DOWNTOWN TRAFFIC SIGNAL OPTIMIZATION

District Department of Transportation

June 2015

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Executive Summary - Downtown Traffic Signal Optimization

Introduction

The District Department of Transportation (DDOT) completed the optimization of traffic signal timing in Downtown DC, improving traffic flow at over 650 intersections in May 2015. The project was a necessity due to the changes in travel patterns and volumes that have emerged from regional growth and development activities; to coordinate newly installed traffic signals; and to reduce conflicts between different modes of travel. The goals of the project were to make DC traffic signals safer and friendlier for pedestrians; improve bus running times and reduce bus delays; improve overall traffic flow; and reduce vehicular traffic emissions. A map of the traffic signals in the project area is shown in **Figure ES-1**.

Figure ES-1: Map of Traffic Signals in the Downtown Project Area

Project Phasing

The project consisted of two phases of work. Phase 1 was generally behind-the-scenes work in preparation for the optimization, which included traffic signal controller software updates, improving pedestrian and vehicle safety by updating pedestrian crossing times and adding “All Red” intervals, and identifying other opportunities for safety and operational improvements such as re-ordering the sequence of left turn phases. Phase 2 work is what was most observable by the public and culminated in implementing optimized signal timing.

Phase 2 (Signal Optimization) of the project involved collecting traffic data at each intersection, building a Synchro™ traffic model which included the traffic signal control and transportation network geometry, developing optimized signal timing plans, implementing the optimized signal timings overnight on April 24, 2015, and making fine-tuning adjustments to the signal timing parameters throughout May 2015.

Cycle Length Selection

Traffic flow patterns throughout the Downtown were evaluated based on traffic trends as to the day of week, and time of day to determine the time of day and day of week schedules – the start and stop times for each of the new timing plans. Five signal timing patterns were developed: AM Peak pattern, Midday Peak pattern, PM Peak pattern, Overnight pattern, and a Weekend pattern.

Prior to starting this project, the existing traffic signal cycle lengths were generally 100 seconds at all times of the day. An extensive qualitative analysis conducted by a team of engineer’s repeatedly observing traffic conditions throughout the Downtown area, and supported by a quantitative assessment using the Synchro™ traffic model resulted in a modest 10-second increase in the AM and PM peak period cycle lengths to 110 seconds. The increase allowed for additional green time to be allocated to reduce congestion at bottleneck locations constrained by the existing 100-second cycle length. However, the increase was limited to 10-seconds to achieve that delicate balance between increasing the cycle length enough to address congestion and delays issues, but low enough to maintain mobility for traffic (vehicles, buses, and pedestrians) not following the mainline traffic flow. The Midday, Weekend, and Overnight and signal timing plans cycle lengths of 100, 100, and 80 seconds were retained.

Signal Timing Design

Once the cycle length was determined, splits (amount of green time for each approach at a traffic signal) and offsets (the time-relationship between when adjacent signals turn green) were optimized. Offsets were designed to progress a platoon of traffic down the corridor with as few stops as possible, except on corridors with extreme oversaturation during the AM and PM peak patterns where a reverse offset strategy was utilized to move the queue from signal to signal.

Implementation & Fine-Tuning

In signal timing, seconds matter. The difference between a successful and unsuccessful signal retiming project is often a matter of a few seconds. For a typical intersection, there are approximately 200 individual parameters that are designed. Great care had been taken to develop each signal timing parameter for each intersection, but the work was not yet complete – the project needed to be implemented. Traffic flow is very sensitive to some of these parameters, in particular the split and offset. Field fine-tuning, which is done immediately after implementation, is the process of making slight (several second) adjustments to these parameters based on observations of actual traffic flows; this fine-tuning process was critical to the project's success.

Improvements

In order to determine if the project met its stated goals, traffic performance data was collected "Before" and "After" the optimized signal timings were implemented and compared. The sources of the performance data included visual observations conducted by the team of traffic signal timing engineers; Vehicle Probe Project (VPP) Suite traffic data analysis software, which analyzes traffic data from INRIX and other commercial sources; Google™ Traffic Maps; "Floating Car" Vehicle Travel Time and Delay measurements; WMATA Metro Bus Automatic Vehicle Location data; *Highway Capacity Manual* Level of Service (LOS) analyses; and a Benefit-Cost analysis.

Vehicle Probe Project Congestion Scan

Analysis of VPP Suite data showed that the **duration** and **extent** of congestion has decreased as a result of the signal timing optimization on all corridors for which traffic data is available, including 9th Street, 11th Street, 12th Street, 14th Street, Massachusetts Avenue, Rhode Island Avenue, and Constitution Avenue.

Figure ES-2 shows a sample of VPP's <u>Congestion Scan</u> tool for Massachusetts Avenue. The Congestion Scan graphically illustrates a speed metric (speed as a percentage of free flow speed) over a segment of roadway. Segments colored green are operating at or near their free flow speed (i.e. little to no congestion), whereas segments colored red or orange are operating under stop and go conditions. The duration may be observed by comparing across (horizontally) the scan and noting the time when the segment changes from red/orange to green, and then comparing between the "before" and "after" conditions. The extent may be observed by comparing the colors along the same segment of roadway between the "before" and "after" conditions. Note the segments that were orange or red in the "before" condition and changed to yellow or green in the "after" condition.

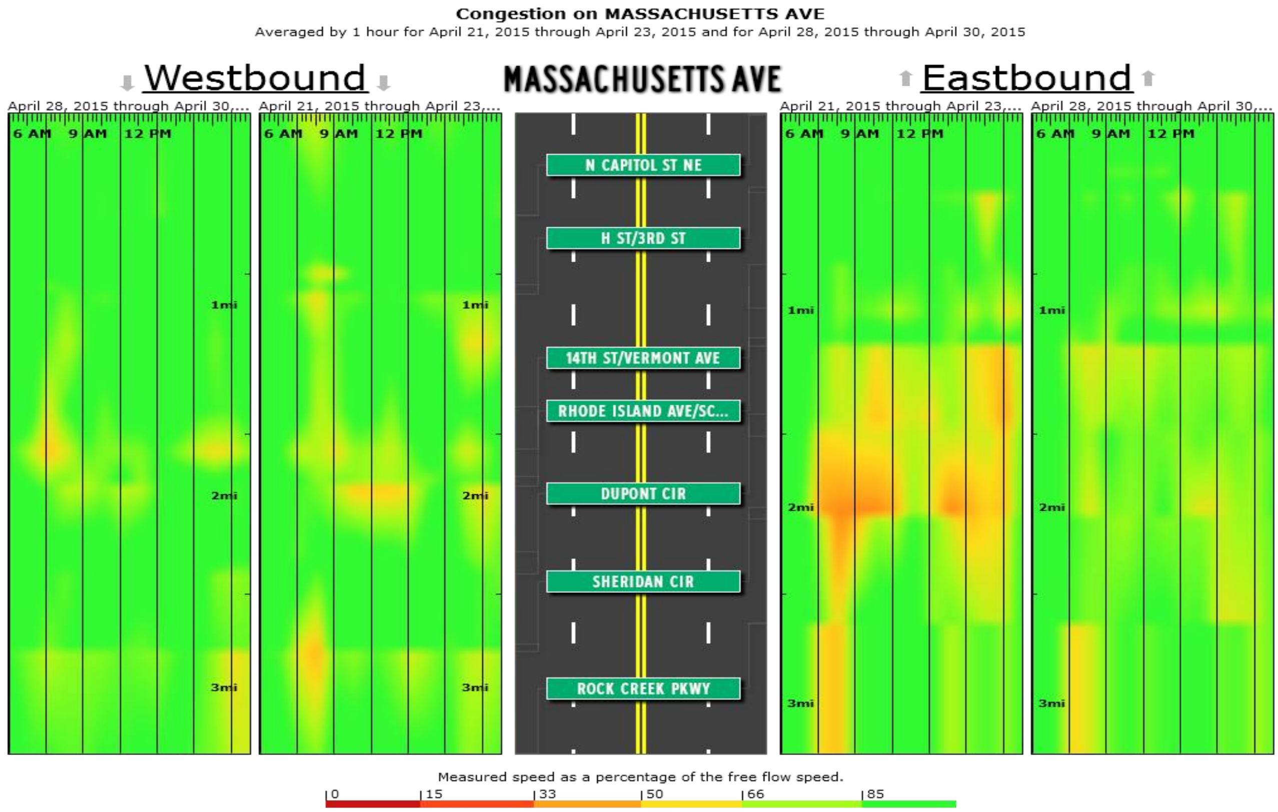

Figure ES-2: RITIS Congestion Scan of Massachusetts Ave from Rock Creek Pkwy to North Capitol

The scans adjacent to the roadway illustrate “before” conditions; outside scans show “after” conditions

Vehicle Probe Project Travel Time Comparison

Analysis of VPP Suite data showed that travel time decreased in the peak direction of the peak hour on all corridors for which traffic data is available, and with some exceptions (such as the off-peak direction for some corridors, but not all) experienced a general reduction in travel times during all times of day and directions. Some specific highlights are:

- Southbound 9th Street travel times decreased significantly during the AM peak period from approximately 7 AM to 9 AM, with savings on the order of 2 to 3 minutes. Northbound savings during the PM peak occurred from 3 PM to 9 PM and range from about 30 seconds to 2 minutes.
- 11th Street exhibits travel time savings throughout the day in both directions with savings of up to 2 minutes during the PM peak.
- 12th Street travel times decreased from 6 AM through 7 PM, with significant decreases during the AM peak period in the range of 1 to 3 minutes. There were some slight increases during the overnight period on the order of magnitude of 15 seconds.

- 14th Street travel times decreased from 10 AM through 7 PM, with significant decreases during the peak directions of the AM and PM peak periods in the range of 2 to 3 minutes.
- Southbound Rhode Island Avenue travel times decreased throughout the day, with significant decreases during the AM peak period in the range of 2 to 3 minutes. Northbound travel times showed significant decreases during the PM peak period.
- Major travel time savings were achieved on Constitution Avenue, particularly during the Midday and PM peak periods where travel time savings were as much as 2 minutes.
- Along Massachusetts Avenue, travel times decreased throughout the AM, Midday and PM peaks with savings as much as 5 minutes during the AM and PM peaks, and in particular on the approaches to DuPont Circle.

Figure ES-3 shows a sample of VPP's Travel Time tool for eastbound Constitution Avenue. Note that Orange illustrates the "before" conditions, and green indicates "after" conditions.

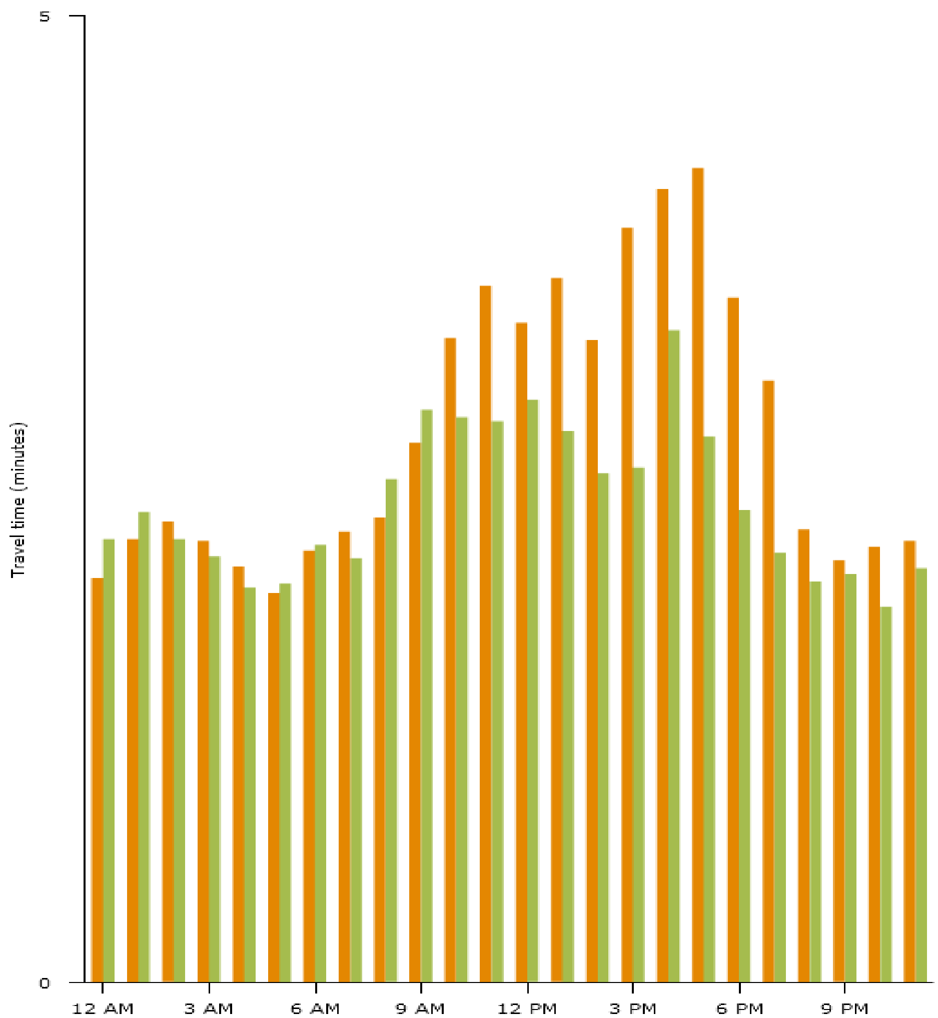

Figure ES-3: Travel Time on EB Constitution Avenue from 23rd Street to Pennsylvania Avenue

Bottleneck Reductions

One of the most visible components of congestion is bottlenecks, and more specifically the queues of vehicles which form as a result. Bottleneck reductions were both observed by the engineering team – a qualitative assessment, and quantitatively evaluated through the VPP Suite's Bottleneck Ranking tool The VPP Suite provided an independent, macro-level, quantitative assessment of this same measure of bottleneck reductions that were observed by the engineering team. The key takeaways from the VPP Suite bottleneck analysis are as follows:

- The average duration of congestion showed a 13% decrease.
- 65% of segments showed a reduction in the average maximum queue length, or remained the same. In contrast, less than one in six locations (13%) recorded an increase in the average max queue length. The remaining 22% of segments reported a bottleneck location but did not provide data to enable a "before" versus "after" comparison.
- Of the 13% of segments that recorded an increase in average max queue:
  - at 8% of these segments, the duration of congestion and/or the number of bottleneck occurrences in the "After" implementation period remained the same or showed an improvement compared with the "Before" time period. At nearly all these locations, the increase in queue length along one segment was simultaneously accompanied by an improvement along the crossing segment.
  - At 5% of these segments, there was a drop in all three bottleneck measurement categories. In several cases, the bottleneck was by design. In other words, the signal timing strategy favored one roadway's movement over another. In other cases, there is deterioration at a local area but the deterioration was "made-up for" by improving overall progression along the corridor for a net reduction in overall corridor travel time.

"Floating Car" Vehicle Travel Time and Delay Improvements

To assess the impact of the signal timing optimization, "Before" travel time studies were collected in April 2015, and compared to "After" travel time studies collected in May 2015. Travel time runs were performed along the entire length of selected routes using the "floating car" method. In this method, a probe vehicle is driven at an average speed along the evaluation route, allowing vehicular speed to be dictated by the platoon speed and within posted speed limit. Key findings are as follows:

- In general, the travel time and delay studies showed travel time improvements on all directions of all 49 routes under each signal timing pattern – AM, Midday, PM, Overnight and Weekend.
- The average travel time reduction, over all corridors was 1 to 1 ½ minutes in the AM, Midday and Weekend peak periods, and 2 minutes during the PM peak period. (Travel times were not collected during the Overnight signal timing pattern). The average length of all the corridors studied was 1.6 miles with a standard deviation of 0.6 miles.

- Some routes, such Pennsylvania Avenue and New York Avenue showed an increase in travel time, usually associated with the off-peak direction of travel (outbound in the AM, inbound in the PM), but not in all cases. This was a consequence of the natural optimization of key corridors, of which these two routes were considered lower priority, and was expected.
- Travel times shown an increase on southbound Connecticut Avenue, which is the critical direction (inbound) during the AM peak hour. However, as noted previously, this data was collected prior to a change to optimize the signal phasing at Connecticut and Florida Avenue, NW, which resulted in an overall improvement to AM peak period Connecticut Avenue travel times.
- In addition to travel times, the frequency of stopping along a corridor was compared between "Before" and "After" conditions for a sample set of 15 routes. Overall, the frequency of stopping decreased by 14% over all signal timing patterns. Specifically, the frequency of stopping was reduced (i.e. improved) by 6% in the AM, 34% in the Midday, 12% in the PM, and 4% in the weekend. Along some routes, such as Pennsylvania Avenue and New York Avenue, where were considered a lower priority in terms of progression of traffic, the frequency of stopping increased. This correlates with the increase in travel times also measured along these same routes.
- The total travel time savings, aggregated over the 49 routes, in each of the peak hours ranges from 30 minutes and 1 ½ hours. This finding is illustrated in **Figure ES-4**. Some explanation is necessary to understand this measure. Consider this hypothetical example, which is based on data the collected from the 49 routes. "Before" the signal timings were optimized, if you drove each of these 60 corridors in the peak 60-minutes of the AM rush hour, it would take you 7 hours, or 7 days (drive one hour each day) to complete all of your trips. "After" the signal timings were optimized, if you drove these same 60 corridors during the same time periods, it would take you a less than 6 hours (or less than 6 days)! Similarly, if you drove these same corridors in the most-congested portion of the Midday peak 60-minutes (around lunch time), the "Before" trips would take over 6 hours whereas the "After" trips would take just over 5 hours. And finally, for the peak 60-minutes of the PM rush hour, the "Before" trips would take almost 8 ½ hours whereas the "After" trips would take 6 hours and 50 minutes!

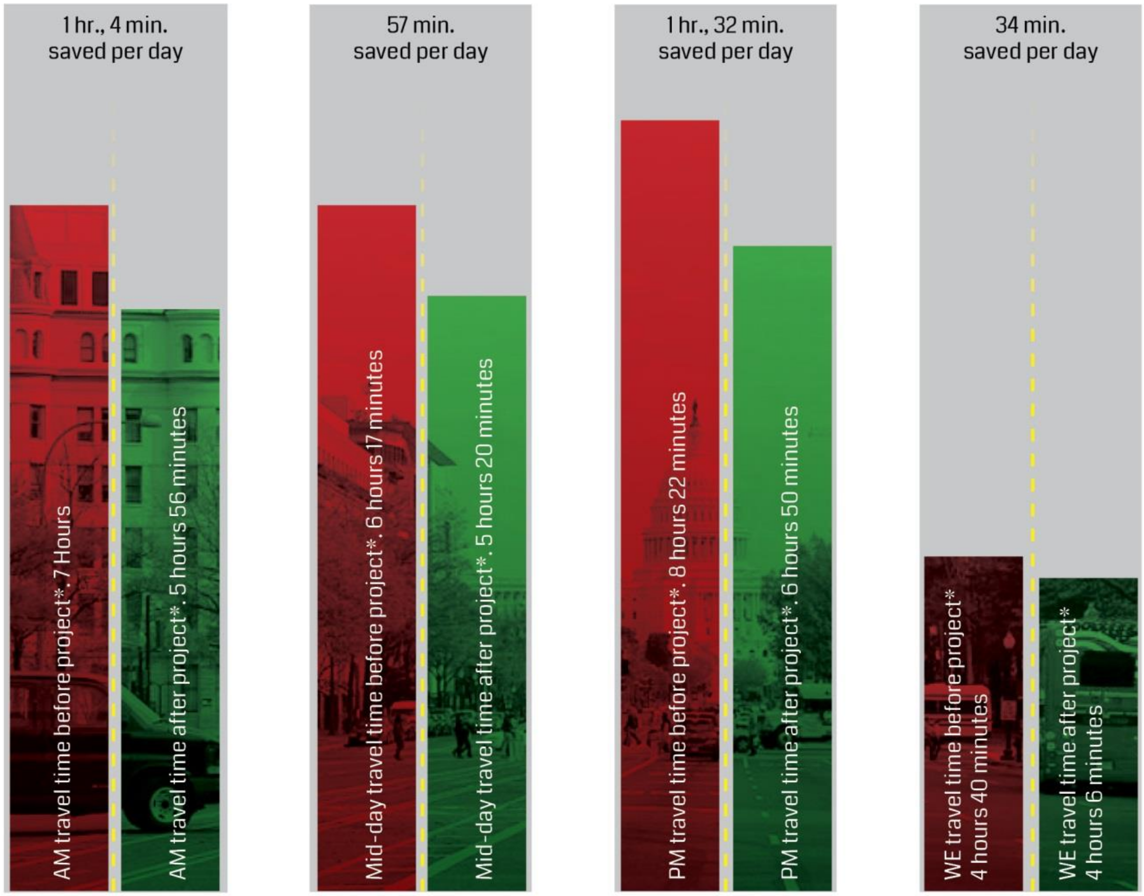

Figure ES-4: Cumulative Travel Time Comparison of Vehicle Travel Time over 49 Routes

Figures **ES-5** through **ES-8** illustrate the travel time improvements by corridor for the AM, Midday, PM and Saturday peak periods, respectively.

