.01%
	100%	*22.244*	*9.135*	7.958	318	0.01%
Reduce speed 5 mph with VMS congestion warning (100% response)		22.264	9.156	7.958	318	0.01%
		I-66 Incident at Nutley				
No strategy		**22.003**	**8.868**	**7.957**	**318**	**0.01%**
HOV restriction removal		22.012	8.876	7.957	318	0.01%
Reduce speed	5 mph	22.008	8.868	7.956	318	0.01%
	10 mph	22.009	8.876	7.957	318	0.01%
VMS: congestion warning (response)	20%	22.006	8.876	7.957	318	0.01%
	30%	22.006	8.873	7.956	318	0.01%
	40%	*21.995*	*8.861*	7.956	318	0.01%
	50%	22.012	8.877	7.956	318	0.01%
	60%	22.022	8.893	7.957	318	0.01%
	80%	*22.001*	8.871	7.957	318	0.01%
	100%	*21.993*	*8.862*	7.957	318	0.01%
HOV removal with VMS congestion warning 20% response		22.012	8.876	7.957	318	0.01%
HOV removal with VMS congestion warning 40% response		22.006	8.871	7.957	318	0.01%

Table 9 Earthquake Simulation Results

Strategy		Average travel time (min)	Average stop time (min)	Average trip distance (mi)	Total vehicles	% of original OD demand	Num. of vehicles not completing their trips	% not completing their trips	Num. of new HOVs
Baseline UE Conditions (“Normal”)		25.233	11.449	7.787	5038699	100%	348	0.01%	NA
UE for earthquake demand (lower bound)		61.537	42.849	8.071	4223181	100%	9577	0.23%	NA
No strategy		88.892	67.362	8.047	4225406	100%	73841	1.75%	NA
Open shoulder lanes		88.979	***67.335***	8.029	4224133	100%	74115	1.75%	NA
Open HOV lanes		89.134	67.869	8.038	4222910	100%	74330	1.76%	NA
Open HOV and shoulder lanes		89.030	67.666	8.023	4222764	100%	73395	***1.74%***	NA
Information: 10%UE 90% pre-trip		***87.198***	***66.672***	8.016	4224357	100%	68328	***1.62%***	NA
Information: 20%UE 80% pre-trip		***83.978***	***63.456***	8.056	4220566	100%	63967	***1.52%***	NA
Information: 30%UE 70% pre-trip		***83.737***	***63.639***	8.015	4223864	100%	56316	***1.33%***	NA
Information: 40%UE 60% pre-trip		***82.880***	***62.482***	8.028	4224123	100%	61746	***1.46%***	NA
Information: 50%UE 50% pre-trip		***79.635***	***59.516***	8.066	4222177	100%	50300	***1.19%***	NA
Information: 60%UE 40% pre-trip		***77.963***	***58.171***	8.103	4221183	100%	39747	***0.94%***	NA
Information: 70%UE 30% pre-trip		***83.333***	***62.976***	7.936	4221572	100%	57926	***1.37%***	NA
Information: 80%UE 20% pre-trip		***77.372***	***57.334***	8.113	4222922	100%	37032	***0.88%***	NA
Information: 90%UE 10% pre-trip		***76.839***	***56.712***	8.115	4222973	100%	36822	***0.87%***	NA
Information: 99%UE 1% pre-trip		***77.916***	***57.570***	8.167	4224219	100%	34782	***0.82%***	NA
Demand: load 30, pause 15		***70.769***	***51.320***	7.933	4220015	100%	74267	1.76%	NA
Demand: load 30, pause 30		***65.588***	***47.346***	7.928	4222322	100%	74978	1.78%	NA
Demand: load 45, pause 15		***79.503***	***58.519***	8.018	4223096	100%	76001	1.80%	NA
Demand: load 45, pause 30		***74.830***	***54.979***	8.079	4223468	100%	62341	***1.48%***	NA
Demand: load 60, pause 15		***79.020***	***58.083***	7.958	4222793	100%	85852	2.03%	NA
Demand: load 60, pause 30		***78.147***	***57.311***	7.968	4219852	100%	78717	1.87%	NA
Demand: load 75, pause 15		***78.791***	***59.094***	7.990	4220977	100%	61704	***1.46%***	NA
Demand: load 75, pause 30		***76.048***	***56.825***	7.963	4221736	100%	65095	***1.54%***	NA
Demand: load 90, pause 15		***85.678***	***64.666***	8.018	4222017	100%	70901	***1.68%***	NA
Demand: load 90, pause 30		***83.703***	***62.871***	8.027	4221652	100%	69974	***1.66%***	NA
Carpool improvisation	1%	***88.072***	***66.990***	8.027	4182262	98.9%	71335	***1.71%***	39795
	2%	***86.818***	***65.845***	8.056	4143725	98.0%	64153	***1.55%***	79148
	3%	***86.003***	***65.291***	8.054	4101903	96.9%	62552	***1.52%***	117373
	4%	***84.952***	***64.546***	8.051	4056882	95.8%	61993	***1.53%***	154914
	5%	***84.172***	***63.984***	8.028	4014664	94.8%	60510	***1.51%***	193468
	6%	***82.441***	***62.473***	8.041	3964956	93.6%	54964	***1.39%***	226760
	7%	***81.209***	***61.944***	8.055	3921311	92.5%	49847	***1.27%***	262141
	8%	***81.067***	***61.780***	8.058	3880920	91.5%	46713	***1.20%***	295813
	9%	***79.180***	***60.076***	8.045	3851730	90.8%	47115	***1.22%***	329591
	10%	***78.904***	***59.849***	8.065	3823685	90.1%	43914	***1.15%***	363417