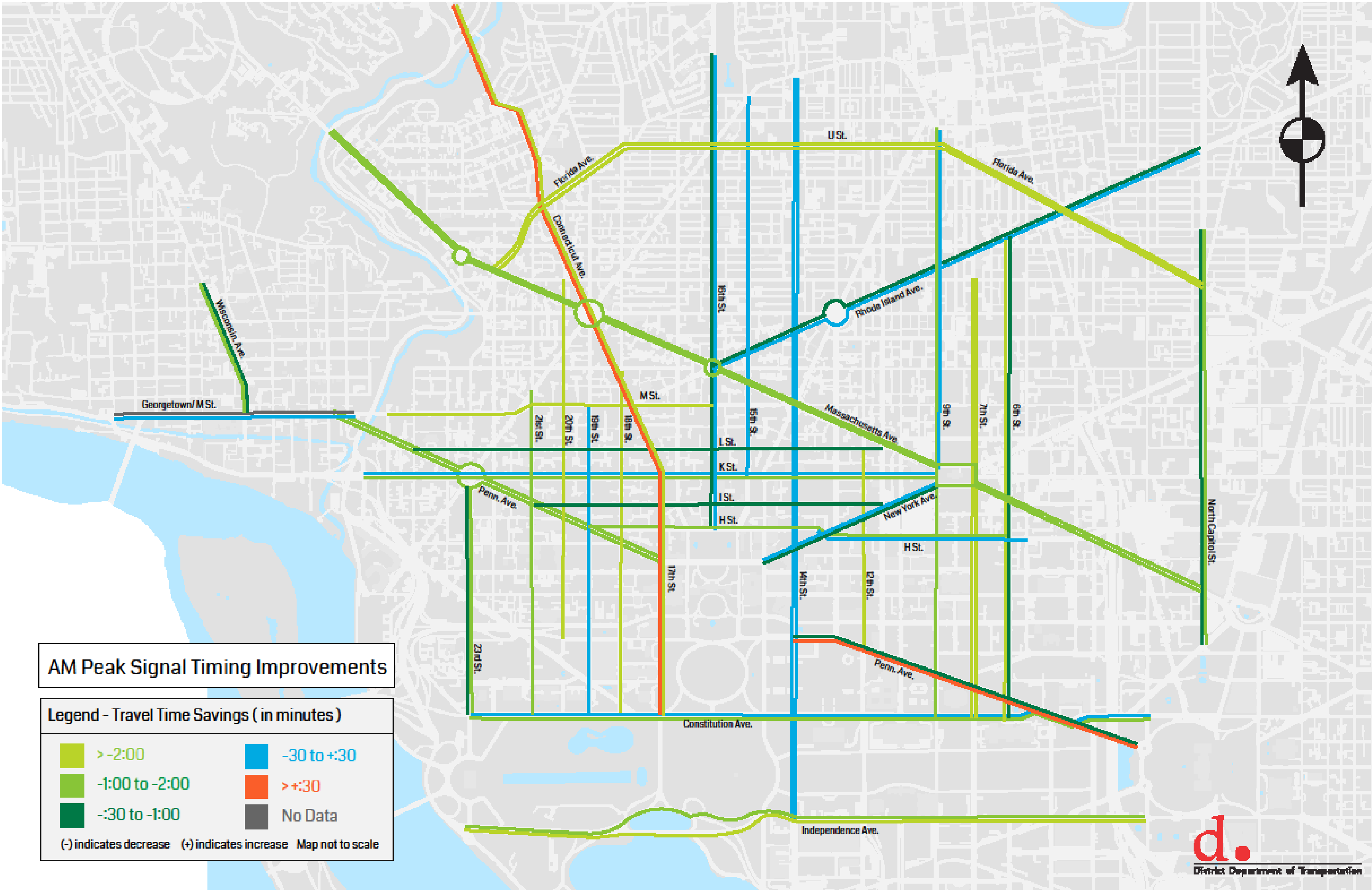

Figure ES-5: AM Peak Hour Travel Time Improvements by Corridor

Note: SB Conn. Ave. travel time was reduced compared to "before" conditions by a signal phase optimization at Florida Avenue after this data was collected

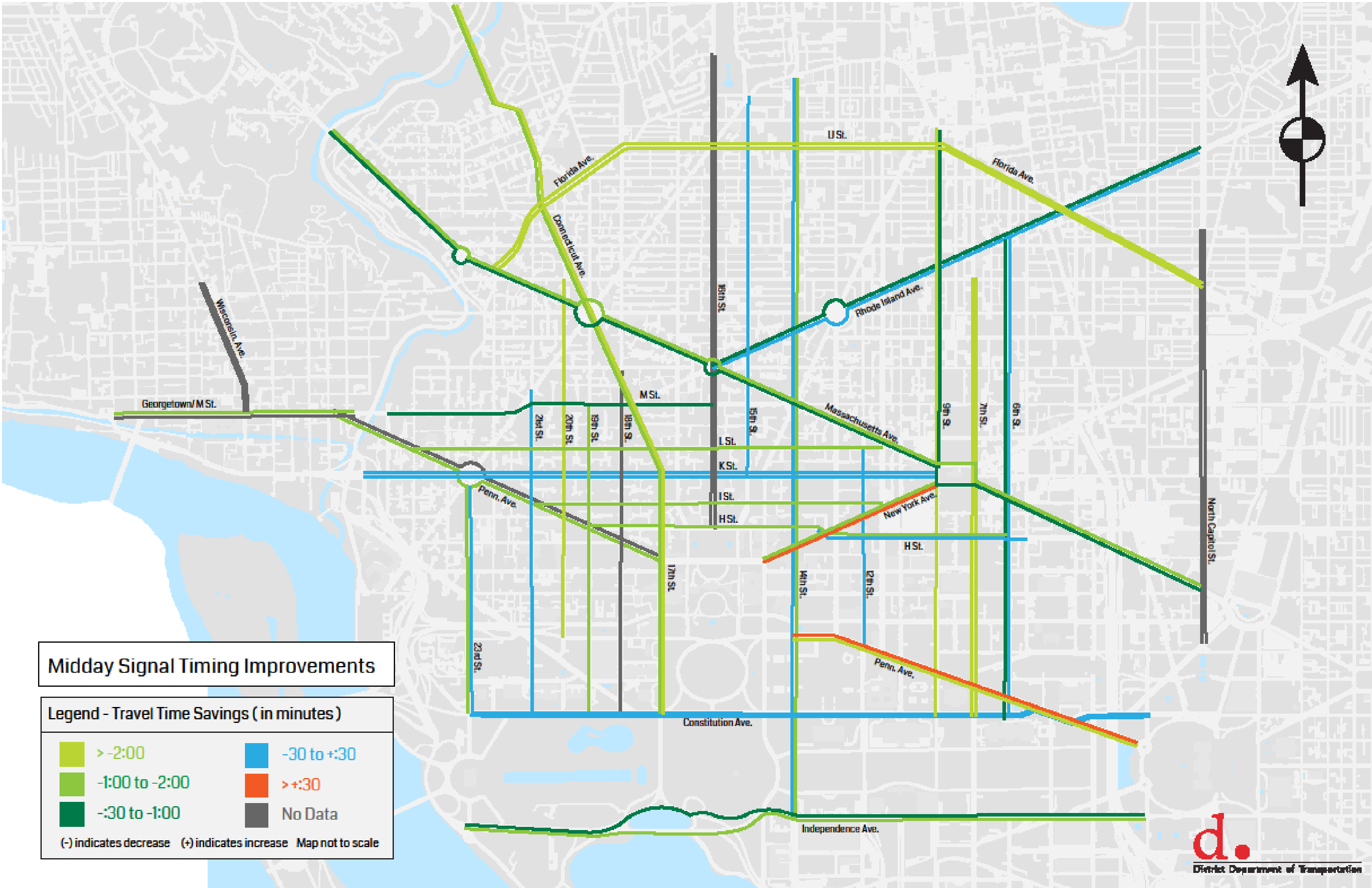

Figure ES-6: Midday Peak Hour Travel Time Improvements by Corridor

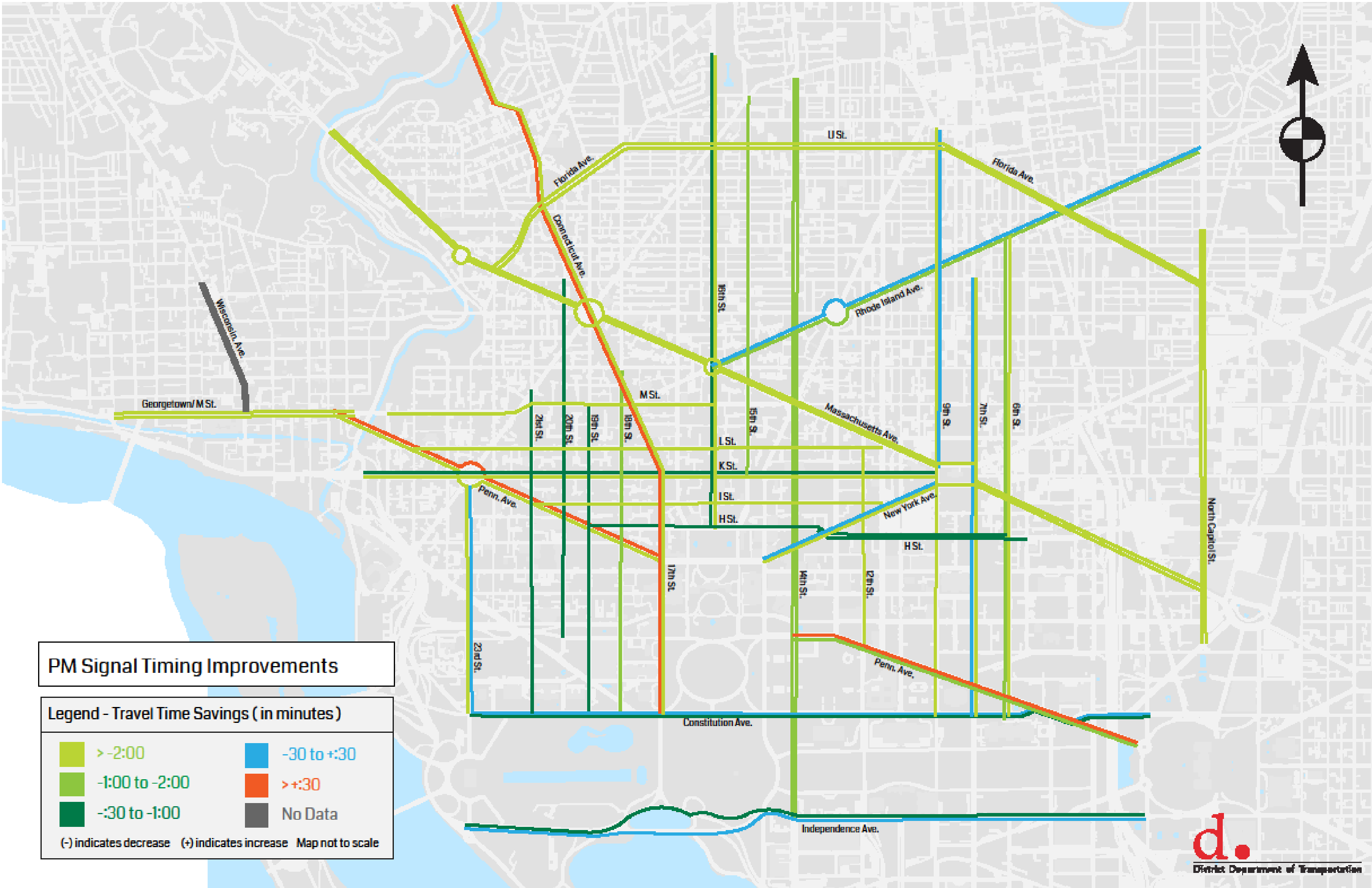

Figure ES-7: PM Peak Hour Travel Time Improvements by Corridor

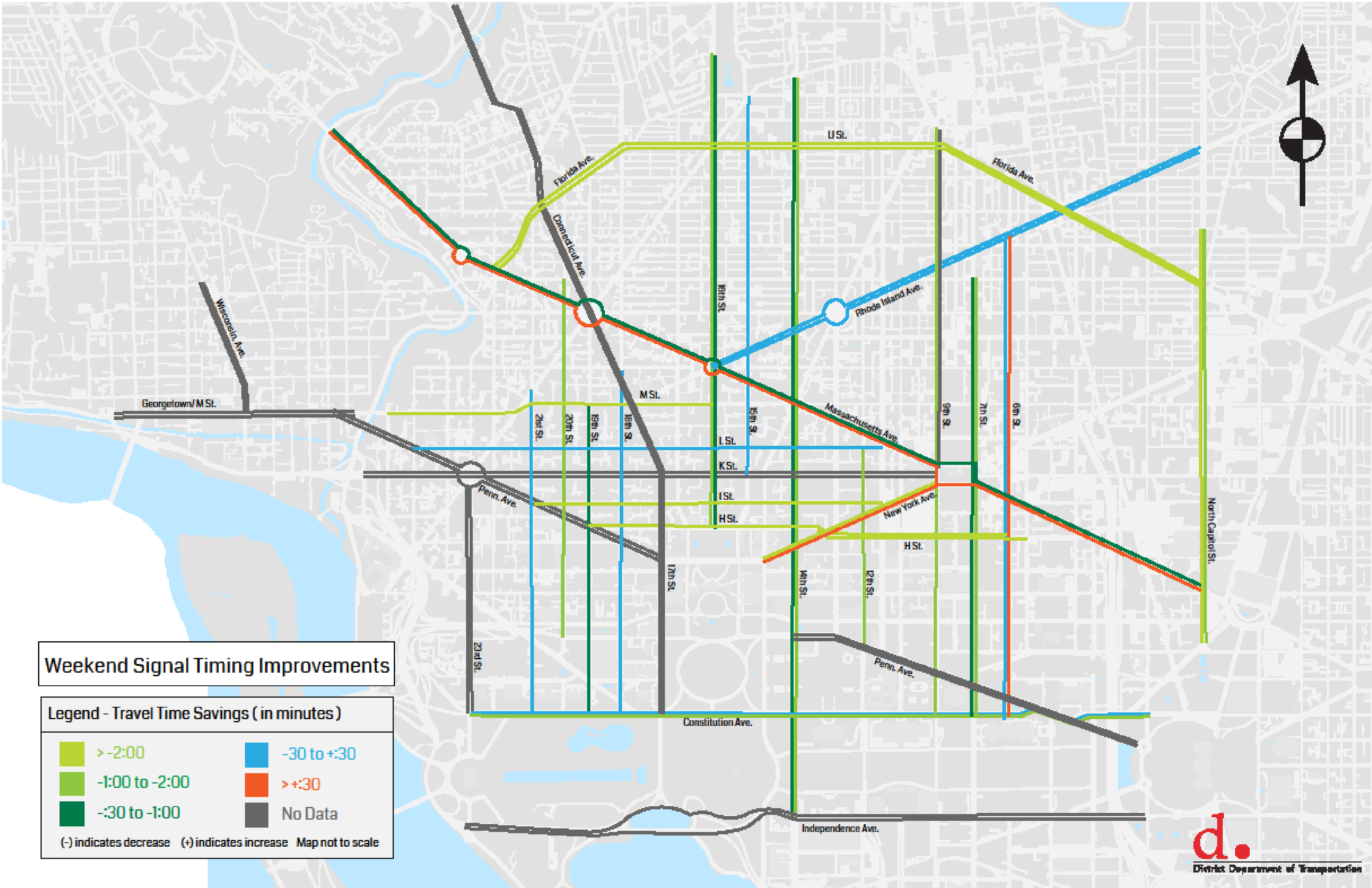

Figure ES-8: Saturday Peak Hour Travel Time Improvements by Corridor

Bus Travel Time Improvements

Improving bus running times and reducing bus delays was one of the goals of the optimization project. WMATA Metro Bus vehicles are equipped with Automatic Vehicle Locators (AVLs) which allow bus locations to be tracked and recorded, and bus delays and running times evaluated. Using this data, bus route travel times within the study area "before" and "after" the signal timing optimization were compared to determine if the project goal of improving bus running times and reducing bus delays was met. Bus travel time was analyzed for the weekday AM, Midday and PM peak periods for forty (40) routes (20 route numbers x 2 directions) with a total average weekday ridership of nearly 90,000 person-trips per day.

The overall Downtown Core bus system experienced significant improvements in travel times throughout the day. AM, Midday and PM Peak bus travel times have improved by average of 4% to 7% across the Downtown Core with an average reduction in absolute travel time over one (1) minute. Changes in individual bus route travel times range from a 7% increase to a 22% decrease. The largest increase in travel time was just under two (2) minutes while the largest decrease was just under ten (10) minutes. The analysis also showed that peak period, peak direction travel times improved more than peak period opposite-direction travel times. In some cases, similar to vehicular experiences, transit line travel times did increase, but they were in the minority in terms of frequency of occurrence and magnitude.

The signal timing optimization reduced travel time on Metro buses, resulting in:

- 359 person-hours of delay reduction in the AM peak hour,
- 185 person-hours of delay reduction in the Midday peak hour,
- 718 person-hours of delay reduction in in the PM hour.
- A daily savings of 1,262 person-hours.
- An annual savings of over 315,000 person-hours.
- The total travel time savings, aggregated over the 40 bus lines, in each of the peak hours ranges from 20 minutes and nearly 1 hour. This finding is illustrated in **Figure ES-9**. Similar to the vehicular total travel time saving mentioned previously, some explanation is necessary to understand this measure. Again, consider the following hypothetical example, "Before" the signal timings were optimized, if you rode each of these 40 lines on a bus in the peak 60-minutes of the AM rush hour, it would take you 10 ½ hours, or 10 ½ days (ride one hour each day) to complete all of your trips. "After" the signal timings were optimized, if you rode these same 40 lines during the same time periods, it would take you just over 10 hours. Similarly, if you rode these same lines in the most-congested portion of the Midday peak 60-minutes (around lunch time), the "Before" trips would take over 10 hours whereas the "After" trips would take just under 10 hours. And finally, for the peak 60-minutes of the PM rush hour, the "Before" trips would take 13 hours whereas the "After" trips would take just over 12 hours!

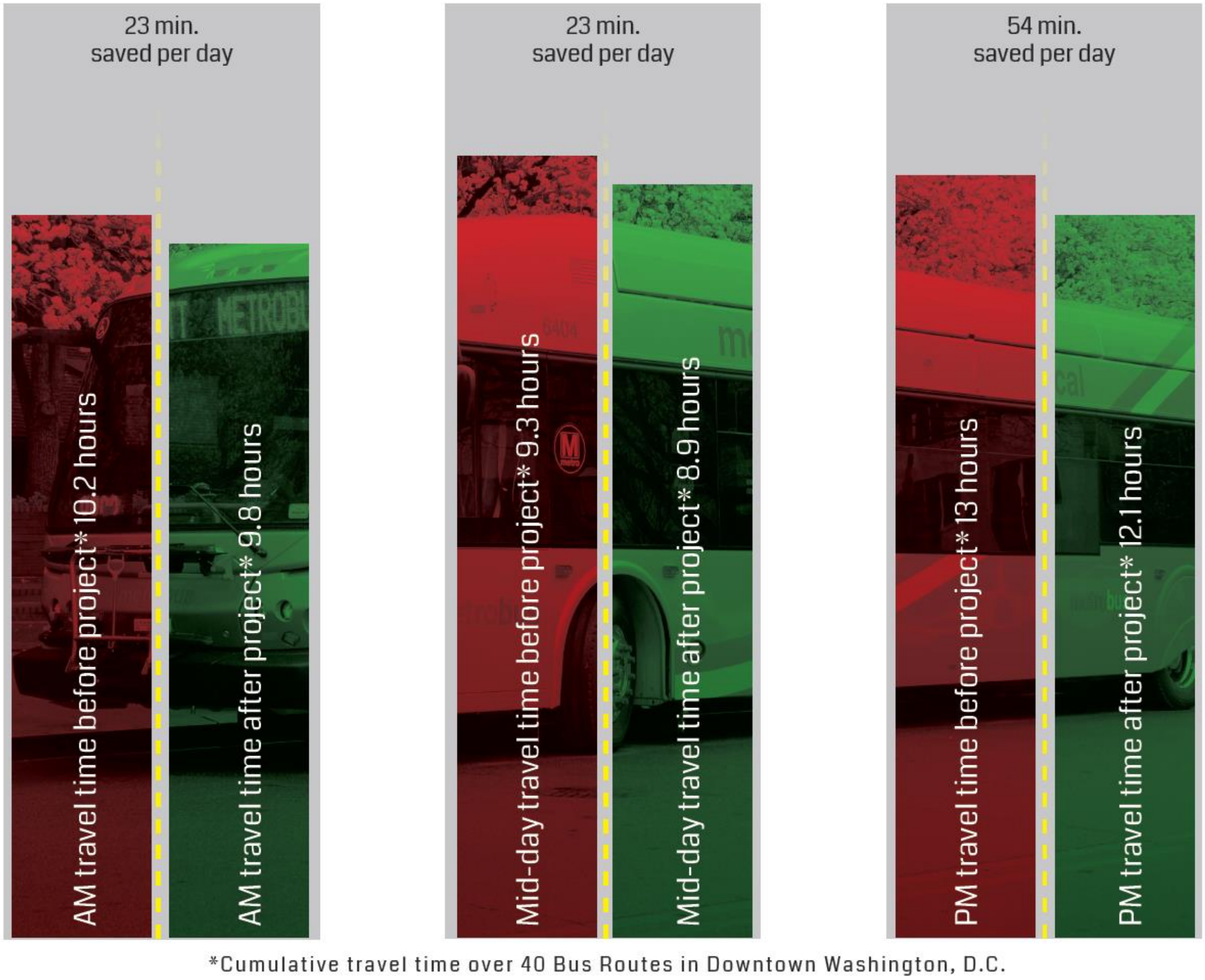

Figure ES-9: Cumulative Travel Time Comparison of Bus Travel Time over 40 Bus Lines

Intersection Level of Service and Delay Improvements

The Synchro^{TM} software models were used to evaluate Level of Service (LOS) and overall intersection delay changes between the "before" and "after" optimization conditions. In general, the intersection LOS did not change between "before" and "after" signal timings, as is expected. However, overall intersection delays did change, and provides a high-level view of the project benefits. The major findings are:

- Delays significantly decreased at 33% of the intersections over all peak periods. Significance is defined as more than 3 seconds decrease in overall intersection delay.
- Delay significantly increased at 11% of the intersections. Significance is defined as more than 3 seconds increase in overall intersection delay. Less than 1% of the intersections that experienced a significant increase in delay were operating at LOS D, E or F. A majority (99%) of the significant delay increases were at LOS A, B or C intersection, and were a natural

consequence requirement of cycle length increases along an entire corridor. It should be noted that while delays increased slightly at individual intersections, the overall corridor travel times were reduced significantly as demonstrated in the previous section.
- The changes in delay at the remaining 56% of intersections were insignificant (+/-3 seconds delay change).

Pedestrian Improvements

Making DC traffic signals safer and friendlier for pedestrians was one of the goals of the optimization project. This goal was met by providing appropriate and sufficient pedestrian clearance (Flashing Don't Walk) intervals, adding All Red intervals, and changing pedestrian traffic signal operations to conform with the 2009 Federal Highway Administration (FHWA) *Manual on Uniform Traffic Control Devices* (MUTCD). The following were accomplished:

- Flashing Don't Walk (FDW) intervals were re-calculated based on a slower pedestrian walking speed of 3.5 feet per second to provide pedestrians more time to cross the street. FDW intervals increased or remained the same at 82% (1,342) of the crosswalks and decreased at 18% (290) of the crosswalks. The locations where FDW times decreased had inappropriately high values (meaning pedestrians were be prohibited from entering the intersection before necessary to require such a prohibition), whereas the locations where FDW times increased had insufficient time for pedestrians to cross prior to the traffic signal optimization. In both cases, the re-calculated values are fully compliant with the FHWA MUTCD.
- All Red intervals were added at 42 intersections. Previously the pedestrian walk indications would start immediately upon termination of the conflicting approach's yellow indication. Adding All Red Intervals improved pedestrian safety by introducing a factor of safety into the crossing time.
- Flashing Walks at 217 intersections were changed to solid Walks in compliance with the MUTCD, which notes a uniform display is necessary for traffic control devices in general to be effective.

Cyclist Improvements

Bikes are one of the fastest growing transportation modes across the country and in the District in particular. Between 2011 and 2012, cyclist traffic in DC increased by nearly 21% to over 7,000 trips per day. With the continued success of the Capital Bikeshare program, the ongoing installation of dedicated cycle facilities, and increased awareness as a result of various programs including Towards ZERO Deaths DC, these numbers have continued to grow.

While cyclists often use the same traffic signal equipment as passenger vehicles, they have very different characteristics which must be accounted for when performing a Traffic Signal Optimization project. One of the key differences between passenger vehicles and cyclists is travel speed. Passenger vehicle travel speed is fairly consistent and is generally at or somewhat above the 25 mph speed limit in the Downtown core. Conversely, cyclist speed is much more variable depending on the characteristics of the rider, the slope of the road and the purpose of their trip (e.g. a courier would be expected to travel much faster than someone out for a sightseeing ride). As a result of this difference in speeds, traffic signal timings designed for 25 mph that provide a smooth ride for motorized vehicles may be disruptive or cause excessive stops for cyclists.

In coordination with DDOT bicycle planners, signal timing engineers surveyed bicycle travel patterns during the AM, Midday and PM peak periods on bicycles and in passenger vehicles at low speed and made numerous fine tuning adjustments to provide improved progression for cyclists. The bicycle travel time and stops before and after these adjustments for Pennsylvania Avenue are shown in **Table 71.**

Table ES-1: Pennsylvania Avenue Cycle Track Travel Time and Stops Before and After Fine Tuning

	Before		After	
	Travel Time	Stops	Travel Time	Stops
AM Eastbound	7:30	5	6:20	5
AM Westbound	8:30	7	7:30	3
MD Eastbound	8:10	8	7:20	5
MD Westbound	8:20	7	8:10	6
PM Eastbound	10:30	8	10:10	7
PM Westbound	7:45	7	8:10	5

While the highly variable characteristics of cyclists pose a challenge to the conventional methods of traffic signal optimization, DDOT was able to leverage their extensive signal timing expertise, internal bicycle planning resources and input from the active DC cyclist community to improve operations for cyclists while balancing the needs of all users including pedestrians, transit vehicles and vehicular traffic.

Benefit-Cost Analysis

The Benefit-Cost analysis revealed that the signal timing optimization benefits outweighed the costs by a factor of 45:1 in the first year. The total annual benefit of the Downtown signal timing optimization is estimated at $96 Million per year, or just under $400,000 per day in terms of increased productivity through less time wasted in traffic, savings due to less fuel consumed, and savings due to the positive environmental impact with reduced emissions. With a total project cost of $2 Million, this benefit represents a payback period of less than 6 days.

The analysis shows that the Downtown signal timing optimization project reduced vehicular carbon emissions by over 167,000 kg per year, and fuel consumption by over 2.3 million gallons per year, meeting the project's goal to reduce vehicular emissions.

Recommendations

While the signal timing optimization has resulted in impressive benefits, there is still room for enhancement which signal timing cannot address. This project identified additional improvements in lane configurations, channelization, signal phasing, pavement markings, signing, and curb-side management which can further improve operations to provide the best possible service to all modes of transportation.

I. Introduction

The District Department of Transportation (DDOT) completed the optimization of traffic signal timing in Downtown DC, improving traffic flow at over 650 intersections in May 2015. The project was a necessity due to the changes in travel patterns and volumes that have emerged from regional growth and development activities; to coordinate newly installed traffic signals; and to reduce conflicts between different modes of travel. The goals of the project were to make DC traffic signals safer and friendlier for pedestrians; improve bus running times and reduce bus delays; improve overall traffic flow; and reduce vehicular traffic emissions.

Traffic signal retiming improves traffic flow along a corridor by timing the traffic signals so that groups of vehicles (referred to as platoons) can travel through the series of signals with minimal or no stopping. Traffic signal optimization improves safety since vehicles stop less often, which reduces the probability for rear-end type crashes, reduces vehicle emissions which lowers our carbon footprint, and reduces our travel costs by reducing the amount of time stopped at red lights, saving us money at the gas station.

This report summarizes the process, methodology, and presents the results of the “Before” and “After” analyses of the Downtown traffic signal optimization. This project included at the optimization of 589 traffic signal controllers, consisting of over 650 different intersections. Note that the intersection versus controller count is different, since at times 1 signal controller controls multiple intersections, such as at DuPont Circle which has 1 controller for all 10 intersections in the circle. The project area included all of Downtown, from 23rd Street in the west, to North Capitol Street in the east, and U Street / Florida Avenue in the north, and to I-395 in the south; the project also included M Street and Wisconsin Avenue in Georgetown. A map of the traffic signals in the project area is shown in **Figure 1**.

II. Signal Timing Optimization Process

The project consisted of two phases of work. Phase 1 was generally behind-the-scenes work in preparation for the optimization, which included traffic signal controller software updates, improving pedestrian and vehicle safety by updating pedestrian crossing times and adding “All Red” intervals, and identifying other opportunities for safety and operational improvements. Phase 2 work is what was most observable by the public and culminated in implementing optimized signal timing.

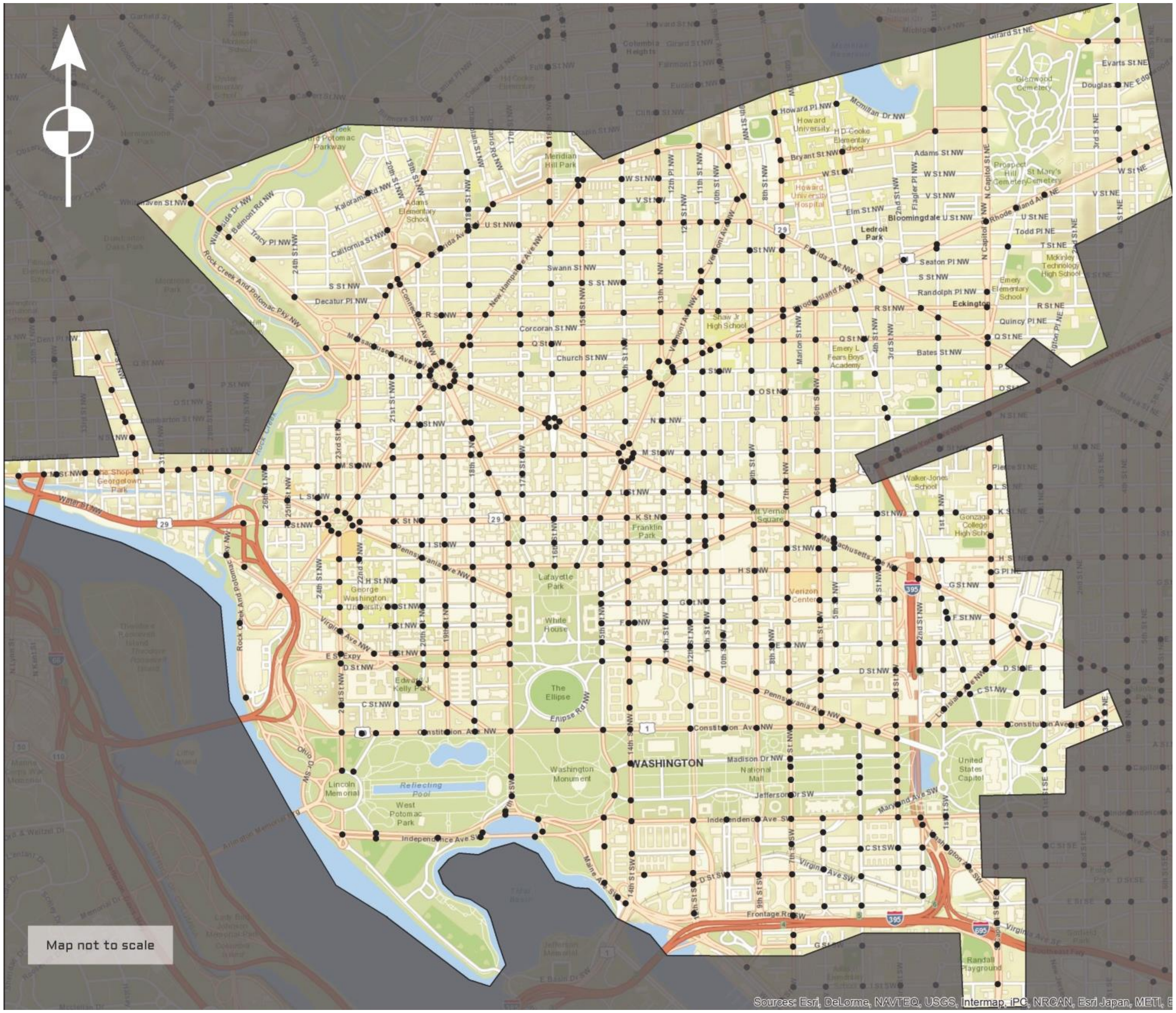

Figure 1: Map of Traffic Signals in the Downtown Project Area

A. Phase 1 – Basic Signal Timings and Operations & Traffic Signal Controller Software Update

The work in Phase 1 was a critical first step in developing a solid foundation to enable the more extensive signal timing changes in Phase 2. These small, but largely unrecognized changes included upgrading the vintage 1980s traffic signal controller software to the latest version; adjusting the duration of the yellow clearance time, and adding or increasing “All Red” time (the duration that all signals are Red between conflicting movements); adjusting the pedestrian Flashing Don’t Walk (countdown) intervals to meet recently-changed national standards; modifying intersection phase orders to improve safety, standardizing all controller settings; replacing and fixing malfunctioning traffic signal communication equipment to enable remote upload and download of signal timing changes; and replacing malfunctioning traffic signal controllers.

The key feature of the new traffic signal controller computer software is the simplification of the tedious process of designing new traffic signal timings, such as were developed under Phase 2 of this massive project, and for small changes that are necessary on a day-to-day basis as a result of traffic incidents, special events, new construction developments opening or the addition of new signals onto DDOT's roadways. With the old 1980's controller software, it would take an engineer up to one full day to develop new signal timing plans for one intersection. Now that this project has been completed, the same task that used to take upwards of one day, now takes just a few hours.

The Yellow, All Red, and Pedestrian Flashing Don’t Walk intervals are safety-critical timings that serve to facilitate the safe transfer of right-of-way between conflicting directions or between different modes of travel. As part of this project, DDOT developed standards for the calculation of these intervals based on the 2009 Federal Highway Administration (FHWA) *Manual on Uniform Traffic Control Devices* (MUTCD) and Institute of Transportation Engineers’ (ITE) best practices. Utilizing DDOT’s new standards, a software program was developed to automate and standardize the process, eliminate calculation errors, and provide a record of results. As a result of this effort, the following were accomplished:

- All Red intervals were added at 42 intersections (previously the green indications would start immediately upon termination of the conflicting approach’s yellow indication),
- Flashing Walks at 217 intersections were changed to solid Walks in compliance with the MUTCD,
- Yellow and all-red intervals were calculated for each phase of all 650 intersections based on approach speed and intersection width, respectively, and
- Flashing Don’t Walk intervals were calculated based on a slower pedestrian walking speed of 3.5 feet per second to provide pedestrians more time to cross the street.

Intersection phase orders were evaluated, and changes were made to improve safety. Specifically, left turn “yellow traps” were eliminated by changing the order of left turn phase sequences, yellow arrows were added to intersections with right turn overlaps to provide a right-of-way transfer between vehicular phases with green arrows, and pedestrian phases (i.e. the yellow arrow warns right turning vehicular traffic that they no longer have the exclusive right-of-way before the Walk interval for pedestrian traffic begins).

The changes made in Phase 1 of the project were critical for creating a foundation for Phase 2, as well as to meet one of the primary project goals of making DC traffic signals safer and friendlier for pedestrians.

Phase 1 began in March 2012 and was completed in April 2015.

B. Phase 2 – Traffic Signal Timing Optimization

The Phase 2 work included the construction of a model of the traffic signal network, and then utilized the model to develop and evaluate traffic signal timing alternatives in a simulated setting that would help in the design of the optimized signal timings. The traffic signal timing optimization process included four basic steps:

1. Construct a model of the traffic signal network for each of typical time periods of travel: AM peak, Midday Peak, PM peak, Weekend, and Late Evening/ Overnight.
2. Evaluate multiple traffic signal timing alternatives with the model and select the preferred alternative,
3. Develop traffic signal timing charts, and
4. Implement and fine-tune the optimized traffic signal timings

1. Model Construction

The Synchro™ and SimTraffic™ software models were used to construct the traffic signal network. Synchro™ is a macroscopic and deterministic traffic signal timing and analysis software program. SimTraffic™ is a microscopic simulation and animation software program. Five models were constructed; one model was created for each signal timing pattern: AM, Midday, PM, Weekend, and Late Evening / Overnight. To develop the signal timing model in Synchro, a significant amount of data was collected to construct the model:

- Existing traffic signal timing and phasing were coded into the models;
- Intersection vehicle and pedestrian traffic counts for the AM, Midday, PM, Weekend, and Late Evening / Overnight time periods;
- Geometric inventory (e.g. number of lanes, posted speed limits, parking restrictions), transit operations (e.g. bus stop locations, frequencies and routes), and parking inventory (locations and times curb side parking is allowed);
- Field observations of existing conditions; and
- Travel time and intersection delay studies to establish the "before" corridor travel characteristics.

2. Signal Timing Optimization & Design

a) Methodology

An assessment of the critical signal timing features of network grouping and cycle length is typically performed using Synchro. However, for the Downtown network, engineers determined that the model was not fully sufficient to assess these features due to the complicated and complex Washington D.C. geometric and traffic signal control network. With these in mind, the approach was modified to use a combination of qualitative and quantitative (i.e. Synchro™ and SimTraffic™ software models) assessments.

The qualitative assessment included operational review by a 15-person team of signal timing engineers and technicians from DDOT staff and supplemented by consultants on 30 key corridors, consisting of approximately 400-signals in the 650-signal network. These corridors were observed by driving the corridor multiple times during the 5 typical time periods of travel (AM, Midday, PM, Weekend, and Overnight) with the aim of:

1) Assessing locations to break coordination into different signal groupings.
2) Assessing the suitability of the existing cycle length, specifically regarding delays, cycle failures, number / frequency of stops, stacking of queues, starvation (green signal but traffic is held at an upstream signal), spillovers, pedestrian-vehicle interactions, and midblock activity (left turns, construction, parking, loading, etc.).

Since such heavy weight was placed on the qualitative assessment made by these persons, it is important to note the qualifications of the persons responsible. The three primary signal timings patterns were divided between three lead engineers: one lead engineer responsible for the AM peak (6 AM to 10 AM), one lead engineer responsible for the Midday and Weekend peaks (10 AM to 2 PM on weekdays; and Saturdays and Sundays), and one lead engineer for the PM peak (2 PM to 8 PM). The qualifications of these individuals include: each lead was involved in the day-to-day project design since the inception of the project in 2011 through the implementation stage in 2015, each lead was intimately familiar with traffic signal operations in the District; each lead is professionally certified in traffic engineering or signal timing; each lead has 18 or more years of signal timing experience; and each lead had designed and implemented optimized signal timings at over 2,000 intersections outside of Washington, D.C.

b) Signal Grouping

The first step in signal timing optimization is to separate the network into groups of signals that would operate in coordination. Each zone or partition would be a group of coordinated signals with harmonic cycle lengths. For the Downtown network, a harmonic cycle length must be used for the entire Downtown network. The reason is that the signal spacing is too close, and traffic volumes too high to logically separate groups of signals. There were some exceptions to this, but they were limited to about a dozen intersections.

c) Cycle Length – A Balancing Act

Prior to starting this project, the existing traffic signal cycle lengths in the Downtown area, with some exceptions, were 100 seconds (1 minute, 40 seconds). The analyses, both qualitative and quantitative, resulted in recommending a modest 10-second cycle length increase for the AM and PM peak periods, and retaining the existing cycle length for the Midday / Weekend and Late Evening / Overnight peak periods.

The qualitative assessment, which was the outcome of the 15-person engineering team performing extensive field observations on each corridor, resulted in a recommendation to either retain the existing 100 second cycle length or increase the cycle length by 10 or 20 seconds. The process of achieving the delicate balance between increasing the cycle length enough to address congestion and delays issues, versus keeping the cycle length low enough for mobility is described below.

(1) Cycle Length - Qualitative Assessment

A review of the bottleneck locations in the Downtown area showed that many are constrained under the existing 100 second cycle length and the flexibility for split (split = amount of green + yellow + red time for an approach) changes to mitigate the observed problems at the bottleneck intersections / choke points would be limited by either 1) the number of phases and minimum times, and/or 2) pedestrian or clearance times. Observations indicated that there were some "fixable" problems at bottleneck intersections / choke points unrelated to the 100-second cycle length limitation; these appeared to be related to offsets and splits. However, a majority of the bottleneck locations were constrained by the existing cycle length, and therefore, the team recommended that the cycle length would need to increase to address congestion at the bottleneck locations. However, the team recommended that the cycle length increase must be kept to a minimum in order to:

1. **Minimize queue lengths in short blocks.** Short block spacing exacerbates problems with longer cycle lengths which result in longer queues that would stack through, and block downstream intersections.
2. **Minimize pedestrian waiting times** and maximize opportunities to cross; consistent with expectations in an urban / multimodal environment,
3. **Reduce Pedestrian-vehicle conflicts**. The rationale for a shorter cycle length for pedestrian-vehicle conflicts is only at intersections with both heavy pedestrian traffic, and heavy turning traffic. At these intersections, turning traffic cannot proceed during the green interval as pedestrians are blocking the path. Frequently, vehicles are only able to turn during the end of the green interval and during the yellow interval. This problem is exacerbated at locations where right turns (and left turns) are made from the through lane and turning vehicles block through traffic. The team recommended increasing the amount of solid Don't Walk interval that occurs over a one-hour period, which would allow more turning traffic to turn during the solid Don't Walk interval / yellow interval. This would, of course, occur at the end of the cycle, and the issue of through lanes being blocked would remain. Thus, the need for a shorter cycle length.
4. **Maximize Opportunities for Left-turning traffic and traffic accessing midblock driveways from shared lanes**. Typically, these movements block through-movement traffic as they are only able to turn at the start of yellow due to heavy traffic flow in the opposite direction. Providing more cycles (i.e. a shorter cycle length) results in a greater number of opportunities in one hour to turn during yellow and clear the approach.

During the AM and PM peak period, the team recommended a 110 second cycle length, which would provide the tradeoffs between the reasons to increase the cycle versus retaining the existing cycle length.

During the Midday and Weekend period, the team recommended retaining the existing or reducing the 100-second cycle length by 10-seconds. Reducing the cycle length was thought to provide a modest reduction in delays. However, maintaining the existing 100 second cycle length would provide some excess green capacity to help accommodate lane closures, blocked lanes due to deliveries, construction work, standing, busses and taxis, parking maneuvers, pedestrian/vehicle turning conflicts, etc. Due to the numerous instances of illegal blocking of lanes (above and beyond the reduction in number of lanes due to on-street parking), the 100-second cycle length option was selected. Furthermore, a quantitative analysis was not performed since and the team recommended that Synchro™ would not be sufficient to evaluate cycle length since the locations and frequencies of the lane blockages varied so much that it would be impossible to account for these blockages in the model.

During the Late Night / Overnight period, the team recommended retaining the existing 80-second cycle length. Traffic and pedestrian volumes are light during these time periods and there is not a need to provide long series of successive green lights along a corridor, which would require a cycle length increase. The goal was therefore to keep the cycle length as low as possible, but still retain coordination throughout the grid network for 95% of the signals. The 80-second cycle length was the lowest cycle that could accomplish this goal. Approximately 5% of the intersections are not able to operate at an 80-second cycle length due to the increases in times for the Walk, Flashing Don't Walk, Yellow and All-Red interval; these intersections operate at cycle lengths from 90 to 120 seconds.

(2) Cycle Length - Quantitative Assessment

A quantitative analysis was also performed in Synchro™ to evaluate the sufficiency of the AM and PM peak period 110-second cycle by comparing it to an optimized 100-second cycle scenario and an alternative operation of a 120-second cycle. A limited amount of SimTraffic™ animations / visualizations were also performed to support the results of the Synchro analyses.

The quantitative analysis compared network delays, stops and emissions under multiple scenarios. The quantitative analyses showed that an optimized 110-second cycle length for entire network would provide greater reductions in delays, result in fewer stops, and greater fuel savings and emissions savings compared to the re-optimized 100 second cycle length or an optimized 120 second cycle length.

d) Split & Offset Optimization

Once the cycle length was selected for each signal timing pattern, work on designing the individual intersection splits and offsets began. Synchro was initially used to develop splits and offsets for each intersection. Final splits and offsets were refined with manual calculations and based on engineering judgment. The signal timing optimization focused on progression based on posted speed limits, reducing delays and stops, minimizing queues, accommodating pedestrian and transit traffic, and improving travel times. The following different strategies were considered, but ultimately rejected:

1. Quarter Offset Strategy: this is not viable with diagonal roadways, circles and squares as it is dependent upon uniform and short block spacing.
2. Simultaneous Greens for all East-West routes, and then for all North-South routes: this is not viable due to disparity in volumes between adjacent routes of the same direction.
3. Uniform Daily Pattern: This strategy is to set one split and offset pattern and apply it for all times of the day, with slight modifications for different directional distributions. This seemed viable since many of the split times are dictated by pedestrians times, but was ultimately rejected since this strategy did not have enough flexibility to accommodate inbound versus outbound versus balance traffic demands.