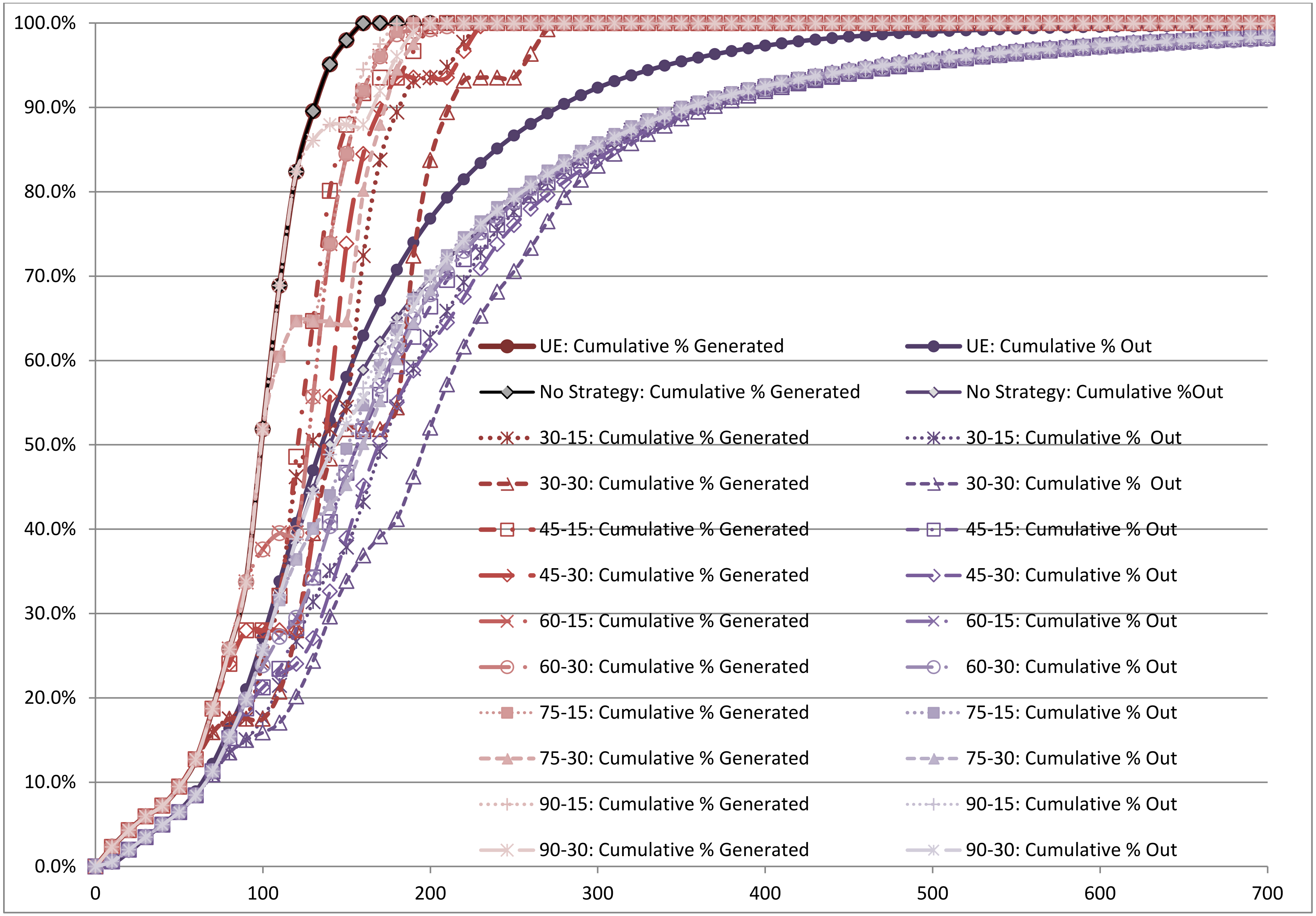

Figure 24 Network Loading and Unloading for Earthquake Demand Strategies

6 Summary and Conclusions

This study investigated the impact of three media-covered transportation disruptions in the Washington, DC metropolitan area – a MetroRail collision, a boom truck that fell over while working on the Silver Line, and an earthquake. These events were compared to a more common traffic incident and traffic and demand management strategies were investigated for their effectiveness in the different event contexts. All of these events occurred on weekdays during the afternoon or evening.

6.1 MetroRail Collision

The MetroRail collision occurred on Monday, June 22, 2009 at 4:58 p.m. The date of this event made a comparison of before and after traffic conditions a challenge. Public schools ended the week before the crash, and the week after the crash experienced some holiday travel related to July 4 as well as the beginning of general summer travel. While the direct impact of the event was confined to the rail system, transit and freeway impacts were considered in case some travelers switched from rail to car. Freeway detectors had some quality issues that further challenged the assessment of impacts. The team did not have access to arterial data, where some impacts may have occurred, particularly near the disrupted MetroRail stations (possible decreases) and the first station of the connected network (possible increases). The two pieces of the MetroRail system would likely be connected through additional bus service.

Freeways considered for the MetroRail event consisted of I-66 in Northern Virginia and I-270, I-95, and I-495 in Maryland. Comparing the pm peak volumes at detector stations on these roads from the same weekday of the week before the crash and the week of the crash and the following week(s), we used an aggregation approach, based on the MAPE formula, to combine the relative changes across the stations of a given road. Because of the seasonal change in traffic and holiday travel, it was difficult to derive any specific impacts attributable to the crash at the aggregated road level for I-66 westbound (peak direction). The three I-66 westbound detectors within the MetroRail service area but outside of the HOV restriction area were generally among those with the greatest magnitude of changes. The changes generally indicated lower vehicle counts after the crash; possibly, a few people avoided the MetroRail but they did not use the freeway, and seasonal effects were also present. Since the volumes were lower, no traffic management