The Priority Corridor strategy was selected and utilized to optimize splits and offsets to meet the competing demands of east-west, diagonal and north-south traffic flows. Each roadway was assigned a priority number based on its importance in the network regarding traffic volume carrying capacity. Only high volume roadways were assigned priority numbers. The roadway with the highest priority was optimized first, and its splits and offsets were “locked” so they could not be changed by subsequent offset optimizations of lower priority roadways. This process continued until the network was fully optimized. For priority No. 1 corridors that intersect, such as Massachusetts Avenue at L Street or 14th Street at Constitution Avenue, the splits and offsets were designed at the intersection point, and offsets worked backwards / away from the intersection point.

In general, the offsets were designed to progress a platoon of traffic down the corridor with as few stops as possible. However, along some corridors, a reverse offset strategy was utilized because of extreme oversaturation to move the queue from signal to signal. In general, the PM peak has more congestion inside of the District than the AM peak. The reason is that the traffic signals at the borders of the Downtown network meter the flow of commuter traffic inbound towards the District; in other words, the congestion is primarily on the freeways in Maryland and Virginia. However, in the PM peak, the commuter traffic is leaving the District. The following corridors were designed with reverse offset progression:

- Westbound Constitution Avenue from 15th to 23rd Street in the PM peak
- Southbound 14th Street from F Street to Constitution Avenue in the PM peak
- L Street from 16th to 13th Street in the PM peak
- Eye Street from Connecticut Avenue to 17th Street in the PM peak
- 17th Street from Independence Avenue to K Street in the AM peak
- Westbound Rhode Island Avenue approaching Florida Avenue in the AM peak
- Westbound M Street from Wisconsin Avenue to Key Bridge in the PM Peak

A simultaneous offset strategy was utilized on K Street, NW. Along K Street, travel conditions are highly variable due to buses stopping at every block, midblock and intersection left turns blocking the left lane. Furthermore, traffic volumes are relatively equal throughout the day. A simultaneous offset pattern ensures a more predictable experience on K Street by allowing both directions to progress through 2-3 signals without stopping – it results in fewer stops and less frustration. Also, if a vehicle gets stopped behind a bus or left turner for an entire cycle, the vehicle is able to proceed through 2-3 signals at the next cycle, as opposed to a normal Progressive Offset pattern, where once you get out of the progression, you have to stop multiple times until the progression "catches-up."

e) Time of Day / Day of Week Analysis

Traffic flow patterns throughout the Downtown were evaluated to determine the time of day schedule – the start and stop times for each of the new timing plans. The analysis was performed by evaluating day–of-week and time-of-day traffic volumes on high volume corridors throughout the Downtown area. **Figure 2, Figure 3,** and **Figure 4** illustrate the data analysis.

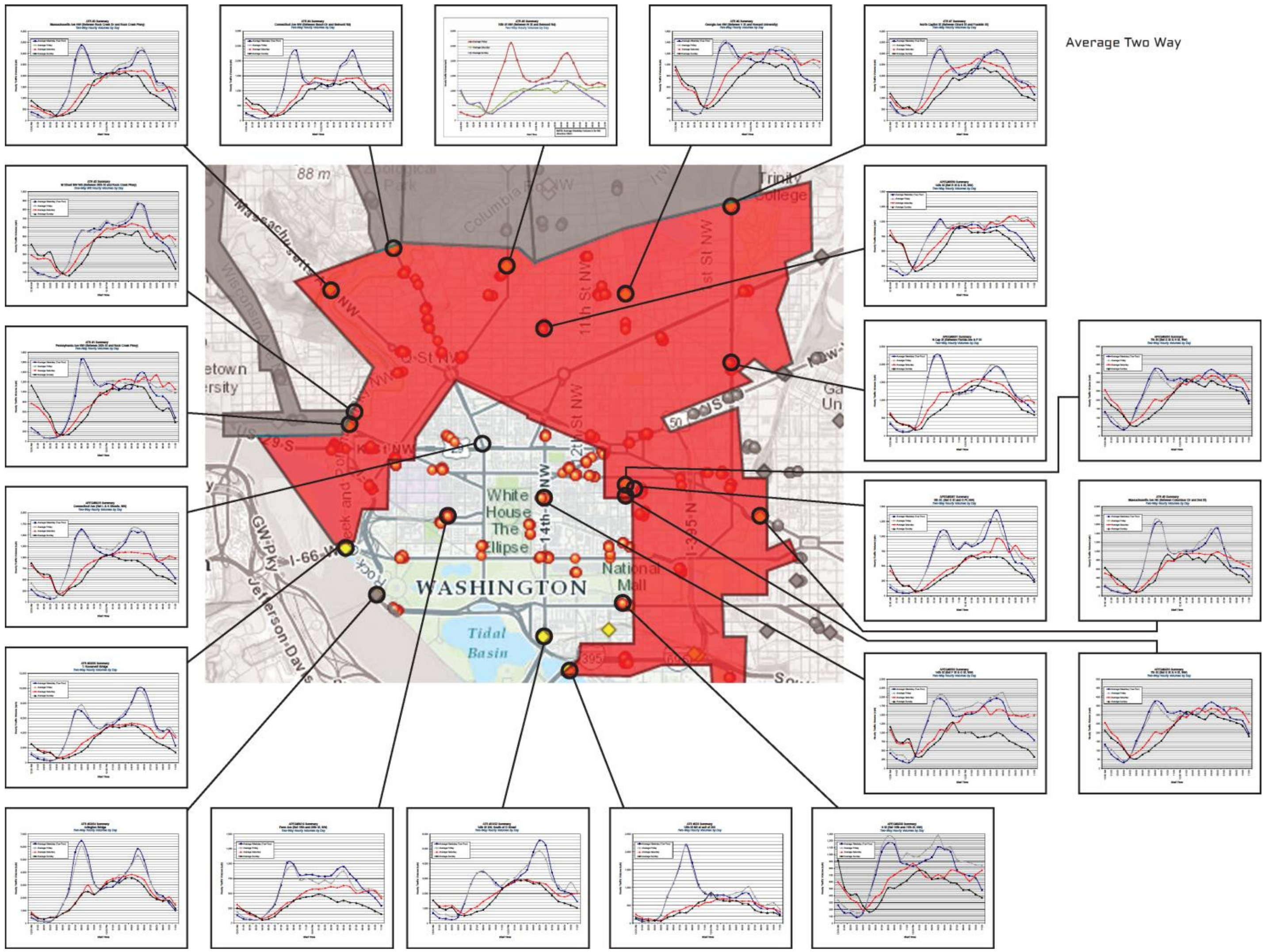

Figure 2: Weekly – Day of Week Traffic Volume Analysis

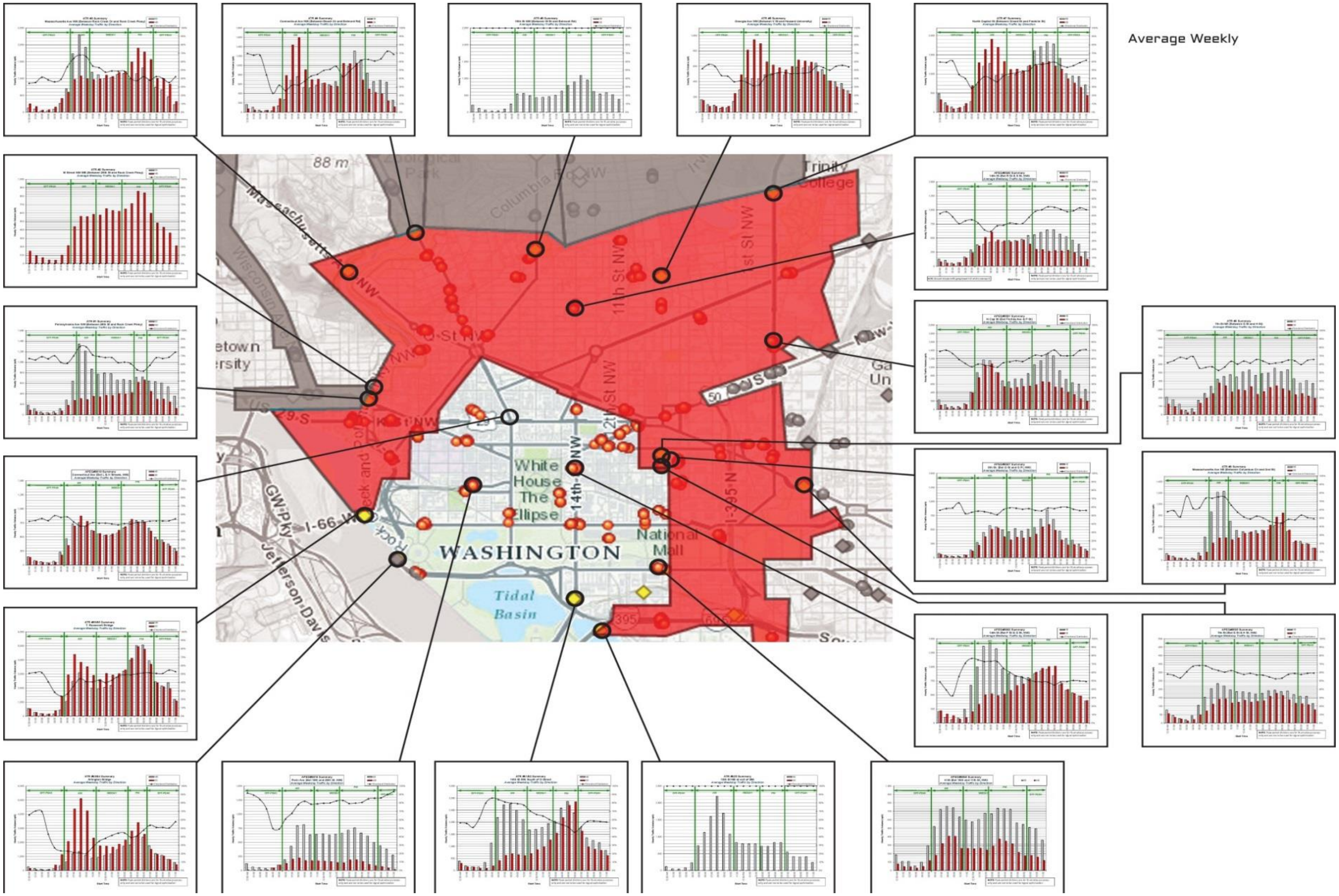

Figure 3: Weekday - Time of Day Traffic Volume Analysis

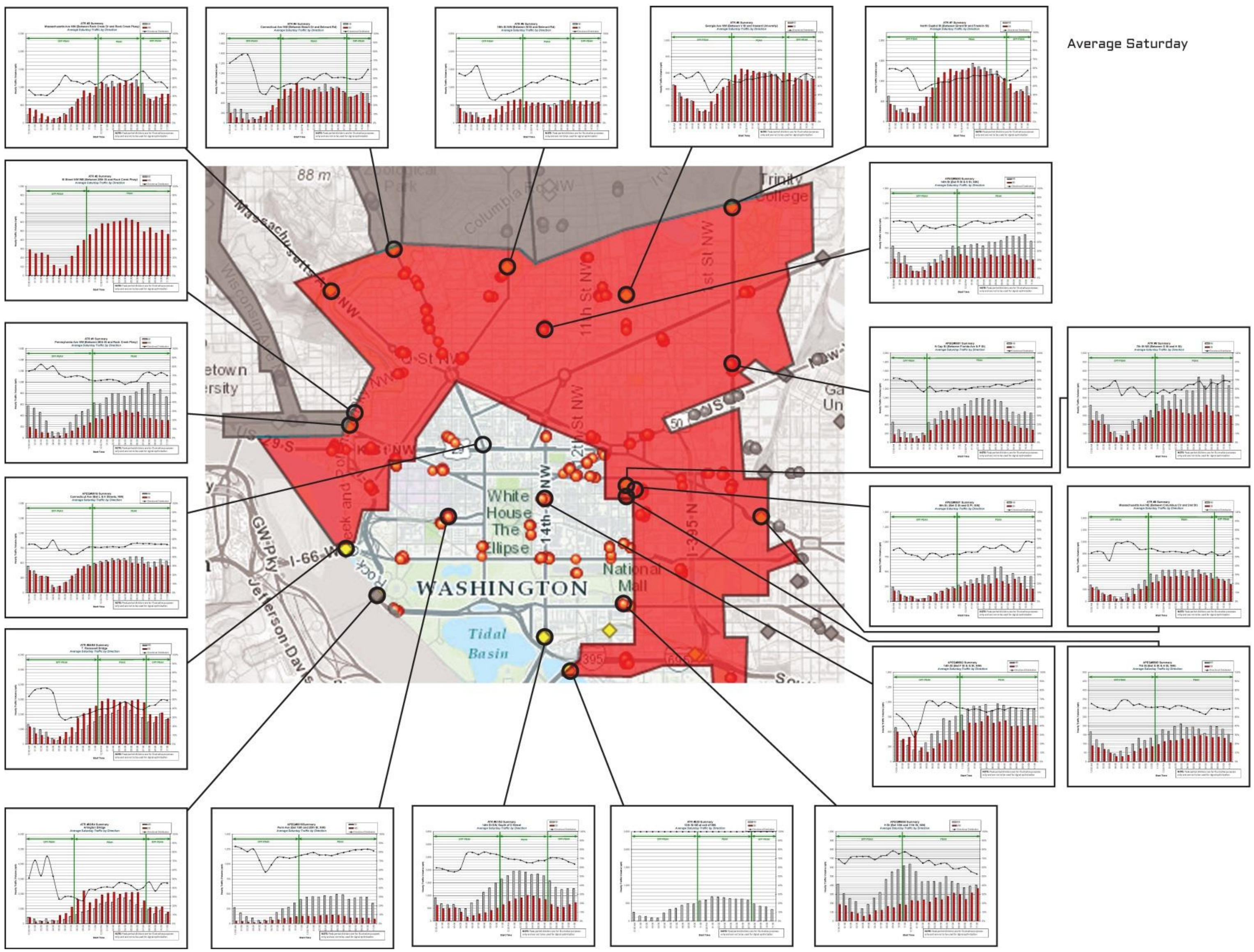

Figure 4: Saturday - Time of Day Traffic Volume Analysis

The time of day schedule tells the signal controllers when to change from one timing plan to another (e.g. from AM to Midday) and was optimized for the fluctuations in traffic throughout each day of the week. The optimized schedule is shown in the table below for the Downtown area. Note that the weekend schedules for Georgetown, U Street and the Verizon Center area (6th and 7th Streets area) are slightly different to accommodate late night activities along these corridors. As shown in **Table 1**, the AM pattern starts at 5 AM and transitions to the Midday pattern at 10 AM which continues until 2 PM; then the PM pattern starts and continues until 8 PM; At 8 PM the Midday pattern starts again and runs until Midnight; from Midnight until 5:00 AM the Overnight pattern runs.

Table 1: Time of Day Schedule

DAY OF WEEK	TIME	SIGNAL TIMING PATTERN
Mon. - Fri.	00:00 - 05:00	Pattern 1: Overnight
	05:00 - 10:00	Pattern 5: AM
	10:00 - 14:00	Pattern 4: Midday
	14:00 - 20:00	Pattern 6: PM
	20:00 - 00:00	Pattern 4: Midday
Sat	00:00 - 08:00	Pattern 1: Overnight
	08:00 - 00:00	Pattern 2: Weekend
Sun	00:00 - 08:00	Pattern 1: Overnight
	08:00 - 18:00	Pattern 2: Weekend
	18:00 - 00:00	Pattern 1: Overnight

3. Timing Chart

After finalizing the optimized models, the next step was to prepare optimized timing charts, called "Dial Sheets" in DDOT, by converting the optimized cycle lengths, splits, and offset times into 170-style force offs. An optimized dial sheet was prepared for each of the 589 controllers in the Downtown.

4. Implementation & Fine Tuning

Phase 2 began in parallel with Phase 1 and was completed in May 2015. During the 2 months preceding the field implementation DDOT tested and addressed all controller communication issues.

At this point in the process, although the signal timings were designed, and field communication malfunctions fixed, there was still a large effort required in order to: transfer the timing parameters from the Dial Sheet format into *QuicNet*, DDOT's electronic database for the computerized signal system server located at the Reeves Center; to download to each traffic signal controller; and to perform quality control to ensure that all data is entered and recorded correctly. The work needed be performed quickly, and immediately before "turn-on" of the optimized signal timing since, during the time the databases are being updated, the computerized signal system computer server and field traffic signal controller databases would not match.

Once the computerized signal system server database is populated with the optimized signal timing, staff "turned-on" the optimized signal timings by downloading the optimized signal timings from the computerized signal system server database to each traffic signal controller. This work was performed overnight from Friday through Saturday, April 24th and 25th. This work was scheduled for an overnight time period to minimize disruptions to traffic patterns and allow any unplanned malfunctions to be addressed

In signal timing, seconds matter. The difference between a successful and unsuccessful signal retiming project is often a matter of a few seconds. Great care had been taken to develop each signal timing parameter for each intersection. For a typical intersection, there are approximately 200 individual parameters that have been designed. Traffic flow is very sensitive to some of these parameters, in particular the split (amount of green time for each approach) and offset (the time-relationship between when adjacent signals turn green), and slight adjustments to these parameters are critical to the project's success. The fine-turning phase consisted of monitoring and adjusting these parameters to obtain the maximum benefit from the signal timing optimization. Fine-tuning was conducted for each signal timing pattern (AM, Midday, PM, Weekend, and Late Evening) throughout the week. The fine-tuning process consisted of driving each corridor within the network multiple times during each peak period and observing the signals and traffic flows to determine if the timings were operating as designed and expected. Adjustments were made and the timings were rechecked for the desired result. This process continued over multiple weeks to ensure that fluctuations in traffic patterns were observed and accommodated. The project was completed by the end of May 2015.

The final step in Phase 2 which began immediately following the fine tuning effort involved a performance evaluation of the optimized signal timings. The results of the performance evaluation are detailed in the following sections.

III. Mobility Improvements

A. Qualitative Assessment of Bottleneck Reductions

The following are some "success" stories where significant operational improvements were observed by the signal timing engineers.

a) Downtown Congestion Reduced from 7 to 8 PM

- Before Conditions: the AM peak pattern operated from 5:30 to 10:00 AM, and the PM peak pattern operated from 2:30 PM until 7 PM; after 7 PM the signal cycle immediately transitioned to an 80 second cycle in the Overnight pattern. However, peak hour traffic continues until 8 PM and under the "Before" conditions, congestion was frequently observed from 7 to 8 PM.
- After Conditions: the revised time-of-day schedule starts the AM and PM plans earlier and operates them later, and brings back the Midday pattern from 8 PM to Midnight (the Midday pattern accommodates more traffic than the Overnight pattern), which has shortened the extent and duration of congestion during the peak periods of travel. Congestion and queueing

that was observed in the “Before” conditions during the shoulders of the peak periods was reduced.

b) 6th Street between M Street and New York Avenue, NW

- Before Conditions: southbound queues were observed extending upstream of the M Street intersection from New York Avenue.
- After Conditions: optimized signal timings reduced the queue for the 6th Street traffic turning onto New York Avenue. In the after condition the queue was significantly reduced and was observed to only extend up to L Street intersection during the AM and PM peak periods.

c) 7th Street/Georgia Ave. at Florida Avenue, NW

- Before Conditions: the southbound left turn movement from Georgia Avenue onto eastbound Florida Avenue experienced consistent cycle failures and queue spill back that at times extended to V Street blocking southbound through traffic on Georgia Ave.
- After Conditions: The timing optimization has significantly reduced the number of cycle failures for the southbound left turn movement, resulting in less queue spill back along southbound Georgia Avenue and improved southbound flow through this section of Georgia Avenue.

d) 7th Street between M Street and New York Avenue

- Before Conditions: Multiple cycle failures and congested conditions were experienced traveling southbound through this section of 7th Street.
- After Conditions: The timing optimization has reduced the frequency of the cycle failures and extent of congestion.

e) 14th Street from New York Avenue to Constitution Avenue, NW

- Before Conditions: during the PM peak hour, there were recurring, multiple cycle failures in this segment on southbound 14th Street through these intersections due to extremely heavy traffic volumes on both 14th Street and Constitution Avenue.
- After Conditions: The timing optimization reduced the frequency and number of cycle failures in this segment. This section of roadway is still very oversaturated.

f) 16th Street at “Eye” Street, NW

- Before Conditions: ongoing southbound lane closure on 16th Street between K Street and ”Eye” Street reduced southbound 16th St to one lane, causing cycle failures and queue spill back that extended beyond the K Street intersection. At times, the queues of traffic on southbound 16th Street would impact flow along K Street.
- After Conditions: The timing optimization has significantly reduced the number of cycle failures on southbound 16th Street at Eye Street, eliminating most of the queuing issues along southbound 16th Street (which still has ongoing southbound lane closures), and their impacts to traffic flow along K Street.

g) 17th Street at H Street, NW

- Before Conditions: multiple cycle failures occurred on northbound 17th Street at the signals between E Street and H Street (approximately 15 minutes travel time) during the AM peak hour. It appeared most of the backup was due to the double right turn onto H Street which has a heavy pedestrian conflict.
- After Conditions: the timing optimization eliminated the cycle failures for 17th Street through vehicles at H Street.

h) 18th Street from E Street to Pennsylvania Avenue, NW

- Before Conditions: during the AM peak hour, there were recurring, multiple cycle failures in this segment on northbound 18th Street through these intersections as Pennsylvania Avenue would have a green signal, but the next intersections to the north at H Street would have a red signal.
- After Conditions: The timing optimization improved progression and reduced the frequency and number of cycle failures.

i) Connecticut Avenue at 18th Street/Jefferson Place, NW

- Before Conditions: multiple cycle failures occurred (up to 15 minutes delay) throughout the AM peak hour on southbound Connecticut Avenue as a result of a green signal at N Street while there was a red signal at 18th Street/Jefferson Place. Queues regularly extended up into the DuPont Circle tunnel. Cycle failures also occurred during the PM peak period as well; however the queues did not extend under DuPont Circle.
- After Conditions: the timing optimization improved coordination and reduced queues and delays – resulting in localized queues only; queues no longer extend under DuPont Circle in the AM peak, and during the PM peak the cycle failures were reduced.

j) L Street at 22nd / New Hampshire Avenue, NW

- Before Conditions: eastbound L Street would regularly experience multiple cycle failures and queues would typically extend up to ¼ mile and into Pennsylvania Avenue during the AM peak.
- After Conditions: The timing optimization significantly reduced the frequency and number of cycle failures and reduced the length of queues.

k) North Capitol Street at P Street

- Before Conditions: it would often take two cycles to clear the northbound queues during the AM peak, and more during the PM peak.
- After Conditions: as a result of the timing optimization, northbound cycle failures were not experienced at this intersection during the AM peak, and the frequency and number of cycle failures were drastically reduced during the PM peak.

l) Logan Circle:

- Before Conditions: traffic flow around Logan Circle was relatively smooth with no operational issues within the circle. However, westbound Rhode Island Avenue did experience queues during the AM peak period that consistently extended from Logan Circle to between 9th Street and 10th Street. This was caused by consistent cycle failures on westbound Rhode Island Avenue entering Logan Circle.