strategies were needed. On I-66 eastbound during the pm peak, the direction of change in volumes varied by day of the week and detector. Within the MetroRail service area, the three detectors each had an average change less than 4% in each of the weeks compared to the week before the crash. Less traffic was present at these locations after the crash (which could be a seasonal effect), and thus traffic management strategies were not needed. For the freeways in Maryland, only five detectors offered consistently good quality data for the weeks of interest. These detectors were fairly far north of the MetroRail service area, making it difficult to attribute changes directly to the MetroRail crash.

The MetroRail system was expected to experience a clearer change in usage than the freeways, and this was the case. The day after the crash (Tuesday) had an obvious drop in total ridership. However, ridership rebounded quickly (Wednesday) to approximately seasonal levels. Perhaps MetroRail riders sought other travel options or cancelled trips, anticipating MetroRail delays the day after the crash. Transit strategies and possible use of alternate stations may have drawn riders back to the system later in the week.

At the MetroRail station level, a predicted number of users was determined based on a trend line drawn from June 2006, 2007, and 2008 data. The five stations (Glenmont, Wheaton, Forest Glen, Silver Spring, and Takoma) on the east leg of the Red Line disconnected from the rest of the rail system had June ridership in 2009 at least 10% below the predicted ridership levels. The next station (Fort Totten) showed an increase in ridership, which may have been due to travelers selecting this station to access the system rather than one of the disconnected stations.

MetroBus and RideOn bus routes serving the disrupted MetroRail stations had total ridership in June 2009 lower than the trend associated with the 2006-2008 data. This result was anticipated, since travelers likely would have preferred to skip the disrupted section of the MetroRail system if they had alternatives available. Thus, it is likely that at least a portion of the bus ridership decrease in June 2009 from the previous years' trend was due to the integration with the disrupted MetroRail system. The percent change in bus ridership from the predicted value was lower in magnitude than that of the rail. This could have been attributed to (1) rail stations being accessed by more modes of transportation than just bus, (2) bus routes serving other origins/destinations, and (3) some bus routes serving multiple rail stations.