- After Conditions: cycle failures entering Logan Circle have been drastically reduced. As a result the queues on westbound Rhode Island Avenue waiting to enter Logan Circle typically did not extend beyond 12th Street.

m) DuPont Circle:

- Before Conditions: traffic flow into and out of DuPont Circle from the Massachusetts Avenue approaches was poor. The coordination with the adjacent signals along Massachusetts Avenue at 18th Street and 20th Street was inefficient, which created queues that extended into the circle, and along Massachusetts Avenue entering and exiting the circle. Queues of vehicles entering the circle from eastbound and westbound Massachusetts Avenue and traveling through the “inner circle” would typically get cut-off and/or stopped traveling away from the circle at 18th Street or 20th Street, which created spillback into the circle. The spillback from the adjacent signals on Massachusetts Avenue at 18th Street and 20th Street would consistently block flow around the “outer circle” creating gridlock conditions (and a lot of horn blowing).
- After Conditions: traffic flow into and out of DuPont Circle was much more efficient. Coordination with the adjacent signals along Massachusetts Avenue at 18th Street and 20th Street was much smoother, with queue spillback into the circle greatly reduced. Traffic entering the circle from either eastbound or westbound Massachusetts Avenue was able to progress efficiently through the inner circle and exit away from the circle through the adjacent signals at 18th Street and 20th Street.

n) Scott Circle

- Before Conditions: traffic flow around Scott Circle was relatively efficient, with occasional cycle failures on the Massachusetts Avenue approaches. The cycle failures on eastbound Massachusetts Avenue during the PM peak period were the most frequent, with queues at times extending from the circle to beyond 17th Street.
- After Conditions: traffic flow into and out of the circle, and along the Massachusetts Avenue approaches was mostly un-changed from the before period. The eastbound cycle failures on Massachusetts Avenue during the PM peak period were slightly less frequent, and the queues were reduced.

o) Thomas Circle

- Before Conditions: traffic flow around Thomas Circle was relatively efficient, with some minor breakdown of flow along the northern portion of the circle from the ramp from westbound Massachusetts Avenue to the exit from the circle onto westbound M Street. This occurred during all peak periods. The heavier 14th Street approaches into and out of the circle flowed well with occasional cycle failures during the peak periods. Traffic flow on southbound 14th Street through the circle was smooth throughout the peak periods. Traffic flow on northbound 14th Street would experience periodic stoppages within the circle, mainly caused by the breakdown of westbound flow around the northern section of the circle, which blocked northbound traffic.

- After Conditions: traffic flow into and out of the circle, and along the 14th Street approaches was mostly un-changed from the before period. However the breakdowns in flow around the northern portion of the circle between the ramp from westbound Massachusetts Avenue and the exit onto westbound M Street, and the disruptions to northbound 14th Street flow through the circle were more frequent. This may have been the result of the increase in cycle length during the AM and PM peak periods, compounded by the short storage areas between the signals. Refer to the recommendations section for a suggestion to help alleviate this congestion.

B. Vehicle Probe Project (VPP) Suite – Traffic Data Analysis

An analysis of the impacts of the signal timing optimization project was performed using the Vehicle Probe Project (VPP) software suite which is part of the Regional Integrated Transportation Information System (RITIS). The Vehicle Probe Project Suite allows agencies to support operations, planning, analysis, research, and performance measures generation using probe data mixed with other agency transportation data. The suite consists of a collection of data visualization and retrieval tools. These web-based tools allow users to download reports, visualize data on maps or in other interactive graphics, and even download raw data for off-line analysis.[1] The I-95 Corridor Coalition, a consortium of state departments of transportation and metropolitan planning organizations (MPO's) along the I-95 corridor (including DDOT), has been purchasing probe vehicle data also known as vehicle probe project (VPP) data from INRIX and other commercial traffic data sources. As part of the purchase agreement, the data is available to member agencies (DDOT is a member agency).

a) VPP Congestion Scan

The VPP suite has many tools available for acquiring a variety of performance data for roadways on which coverage exists. One of them is the Congestion Scan tool which graphically illustrates a speed metric (speed as a percentage of free flow speed) over a segment of roadway. Segments colored green are operating at or near their free flow speed (i.e. little to no congestion), whereas segments colored red or orange are operating under stop and go conditions. Graphics were generated from VPP for a comparison of the impact of the optimized signal timings. These graphics compare the average of three weekdays (Tuesday, Wednesday, and Thursday) between the week before the optimized signal timings were implemented (April 21 through 23, 2015) and for the week after the optimized signal timing (April 28 through 30, 2015). The Congestion Scan tool is not available for all roadways or segments. **Figure 5**, **Figure 6**, **Figure 7**, **Figure 8**, **Figure 9**, **Figure 10**, and **Figure 11** present the results for the corridors for which this tool is available. From these graphics, it may be observed that:

- The **duration** of congestion has decreased as a result of the signal timing optimization. The duration may be observed by comparing across (horizontally) the scan and noting the time

[1] http://www.cattlab.umd.edu/?portfolio=vehicle-probe-project-suite

when the segment changes from red/orange to green, and then comparing between the "before" and "after" conditions.

- The **extent** of congestion has decreased as a result of the signal timing optimization. The extent may be observed by comparing the colors along the same segment of roadway between the "before" and "after" conditions. Note the segments that were orange or red in the "before" condition and changed to yellow or green in the "after" condition.

b) VPP Travel Time Comparison

The VPP suite also provides a Travel Time tool which compares travel time over a segment of roadway between two different time periods. The following graphics were generated from VPP for a comparison of the impact of the optimized signal timings. These graphics compare the average of three weekdays (Tuesday, Wednesday, and Thursday) between the week before the optimized signal timings were implemented (April 21 through 23, 2015) and for the week after the optimized signal timing (April 28 through 30, 2015). Once again, the Travel Time tool is not available for all roadways or segments. **Figure 12**, **Figure 13**, **Figure 14**, **Figure 15**, **Figure 16**, **Figure 17**, and **Figure 18** present the results for the corridors for which this tool is available. From these graphics, it may be observed that travel time has significantly decreased in the AM and PM peak periods:

- Southbound 9th Street travel times decreased significantly during the AM peak period from approximately 7 AM to 9 AM, with savings on the order of 2 to 3 minutes. Northbound savings during the PM peak occurred from 3 PM to 9 PM and range from about 30 seconds to 2 minutes.
- 11th Street exhibits travel time savings throughout the day in both directions with savings of up to 2 minutes during the PM peak.
- 12th Street travel times decreased from 6 AM through 7 PM, with significant decreases during the AM peak period in the range of 1 to 3 minutes. There were some slight increases during the overnight period on the order of magnitude of 15 seconds.
- 14th Street travel times decreased from 10 AM through 7 PM, with significant decreases during the peak directions of the AM and PM peak periods in the range of 2 to 3 minutes. There were some slight increases during the overnight period on the order of magnitude of 30 seconds to 1 minute.
- Southbound Rhode Island Avenue travel times decreased throughout the day, with significant decreases during the AM peak period in the range of 2 to 3 minutes. Northbound travel times showed significant decreases during the PM peak period.
- Major travel time savings were achieved on Constitution Avenue, particularly during the Midday and PM peak periods where travel time savings were as much as 2 minutes.
- Along Massachusetts Avenue, travel times decreased throughout the AM, Midday and PM peaks with savings as much as 5 minutes during the AM and PM peaks, and in particular on the approaches to DuPont Circle.

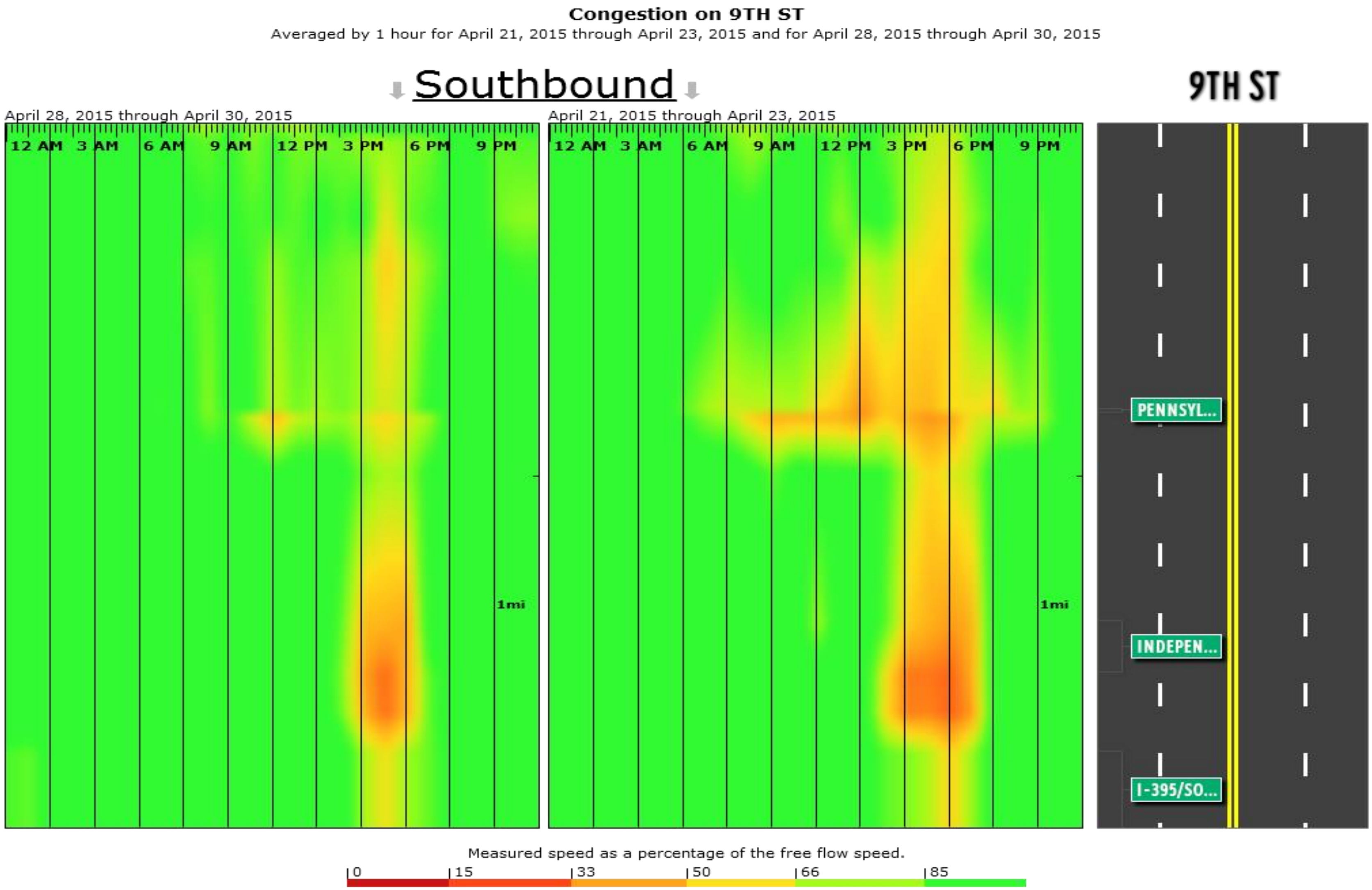

Figure 5: Congestion Scan of 9th St from G Street to Mt. Vernon Square

Right shows “before” conditions; left side “after” conditions

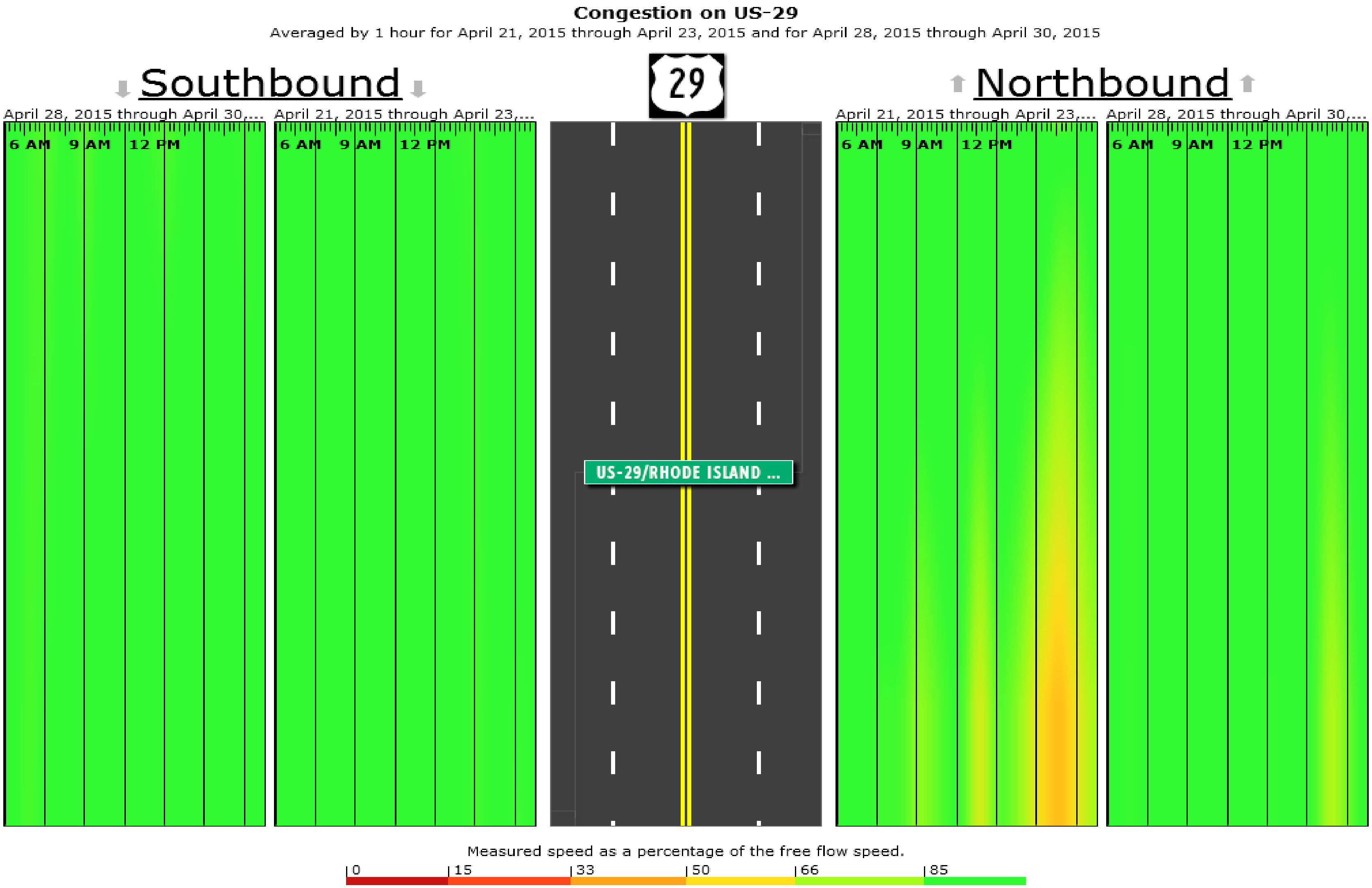

Figure 6: Congestion Scan of 11th St from Rhode Island to Mass Ave, NW

The scans adjacent to the roadway illustrate “before” conditions; outside scans show “after” conditions

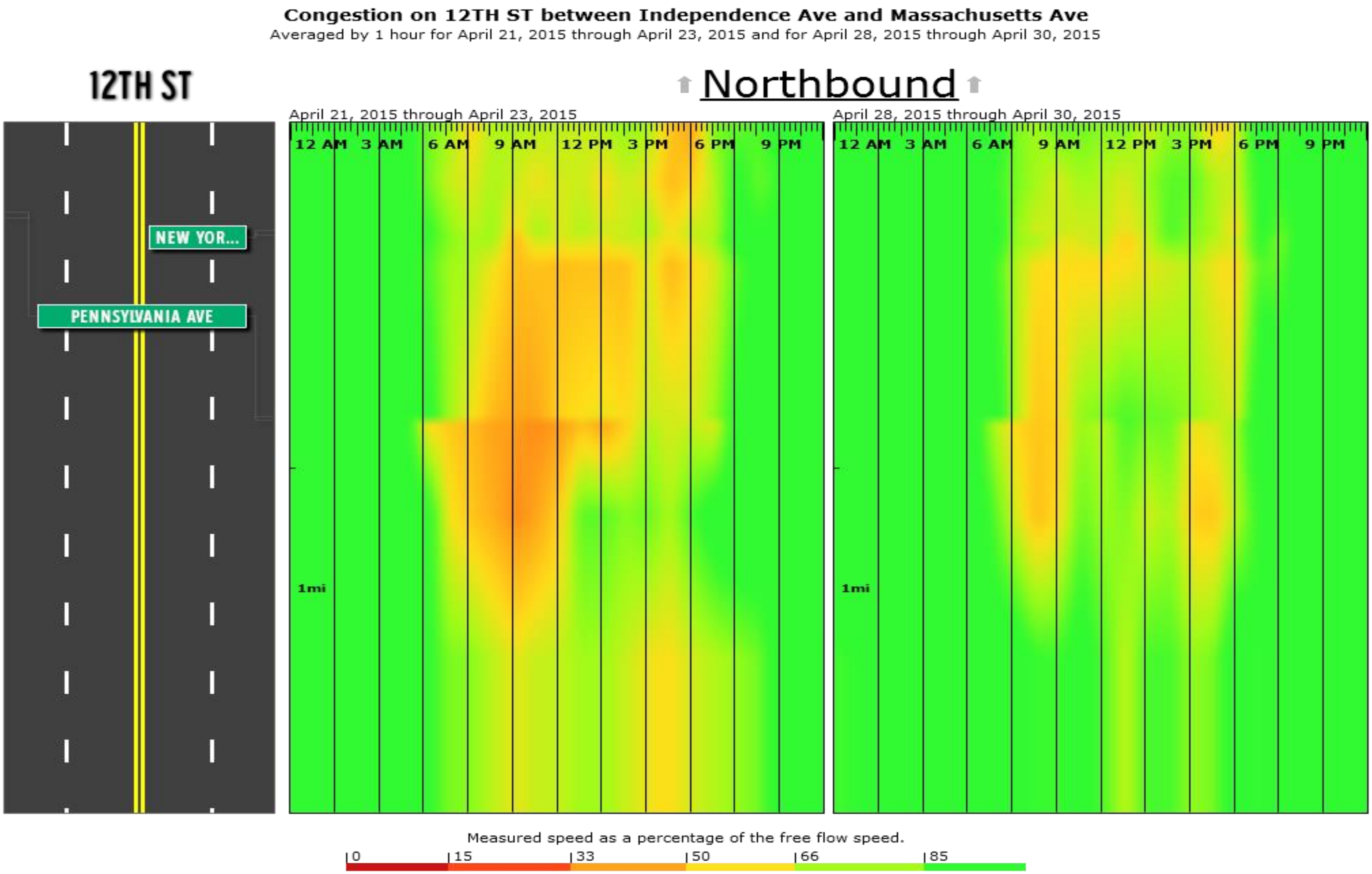

Figure 7: Congestion Scan of 12th St from Independence to Mass Ave, NW

Left shows “before” conditions; right side “after” conditions.