Other MetroBus routes serving the neighborhoods in the vicinity of the disrupted stations had increased ridership changes (actual to predicted) in June with magnitudes greater than the ridership changes from the predicted values of April and May. A bus route connecting the east and west legs of the MetroRail Red Line south of the Fort Totten station on the east leg had actual ridership that was highest in June; possibly some passengers switched from rail to bus. The peak increase in percent change for another bus route in June may be attributable to riders using this route to avoid the disrupted portion of the MetroRail line, since this bus route connected the Takoma Park station (first one north of the incident) with the Fort Totten station (just south of the incident). Although the actual average weekday ridership for June was lower than April and May, it was higher than July.

Overall, the effects of the MetroRail crash appeared to focus on the transit system rather than the freeways. Rail ridership decreased at the disconnected stations but increased at the first connected station. Bus ridership with stops at the disconnected stations decreased while a few routes connecting the disconnected stations to connected stations or connected stations to connected stations had increased ridership, either actual or above predicted values, accounting for seasonal effects.

6.2 Boom Truck Incident

The boom truck incident occurred on Tuesday, March 13, 2012 near 4:00 p.m. and blocked both of the general purpose lanes. A bus lane on the shoulder allowed some movement of traffic around the boom, preventing the speed on the impacted road segment from reaching 0. The speed was around 10% of the speed limit. The accident caused severe congestion near the incident section on VA-267 but did not appear to have a noticeable impact on other major roads like VA-7 and I-66. However, delays in bus service were experienced by riders connecting at the West Falls Church Metro Station. The local effects of the boom truck accident appeared to be similar to severe vehicle crashes that block multiple lanes of a high-speed road/freeway.

6.3 Earthquake

An earthquake occurred in central Virginia on Tuesday, August 23, 2011 at 1:51 p.m. and was felt along the East Coast. No freeway lanes were blocked but the MetroRail system in Washington, DC operated at slower speeds. Employees were released early from work, shifting the demand, and freeway congestion occurred earlier and at more locations than usual. The demand change and its effects were more network-wide than the impacts of the boom truck incident and regular traffic incidents. The main reason for the difference in impact between the boom truck accident and the earthquake lay in the difference in the incident nature. The boom truck accident resulted in capacity reduction on a major road (VA-267), which led to localized congestion. In comparison, the earthquake caused the change of demand patterns and widespread congestion.

6.4 Strategies

The nature of disruptive events - whether their impacts are multi-modal, localized or widespread, and primarily capacity or demand based – as well as their locations, severity, timing, and duration can impact the effectiveness of strategies. When the impact is a general, widespread surge in demand, such as that associated with the earthquake, demand-based strategies can be more effective than capacity-based strategies. Demand-based strategies, such as carpool improvisation, can reduce the overall number of vehicles trying to use the network. Other strategies, such as pausing demand loading or otherwise spreading the demand over time, reduce the number of vehicles simultaneously trying to enter the network, and vehicles already in the network experience less congestion and reach their destinations more quickly.

For both demand and capacity-influencing events, information-based strategies can reduce stopped time and travel time. The effectiveness of the strategy depends on how many travelers receive the information and respond appropriately. The “ideal” response rate is situation dependent. In the case of mandatory detours, other strategies may also be needed. If the detouring traffic overwhelms the capacity of the links or intersections of the route, signal timing or other capacity and routing strategies may be needed.

Capacity-based strategies, such as opening HOV facilities to general traffic and opening shoulder lanes, need to be carefully considered. Drivers who shift to separated HOV facilities would have different, potentially longer routes and merging at the access and egress points may induce congestion and lengthen travel times at different segments of the network. Another consideration for this strategy is the utilization of the HOV facilities. If they are normally heavily utilized, adding traffic could cause congestion on these facilities as well as the main lanes, requiring a careful balance across the two facilities.

Speed-based strategies also need to be carefully implemented. The right speed limit reductions can reduce stopped time, and in some situations, the overall average travel time. However, reducing the speed too much increases both stopped and average travel time. Furthermore, if volumes are high and congestion is such that traffic is traveling below the speed limit, reducing the speed limit may have a safety consideration, but may not be effective at reducing travel time.

6.5 Future Directions

Only a few types of disruptions were investigated in this study in order to manage the scope of the project. However, many other types of disruptions exist and can be investigated and compared in future studies. Also, as more data become reliably available, other types of impacts can be explored, such as those to arterial roadways and to individual travelers.

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