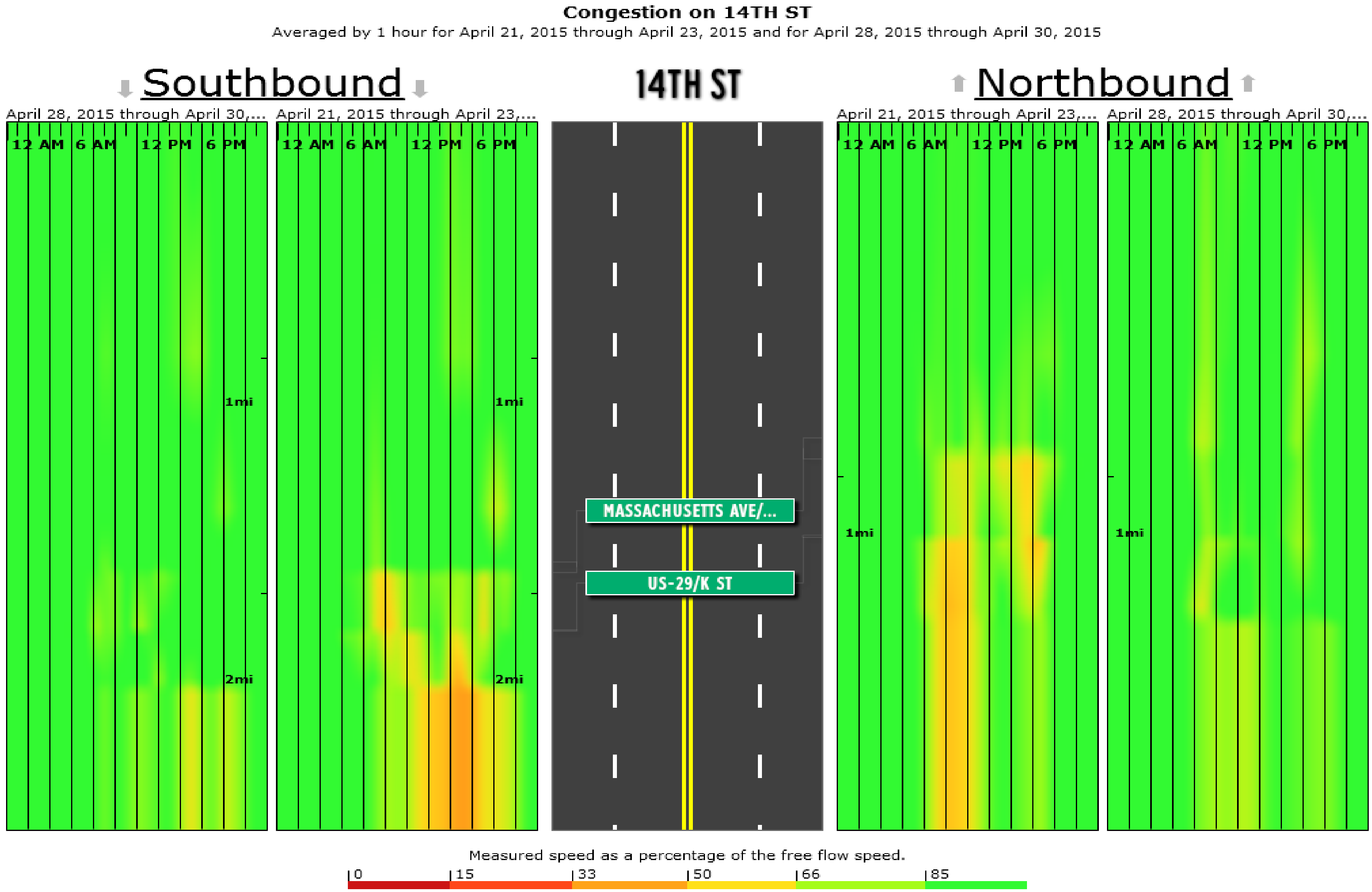

Figure 8: Congestion Scan of 14th Street from Constitution Avenue to Thomas Circle, NW

The scans adjacent to the roadway illustrate “before” conditions; outside scans show “after” conditions

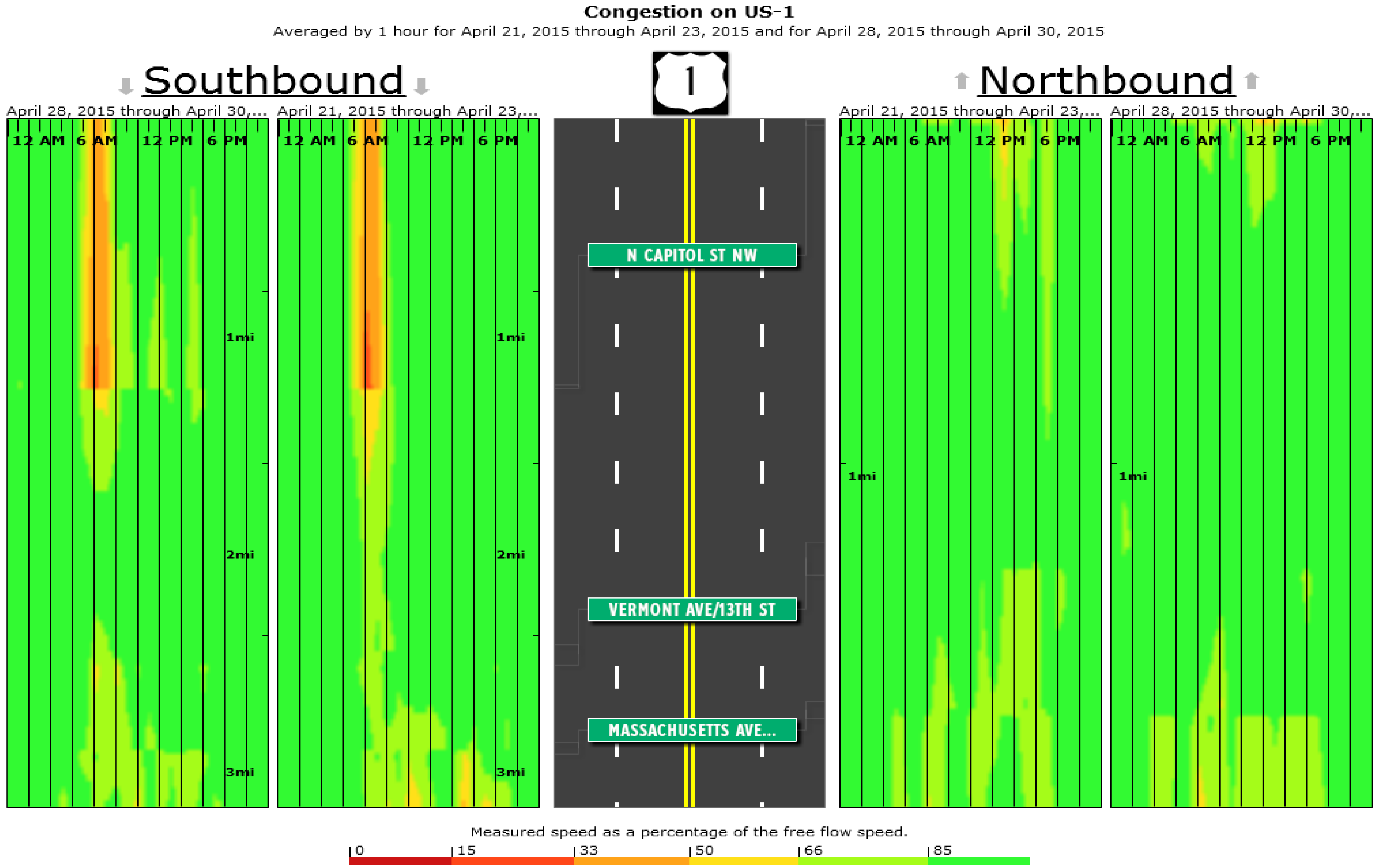

Figure 9: RITIS Congestion Scan of Rhode Island Ave from North Capitol to Connecticut Avenue, NW

The scans adjacent to the roadway illustrate “before” conditions; outside scans show “after” conditions

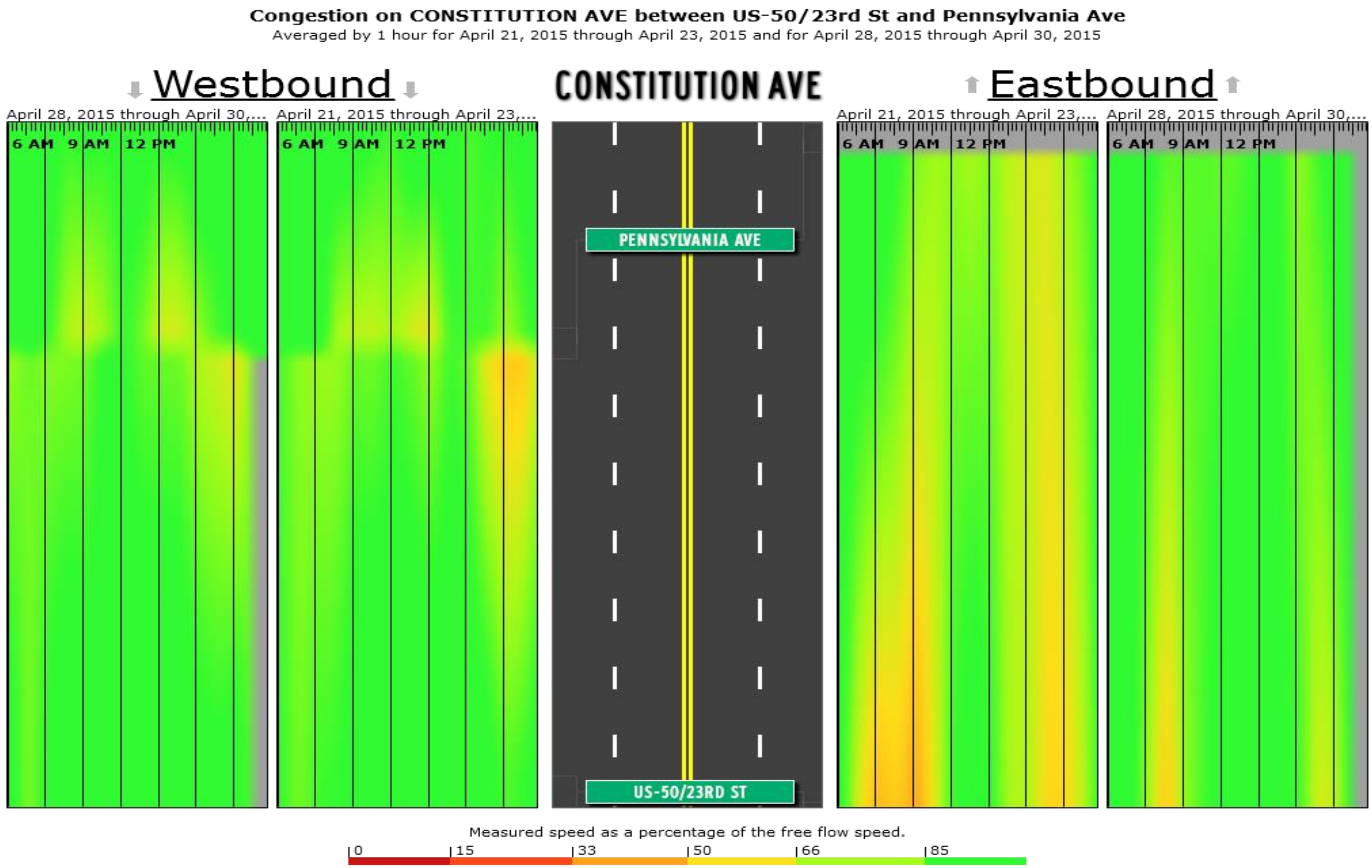

Figure 10: RITIS Congestion Scan of Constitution Ave from 23rd St to Pennsylvania Ave

The scans adjacent to the roadway illustrate “before” conditions; outside scans show “after” conditions

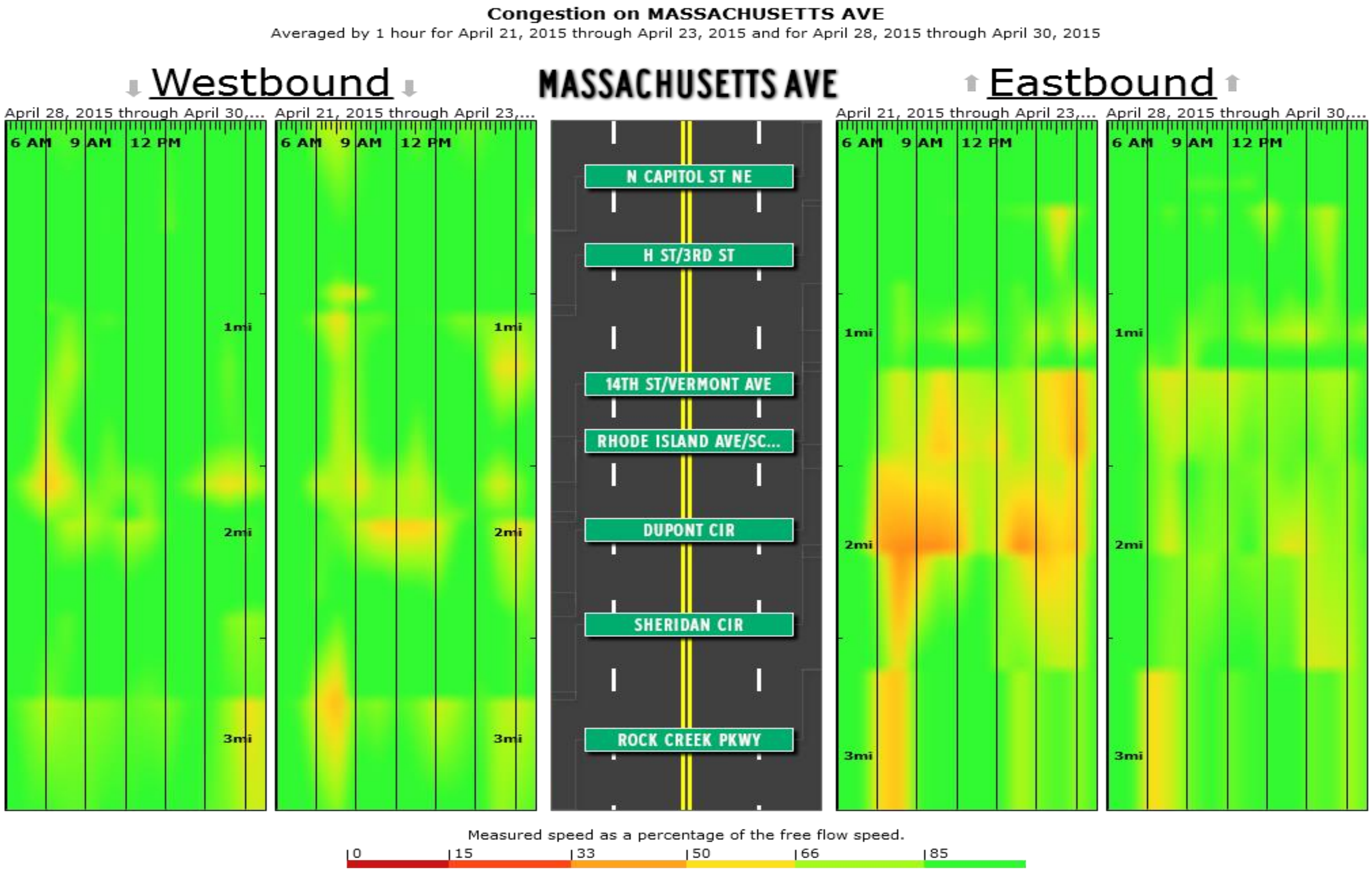

Figure 11: RITIS Congestion Scan of Massachusetts Ave from Rock Creek Pkwy to North Capitol

The scans adjacent to the roadway illustrate “before” conditions; outside scans show “after” conditions

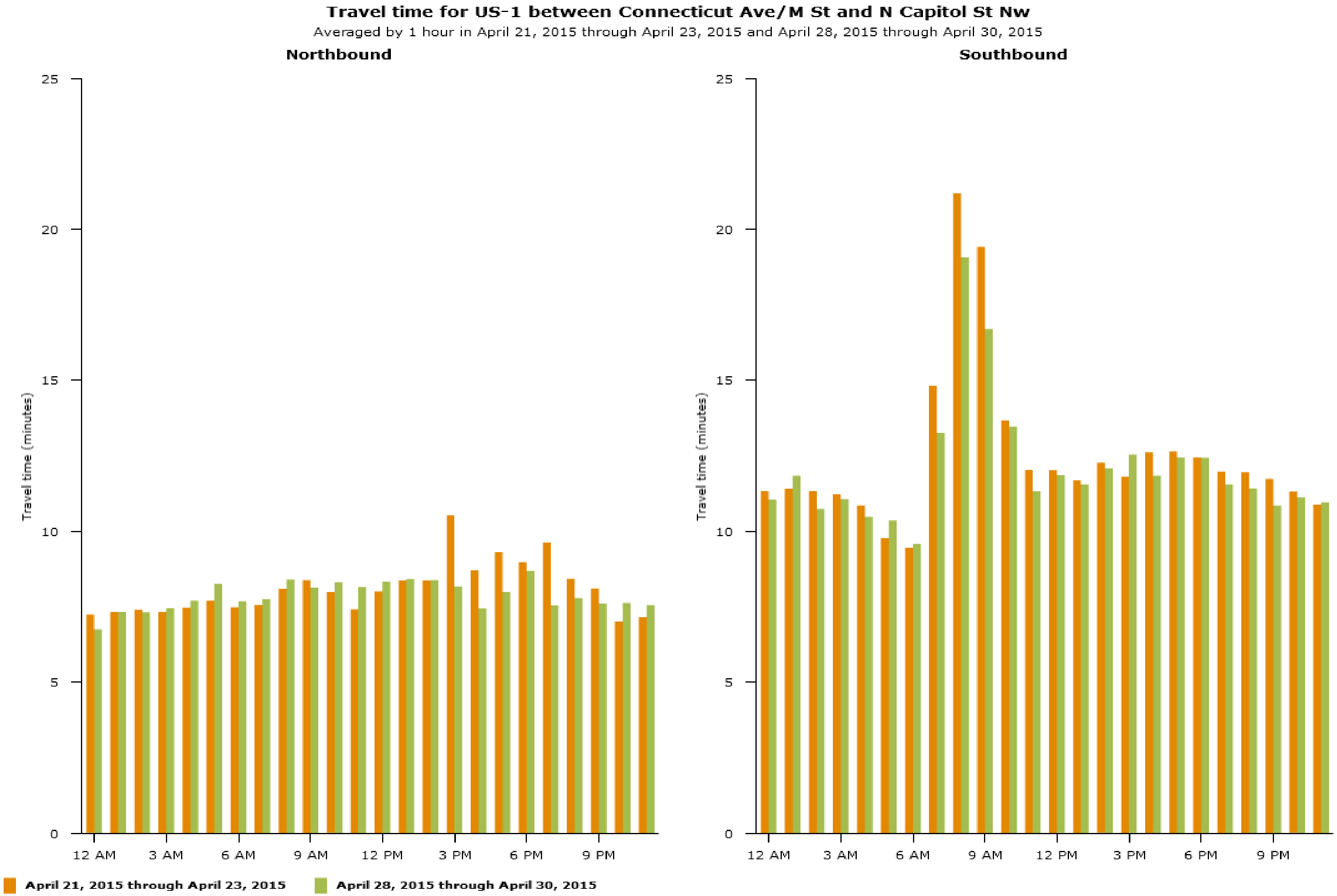

Figure 12: Travel Time on 9th St from G Street to Mt. Vernon Square

Orange indicates "before" conditions; Green indicates "after" conditions.

Figure 13: Travel Time on 11th St from Rhode Island Ave to Mass Ave

Orange - “before” conditions; Green indicates “after” conditions

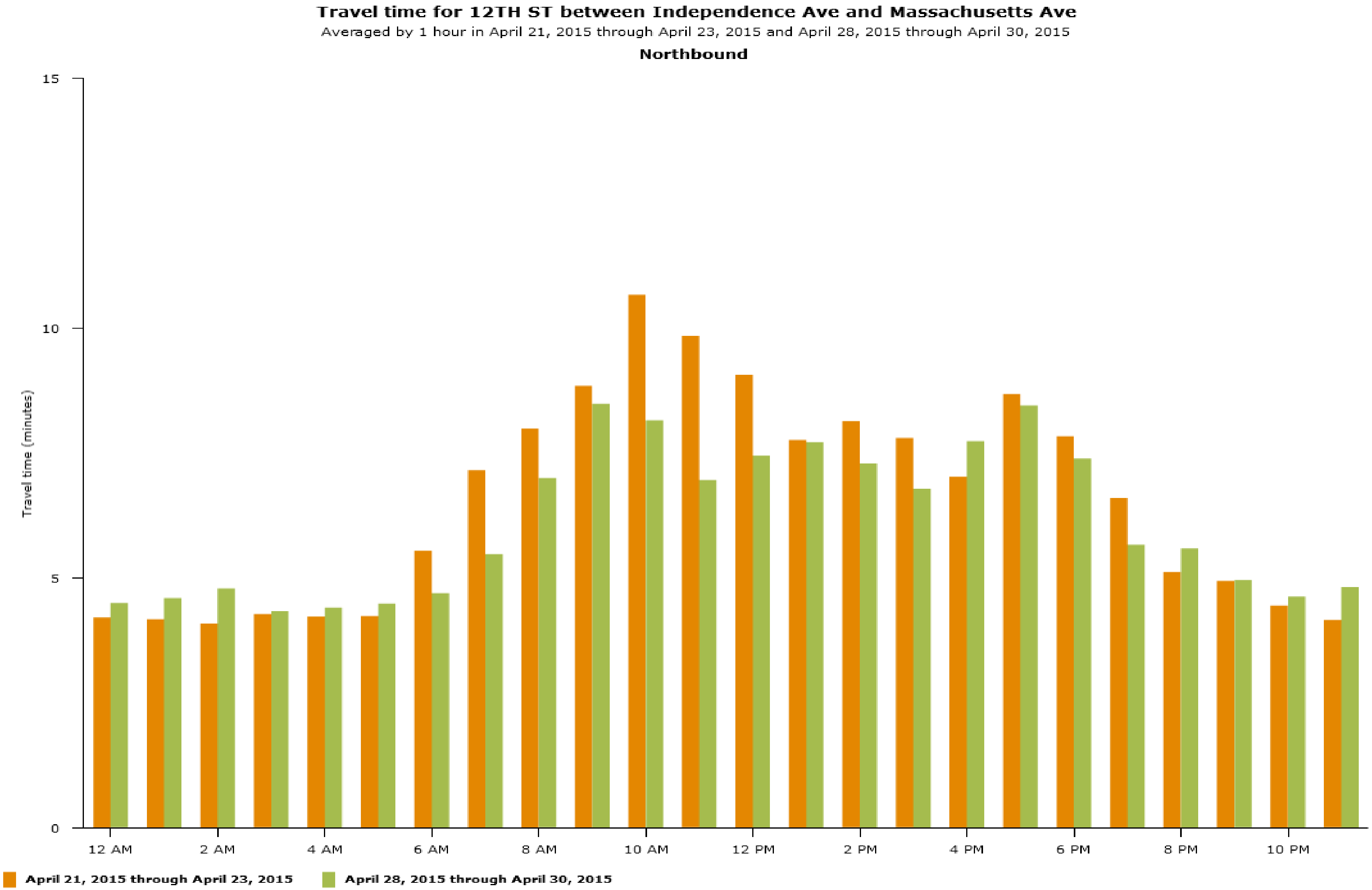

Figure 14: Travel Time on 12th St from Independence to Mass Ave

Orange - "before" conditions; Green indicates "after" conditions

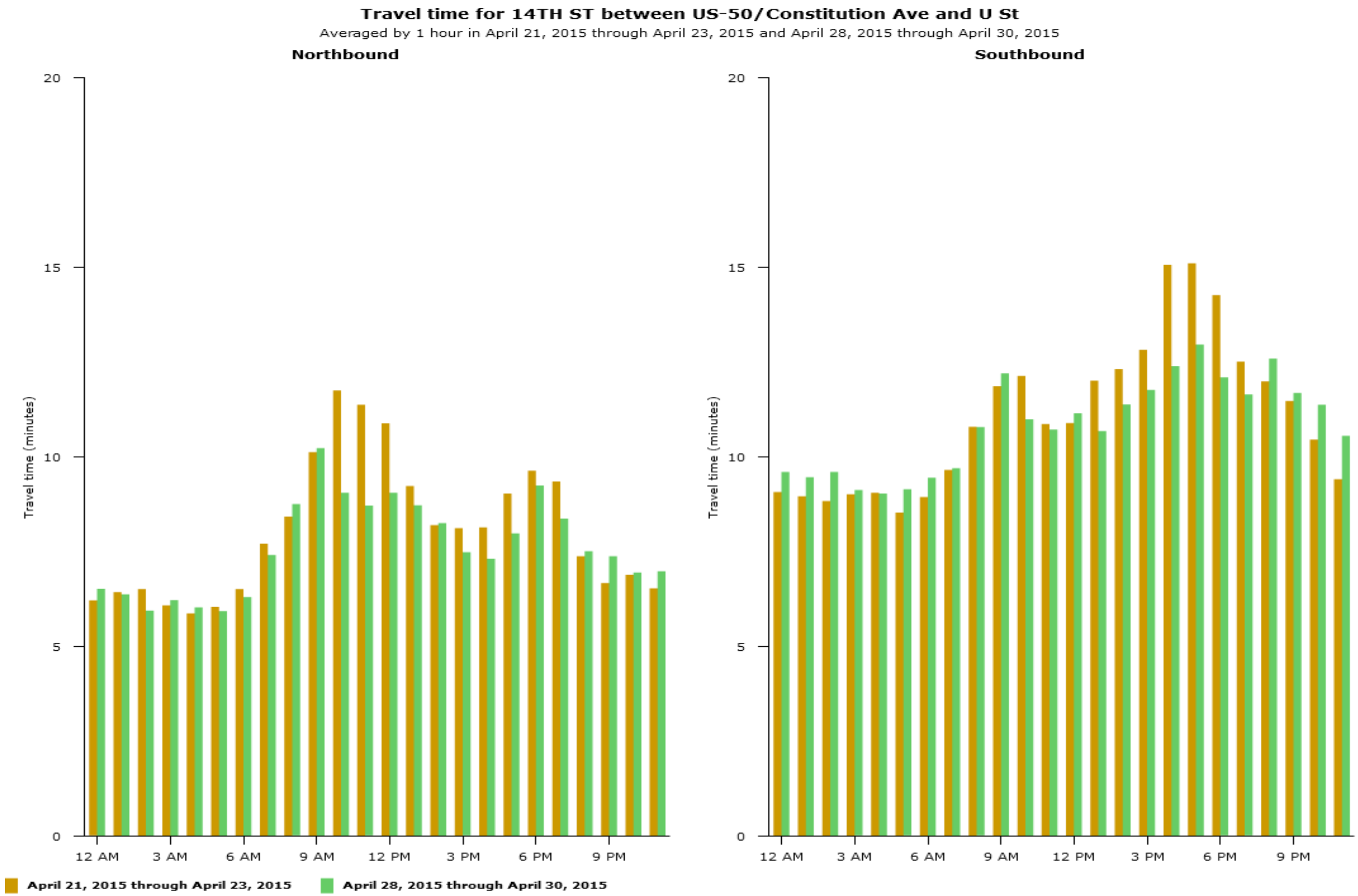

Figure 15: Travel Time on 14th St from Constitution to Thomas Circle

Orange - "before" conditions; Green indicates "after" conditions

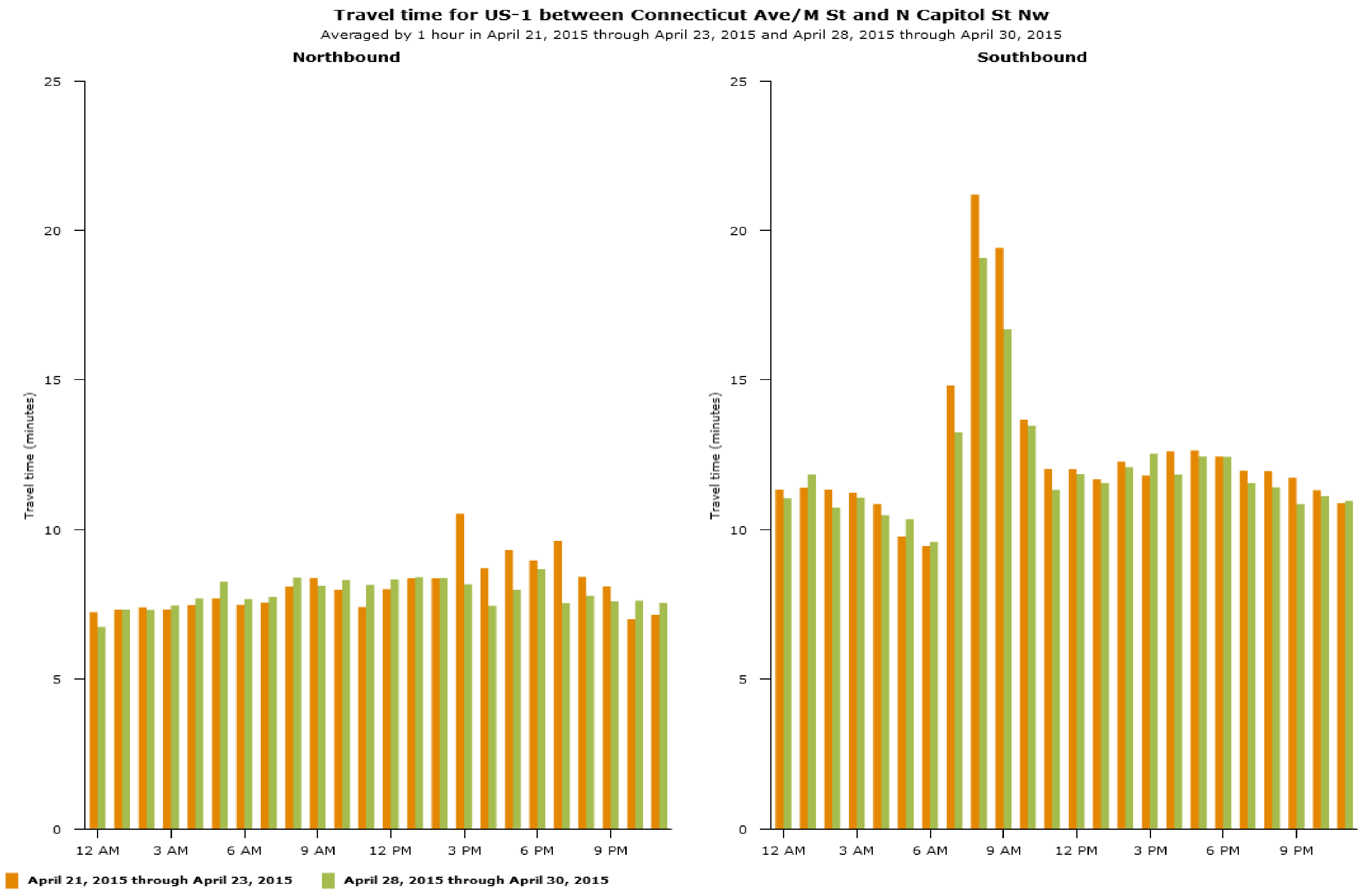

Figure 16: Travel Time on Rhode Island Ave from North Capitol to Connecticut Avenue, NW.

Orange indicates "before" conditions; Green indicates "after" conditions

Figure 17: Travel Time on Constitution Avenue from 23rd Street to Pennsylvania Avenue.

Orange - "before" conditions; Green indicates "after" conditions

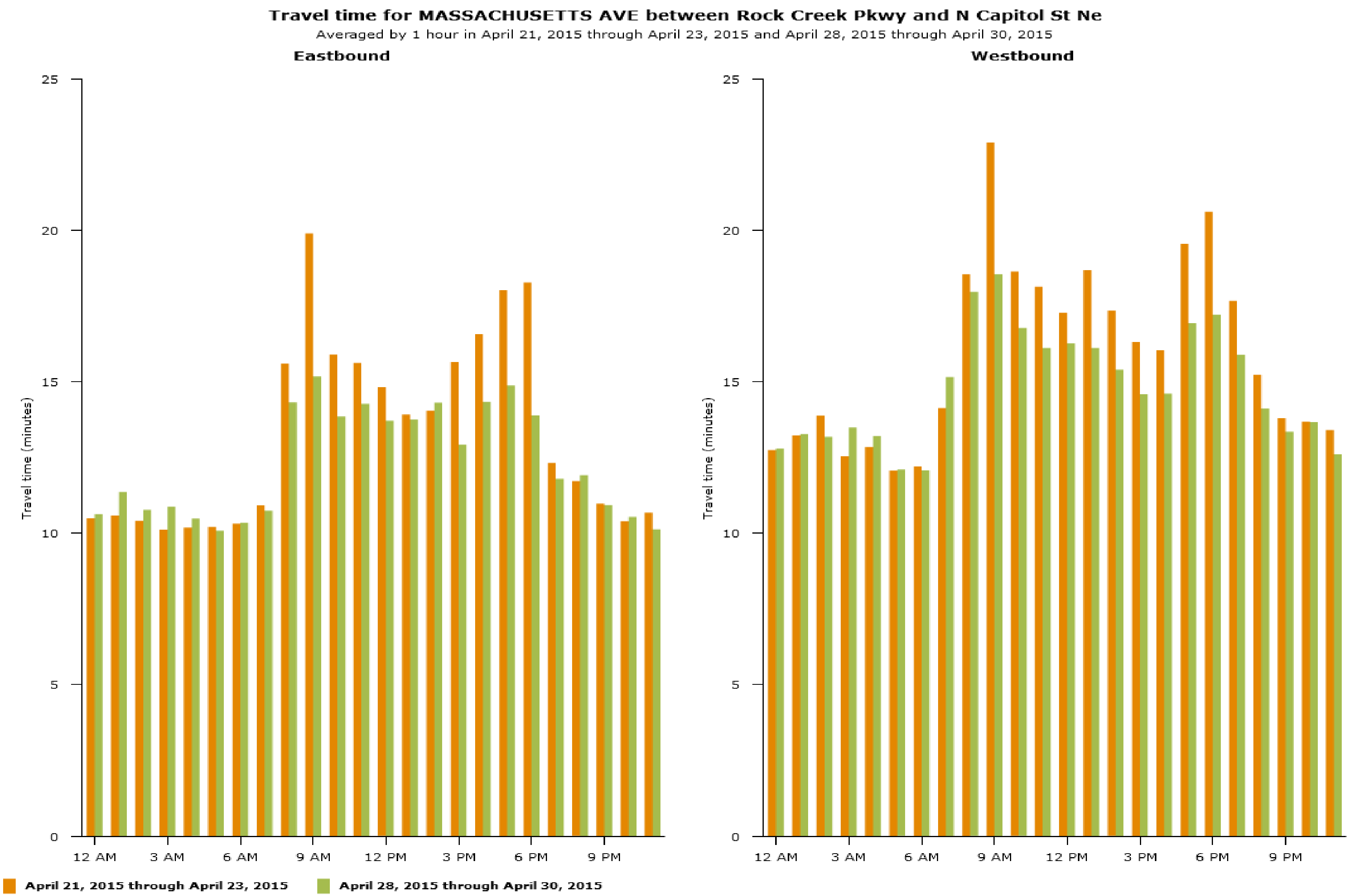

Figure 18: Travel Time on Massachusetts Avenue from Rock Creek Parkway to North Capitol.
Orange - "before" conditions; Green indicates "after" conditions

c) VPP Bottleneck Ranking

One of the most visible components of congestion is bottlenecks[2], and more specifically the queues of vehicles which form as a result. Section A summarized the bottleneck reductions observed by the engineering team – a qualitative assessment. The purpose of this section is to present an independent, macro-level, quantitative assessment of this same measure of bottleneck reductions.

The VPP suite provides a Bottleneck Ranking tool which ranks bottleneck segments based on the average maximum queue length, their average duration and the number of occurrences. This tool was utilized to obtain bottleneck data for all roadways within the Downtown area with available coverage. Data was obtained along these segments for Tuesdays, Wednesdays, and Thursdays during the periods of 04/21 – 04/23, 2015 and 05/05 and 05/07, 2015, representing the "Before" and "After" optimization conditions. The locations were filtered to include bottlenecks with an average queue length of at least 0.3 miles (to account for the urban nature of the project area) during the "before" optimization time period to provide a representative sample. Discounting freeway segments (which are the highest ranked bottleneck segments), there were 137 arterial bottleneck segments.

The results of this analysis are shown in **Table 2**, with cells showing an improvement highlighted in GREEN and cells showing deterioration highlighted in RED. The value "#N/A" could either mean that data was not available or that no bottlenecks were detected in the specified duration. Thirty segments (22% of total) return a record displayed "#N/A" in the "After" time period. Therefore, entries with the value "#N/A" have been filtered out from the table for the purposes of clarity although they were retained in the numerical analysis because although there is no data, there is still a recorded bottleneck at that segment. The key takeaways from the bottleneck analysis are as follows:

- The average duration of congestion showed a 13% decrease.
- The average maximum queue lengths remained the same or showed a reduction at nearly two-third (89 segments) of the locations. In contrast, less than one in six locations, 13% (18 locations) recorded an increase in the average max queue length.

In 12 of the 18 segments that recorded an increase in average max queue, the duration of congestion and/or the number of bottleneck occurrences in the "After" implementation period remained the same or showed an improvement compared with the "Before" time period. At nearly all these locations, the increase in queue length along one segment was simultaneously accompanied by an improvement along the crossing segment. For example, the average max queue length on EB Constitution Avenue at 14th Street increased by 27% from 0.52 miles to 0.66 miles with the bottleneck ranking climbing from 21 to 13. However, the average max queue length on SB 14th

[2] Wikipedia defines a traffic bottleneck as a localized disruption of vehicular traffic on a street, road, or highway. As opposed to a traffic jam, a bottleneck is a result of a specific physical condition, often the design of the road, badly timed traffic lights, or sharp curves. http://en.wikipedia.org/wiki/Traffic_bottleneck

Street at Constitution decreased by 18% from 0.62 to 0.51 with the bottleneck ranking dropping from 13 to 93.

There were only 6 locations (4% of total) that showed a drop in all three bottleneck measurement categories (i.e., queue length, duration and occurrences). In order to determine the reason for the deterioration, we compared this data to the other performance metrics utilized in this project. In several cases, the bottleneck was by design. In other words, the signal timing strategy favored one roadway's movement over another. For example, Constitution Avenue progression was favored over Pennsylvania Avenue progression due to the higher travel demands along Constitution Avenue. In other cases, there is deterioration at a local area but the deterioration was "made-up for" by improving progression along the corridor for a net reduction in overall corridor travel time. For example, the bottleneck worsened along M Street at New Hampshire Avenue, which was by design in order to reduce congestion along New Hampshire Avenue; however, overall M Street progression was improved and congestion was showed to decrease, mitigating the impact of making one bottleneck location worse.

Table 2: Major Bottleneck Lengths and Durations "Before" and "After" Optimization

Bottleneck Direction and Location	Avg. Max. Queue			Avg. Bottleneck Duration			Occurrences		
	Before (miles)	After (miles)	%	Before (mins.)	After (mins.)	%	Before	After	%
EB Massachusetts Avenue at Thomas Circle	1.32	0.53	60%	71	49	31%	40	34	15%
EB L Street at Connecticut Avenue	1.04	0.84	19%	102	66	35%	27	25	7%
EB Massachusetts Avenue at Scott Circle	1.29	1.07	17%	93	67	28%	22	22	0%
WB Independence Avenue at 23rd Street/Ohio Drive	1.23	1.18	4%	102	106	-4%	20	32	-60%
SB 9th Street at Maine Ave	0.95	0.53	44%	137	83	39%	19	31	-63%
NB 12th Street at Rhode Island Avenue	0.77	0.01	99%	202	33	84%	15	6	60%
NB 12th Street at Massachusetts Avenue	0.52	0.81	-56%	155	150	3%	27	27	0%
SB 14th Street at Constitution Avenue	0.62	0.51	18%	97	24	75%	28	14	50%
WB K Street at Washington Circle	1.06	0.95	10%	130	132	-2%	10	7	30%
SB 17th Street at Independence Avenue	0.62	0.66	-6%	81	83	-2%	26	24	8%
WB Constitution Avenue at 23rd Street	0.98	0.97	1%	125	121	3%	10	10	0%
NB 18th Street at Connecticut Avenue	0.49	0.02	96%	96	24	75%	24	6	75%
EB Constitution Avenue at 14th Street	0.52	0.66	-27%	83	83	0%	24	24	0%

Bottleneck Direction and Location	Avg. Max. Queue			Avg. Bottleneck Duration			Occurrences		
	Before (miles)	After (miles)	%	Before (mins.)	After (mins.)	%	Before	After	%
NB 15th Street at New York/Pennsylvania Avenue	0.51	0.34	33%	52	38	27%	38	21	45%
EB New York Avenue at L/5th Street	0.87	0.87	0%	128	207	-62%	9	7	22%
EB Virginia Avenue at Constitution Avenue	0.74	0.49	34%	82	36	56%	16	4	75%
SB Rhode Island Avenue at Logan Circle	2.09	0.67	68%	75	23	69%	6	6	0%
WB Maine Avenue at East Basin Drive	0.42	0.38	10%	83	67	19%	26	27	-4%
SB 15th Street at Independence Avenue	0.6	0.56	7%	98	69	30%	14	12	14%
NB 14th Street at Constitution Avenue	0.7	0.63	10%	84	89	-6%	14	17	-21%
WB Constitution Avenue at 14th Street	0.71	0.71	0%	48	58	-21%	23	22	4%
WB Massachusetts Avenue at DuPont Circle	0.5	0.51	-2%	74	61	18%	21	25	-19%
SB 16th Street at H Street	0.43	0.2	53%	67	115	-72%	25	11	56%
WB K Street (Service Road) at 25th Street	1.3	1.03	21%	136	97	29%	4	3	25%
EB L Street at Massachusetts Avenue	1.49	1.2	19%	149	88	41%	3	5	-67%
EB Constitution Avenue at Pennsylvania Avenue	0.71	0.71	0%	34	31	9%	27	17	37%
EB K Street at 14th Street	0.56	0.56	0%	56	67	-20%	18	13	28%
EB Maine Avenue at 6th Street	0.47	0.23	51%	53	40	25%	19	15	21%
SB 12th Street at Independence Avenue	0.78	0.72	8%	89	22	75%	6	3	50%
SB 7th Street at Constitution Avenue	0.62	0.62	0%	38	46	-21%	17	21	-24%
EB K Street at Vermont Avenue/15th Street	0.64	0.94	-47%	62	76	-23%	10	14	-40%
EB Pennsylvania Avenue at 19th Street/H Street	0.67	0.43	36%	72	31	57%	7	20	-186%
EB E Street at 15th Street	0.55	0.41	25%	121	96	21%	5	19	-280%
WB Constitution Avenue at 17th Street	0.38	0.37	3%	45	48	-7%	19	26	-37%
SB 19th Street at E Street	0.39	0.52	-33%	42	71	-69%	19	13	32%
SB New Hampshire Avenue at Connecticut Avenue	0.4	0.25	38%	29	34	-17%	26	36	-38%
WB Massachusetts Avenue at Scott Circle	0.34	0.26	24%	42	36	14%	20	29	-45%
EB Q Street at Rhode Island Avenue	1.15	1.14	1%	60	206	-243%	4	7	-75%
SB 16th Street at Scott Circle	0.62	0.44	29%	29	28	3%	15	16	-7%
WB M Street at Connecticut Avenue	0.38	0.2	47%	30	28	7%	23	11	52%

Bottleneck Direction and Location	Avg. Max. Queue			Avg. Bottleneck Duration			Occurrences		
	Before (miles)	After (miles)	%	Before (mins.)	After (mins.)	%	Before	After	%
WB L Street at Massachusetts Avenue	0.46	0.35	24%	39	37	5%	14	10	29%
WB Independence Avenue at 14th Street	0.79	0.79	0%	39	29	26%	8	8	0%
SB 13th Street at K Street	0.3	0.24	20%	40	21	48%	20	10	50%
SB 14th Street at Independence Avenue	0.31	0.29	6%	31	36	-16%	23	25	-9%
SB Connecticut Avenue at DuPont Circle	0.54	0.45	17%	49	64	-31%	8	8	0%
EB K Street at Connecticut Avenue/17th Street	0.54	0.24	56%	26	29	-12%	15	29	-93%
NB 14th Street at Independence Avenue	0.32	0.3	6%	35	24	31%	18	18	0%
WB P Street at Logan Circle	0.37	0.11	70%	39	29	26%	13	15	-15%
EB H Street at 14th Street	0.48	0.44	8%	41	36	12%	9	8	11%
WB Independence Avenue at 17th Street	1.09	0.42	61%	50	58	-16%	3	5	-67%
NB 12th Street at Independence Avenue	0.37	0.34	8%	50	20	60%	8	4	50%
WB Massachusetts Avenue at Thomas Circle	0.33	0.35	-6%	29	21	28%	15	6	60%
WB Pennsylvania Avenue at Washington Circle/K Street	0.55	0.53	4%	82	39	52%	3	4	-33%
WB Independence Avenue at Washington Avenue	0.42	0.19	55%	28	20	29%	11	9	18%
EB Independence Avenue at 14th Street	0.4	0.45	-13%	45	38	16%	7	13	-86%
SB 13th Street at Logan Circle	0.72	0.57	21%	28	31	-11%	6	16	-167%
SB New Hampshire Avenue at K Street	0.84	0.46	45%	47	25	47%	3	3	0%
EB Q Street at 14th Street	0.45	0.29	36%	28	44	-57%	9	15	-67%
NB 7th Street at K Street/Massachusetts Avenue	1.00	1.54	-54%	51	93	-82%	2	3	-50%
NB 6th Street at H Street	0.52	0.49	6%	39	63	-62%	5	1	80%
NB 20th Street at New Hampshire Avenue	0.32	0.2	38%	52	27	48%	6	5	17%
EB Rhode Island Avenue between Scott and Logan Circles	0.36	0.36	0%	23	26	-13%	12	13	-8%
WB Massachusetts Avenue at Sheridan Circle	0.71	1.02	-44%	44	54	-23%	3	1	67%
SB 3rd Street at E Street	0.44	0.3	32%	23	19	17%	9	4	56%
EB L Street at 14th Street	0.37	0.33	11%	40	39	3%	6	17	-183%
NB 7th Street at Constitution Avenue	0.46	0.51	-11%	39	30	23%	5	10	-100%
EB Q Street at 16th Street	0.6	0.6	0%	63	62	2%	2	1	50%

Bottleneck Direction and Location	Avg. Max. Queue			Avg. Bottleneck Duration			Occurrences		
	Before (miles)	After (miles)	%	Before (mins.)	After (mins.)	%	Before	After	%
NB 7th Street at Mount Vernon Place/New York Avenue	1.41	1.37	3%	51	55	-8%	1	1	0%
NB New Hampshire Avenue at U Street	0.60	0.6	0%	60	25	58%	2	1	50%
EB Constitution Avenue at 15th Street	0.38	0.31	18%	21	25	-19%	9	6	33%
NB 15th Street at Constitution Avenue	0.31	0.31	0%	24	22	8%	9	7	22%
NB 14th Street at New York Avenue	0.5	0.42	16%	21	38	-81%	6	31	-417%
SB 3rd Street at Constitution Avenue	0.53	0.35	34%	29	26	10%	4	9	-125%
WB M Street at 6th Street	0.32	0.12	63%	27	37	-37%	7	4	43%
WB K Street Northwest Service Road at Pennsylvania Ave/23rd Street	0.84	0.77	8%	33	45	-36%	2	5	-150%
SB 6th Street at Constitution Avenue	0.64	0.05	92%	43	20	53%	2	1	50%
NB 7th Street at Independence Avenue	0.35	0.36	-3%	19	26	-37%	8	6	25%
WB Independence Avenue at 15th Street/ Raoul Wallenburg Place	0.85	0.09	89%	31	25	19%	2	3	-50%
EB Independence Avenue at Washington Avenue	0.64	0.64	0%	26	31	-19%	3	6	-100%
SB 3rd Street at Independence Avenue	0.42	0.4	5%	22	40	-82%	5	6	-20%
NB 20th Street at Pennsylvania Avenue	0.40	0.28	30%	36	73	-103%	3	7	-133%
EB L Street at Vermont Avenue	0.49	0.37	24%	22	19	14%	4	4	0%
WB Independence Avenue at 7th Street	0.42	0.37	12%	20	48	-140%	5	14	-180%
EB Constitution Avenue at 17th Street	0.57	0.57	0%	23	23	0%	3	4	-33%
EB Constitution Avenue at 9th Street	0.47	0.47	0%	39	33	15%	2	1	50%
NB 17th Street at E Street	0.33	0.48	-45%	36	108	-200%	3	6	-100%
SB 14th Street at Rhode Island Avenue	0.56	0.73	-30%	20	20	0%	3	5	-67%
SB 7th Street at Independence Avenue	0.31	0.54	-74%	20	38	-90%	5	9	-80%
NB 12th Street at H Street	0.33	0.33	0%	23	26	-13%	4	4	0%
NB 17th Street at Constitution Avenue	0.30	0.3	0%	25	28	-12%	4	15	-275%
EB K Street at Massachusetts Avenue/K Street	0.58	0.58	0%	51	137	-169%	1	4	-300%
NB 12th Street at Constitution Avenue	0.42	0.31	26%	19	20	-5%	3	5	-67%

Bottleneck Direction and Location	Avg. Max. Queue			Avg. Bottleneck Duration			Occurrences		
	Before (miles)	After (miles)	%	Before (mins.)	After (mins.)	%	Before	After	%
NB 3rd Street at Independence Avenue	0.3	0.3	0%	20	30	-50%	4	13	-225%
WB Pennsylvania Avenue at 9th Street	0.39	0.34	13%	19	25	-32%	3	10	-233%
WB Constitution Avenue at Louisiana Avenue	0.52	0.52	0%	19	24	-26%	2	6	-200%
NB 13th Street at H Street	0.3	0.3	0%	21	19	10%	3	2	33%
EB New York Avenue at 10th Street	0.35	0.34	3%	26	34	-31%	2	1	50%
NB 13th Street at Rhode Island Avenue/Vermont Avenue	0.37	0.3	19%	23	19	17%	2	1	50%
WB Pennsylvania Avenue at 14th Street	0.76	0.61	20%	22	29	-32%	1	6	-500%
WB M Street at New Hampshire Avenue	0.4	0.64	-60%	38	77	-103%	1	8	-700%
EB P Street at 16th Street	0.33	0.18	45%	19	37	-95%	2	12	-500%
SB Louisiana Avenue at Constitution Avenue	0.3	0.34	-13%	20	27	-35%	2	6	-200%
EB Pennsylvania Avenue at 9th Street	0.45	0.45	0%	21	19	10%	1	6	-500%
NB 13th Street at New York Avenue	0.33	0.01	97%	25	25	0%	1	7	-600%
WB K Street at 14th Street	0.32	0.32	0%	23	64	-178%	1	1	0%
SB 4th Street at Independence Avenue	0.31	0.31	0%	24	16	33%	1	1	0%
EB Pennsylvania Avenue at Constitution Avenue	0.31	0.41	-32%	20	29	-45%	1	13	-1200%

C. Google Traffic Comparison

Additional evidence of congestion reductions can be derived from Google Maps Traffic® which uses crowd sourced traffic data to graphically represent traffic conditions. Traffic conditions are typically represented on a color scale where green indicates faster moving traffic while yellow and red indicates slower moving traffic. **Figure 19** and **Figure 20** show the traffic conditions in the vicinity of Constitution Avenue and Independence Avenue "Before" and "After" optimization at 8:00 AM. **Figure 21** and **Figure 22** show the same comparison at 4:00 PM. All illustrate significant areas of congestion reduction.

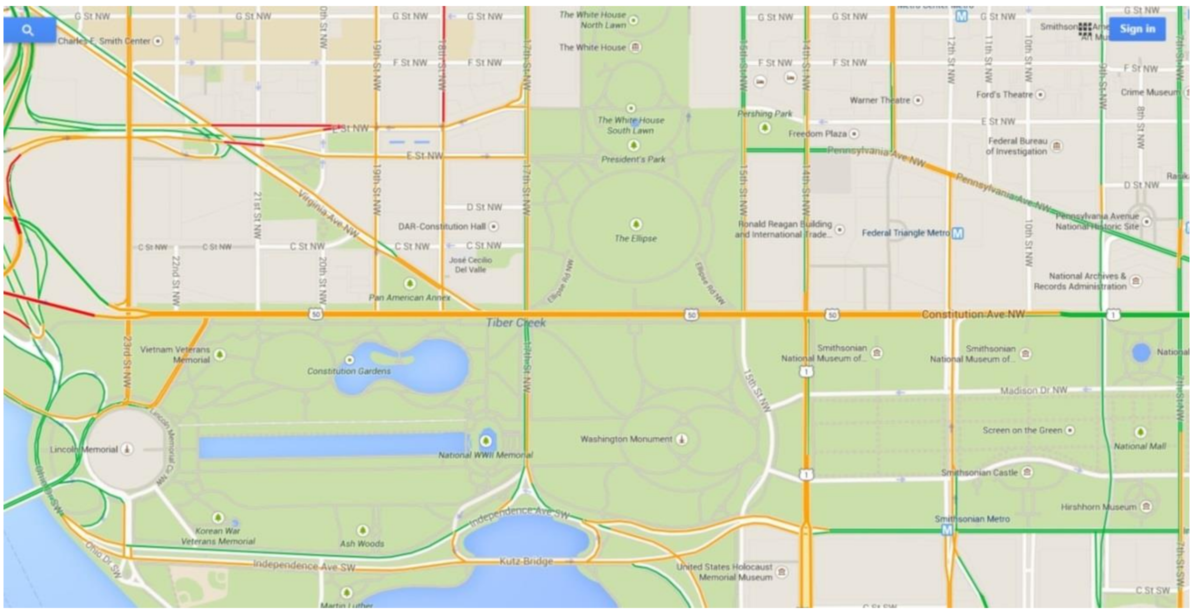

Figure 19: Google Traffic – Typical Traffic at 8 AM on a Tuesday

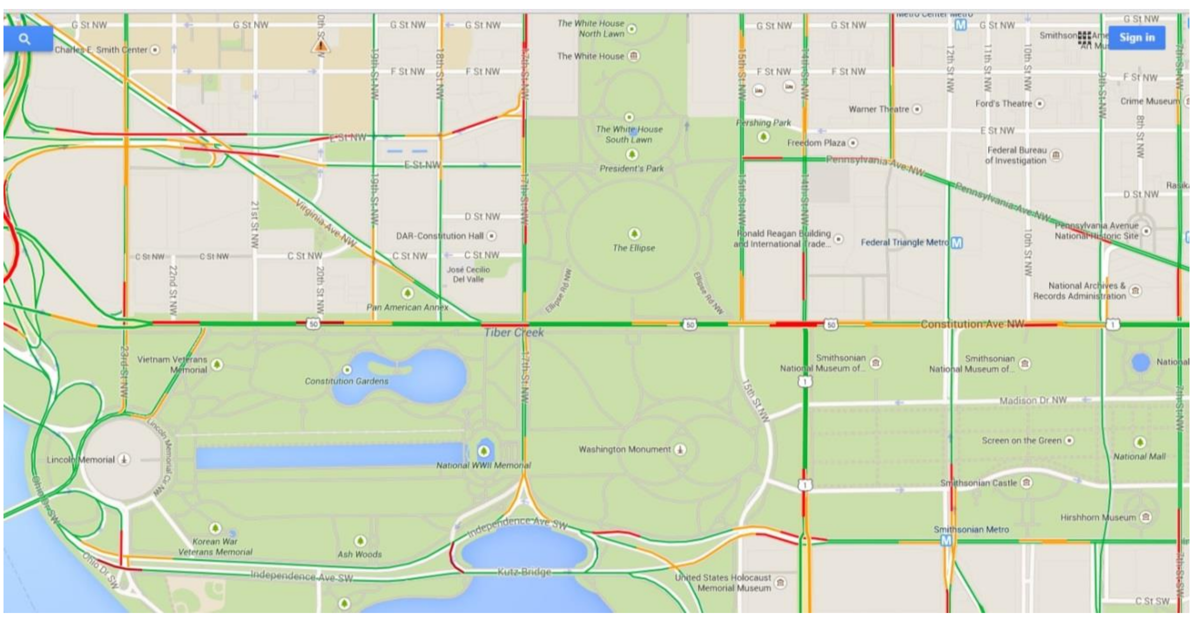

Figure 20: Google Traffic – Live Traffic at 8 AM on a Tuesday – "After" Signal Timing Optimization

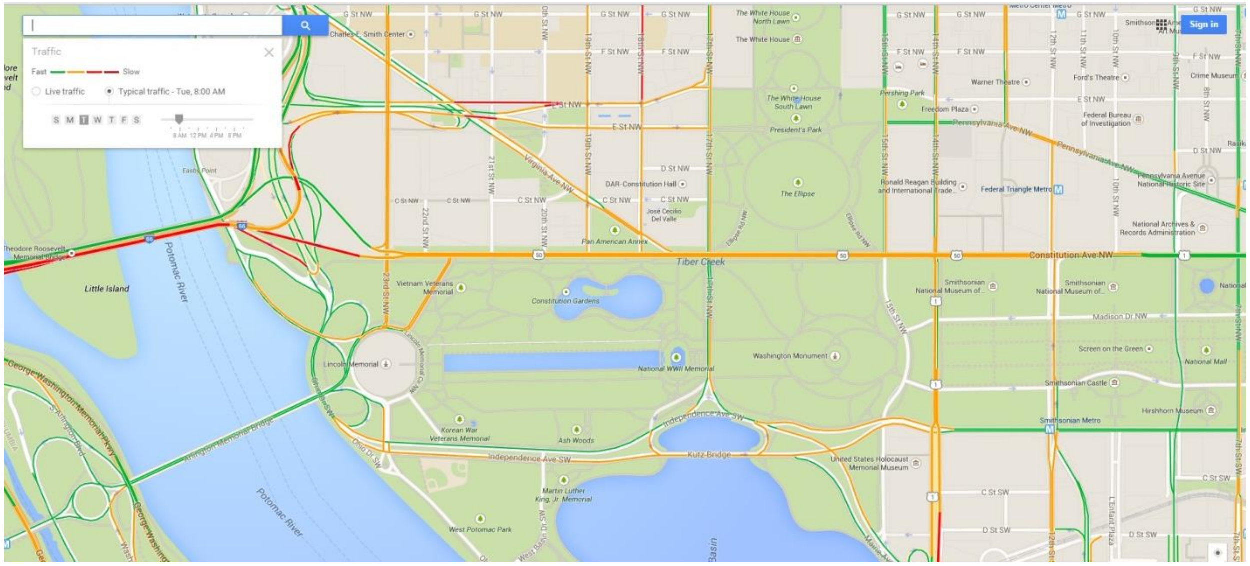

Figure 21: Google Traffic – Typical Traffic at 4 PM on a Tuesday

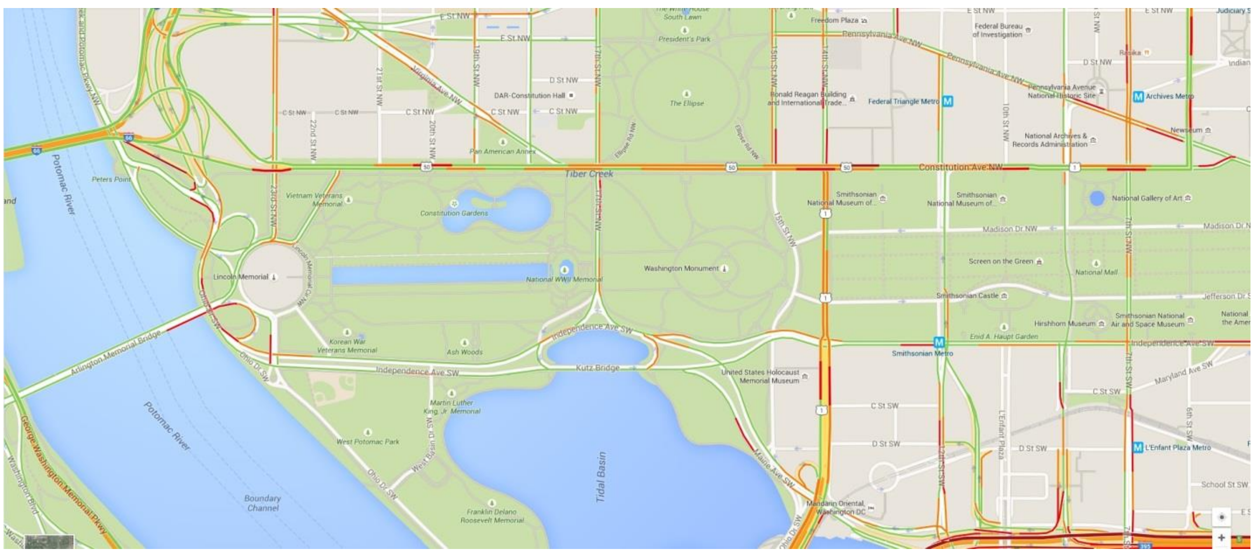

Figure 22: Google Traffic – Live Traffic at 4 PM on a Tuesday – "After" Signal Timing Optimization

Figure 23 and **Figure 24** show the traffic conditions in the vicinity of Connecticut Avenue "Before" and "After" optimization at 8:15 AM on Tuesday, June 9th, 2015. The snapshots illustrate significant improvements on southbound Connecticut Avenue, particularly between Florida Avenue and K Street. In late May, 2015, after the probe vehicle travel time and delay data were collected, DDOT made an additional change to optimize the signal phasing at Connecticut and Florida Avenue, NW, which resulted in an overall improvement to AM peak period Connecticut Avenue travel times. Note that this is different result than shown in the following section (refer to Figure 25: AM Peak Improvements), which shows that southbound Connecticut Avenue travel times increased.

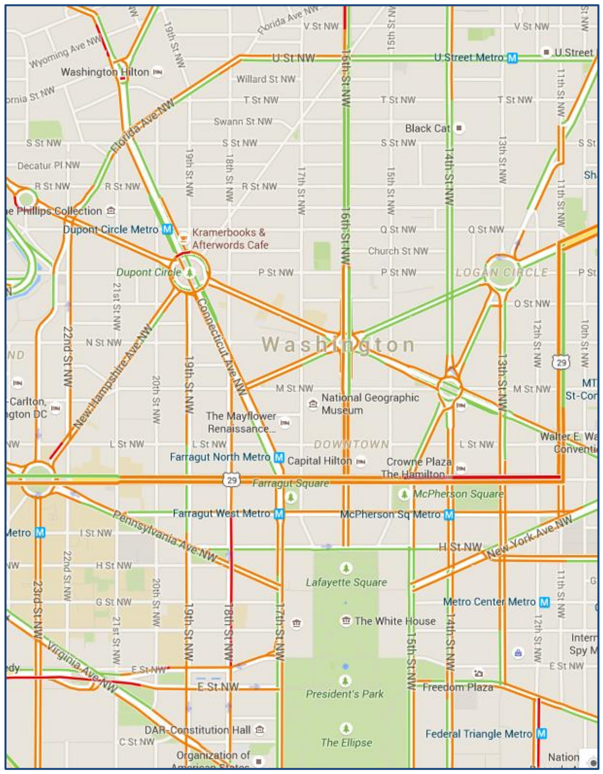

Figure 23: Google Traffic – Live Traffic at 8:15 AM – "Before" Signal Timing Optimization

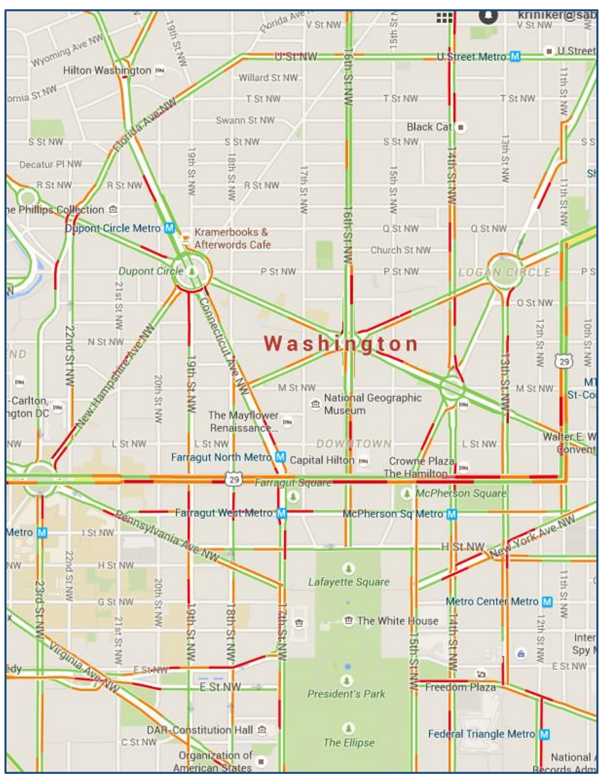

Figure 24: Google Traffic – Live Traffic at 8:15 AM – "After" Signal Timing Optimization

D. "Floating Car" Vehicle Travel Time and Delay Improvements

To assess the impact of the signal timing optimization, "Before" travel time studies were collected in April 2015, and compared to "After" travel time studies collected in May 2015. Travel time runs were performed along the entire length of 49 routes (for the purposes of this report a route is considered one direction due to the multiple on-way streets downtown) using the "floating car" method. In this method, a probe vehicle is driven at an average speed along the evaluation route, allowing vehicular speed to be dictated by the platoon speed and within posted speed limit. Travel time data was collected using GPS (Global Positioning System) equipment and analyzed using the Tru-Traffic software program. The results of the travel time studies are tabulated in **Table 3** and illustrated in **Figures 26-28** for the AM, Midday, PM and Saturday peak periods respectively.

- In general, the travel time and delay studies showed travel time improvements on all directions of all 49 routes under each signal timing pattern – AM, Midday, PM, Overnight and Weekend.
- The average travel time reduction, over all corridors was 1 to 1 ½ minutes in the AM, Midday and Weekend peak periods, and 2 minutes during the PM peak period. (Travel times were not collected during the Overnight signal timing pattern). The average length of all the corridors studied was 1.6 miles with a standard deviation of 0.6 miles.
- Some routes, such Pennsylvania Avenue and New York Avenue showed an increase in travel time, usually associated with the off-peak direction of travel (outbound in the AM, inbound in the PM), but not in all cases. This was a consequence of the natural optimization of key corridors, of which these two routes were considered lower priority, and was expected.
- Travel times shown an increase on southbound Connecticut Avenue, which is the critical direction (inbound) during the AM peak hour. However, as noted previously, this data was collected prior to a change to optimize the signal phasing at Connecticut and Florida Avenue, NW, which resulted in an overall improvement to AM peak period Connecticut Avenue travel times.
- In addition to travel times, the frequency of stopping along a corridor was compared between "Before" and "After" conditions for a sample set of 15 routes. Overall, the frequency of stopping decreased by 14% over all signal timing patterns. Specifically, the frequency of stopping was reduced (i.e. improved) by 6% in the AM, 34% in the Midday, 12% in the PM, and 4% in the weekend. Along some routes, such as Pennsylvania Avenue and New York Avenue, where were considered a lower priority in terms of progression of traffic, the frequency of stopping increased. This correlates with the increase in travel times also measured along these same routes.

Table 3: "Before" versus "After" Signal Timing Optimization Travel Times (Minutes)

Route	AM		Midday		PM		Saturday	
	"Before"	"After"	"Before"	"After"	"Before"	"After"	"Before"	"After"
EB Constitution[1] 23rd to 14th NW	5:34	4:22	4:15	3:57	6:01	5:20	4:30	3:30
WB Constitution[1] 14th NW to 23rd	3:38	3:57	3:13	3:34	4:19	4:22	3:45	4:10
EB Independence 1st SW to 23rd	10:00	7:33	9:75	9:01	10:13	9:48	Construction / No Data	Construction / No Data
WB Independence 23rd to 1st SW	10:45	8:46	8:44	7:50	13:09	12:30	Construction / No Data	Construction / No Data
EB New York Avenue 9th to 15th NW	5:20	4:50	4:11	4:53	6:57	3:31	4:30	5:38
WB New York Avenue 9th to 15th NW	4:32	4:51	5:24	4:20	5:34	5:54	5:53	3:51
NB 7th Street Maine to Howard U	17:50	15:19	23:33	19:00	22:24	18:27	19:19	17:54
SB 7th Street Howard U to Maine	21:41	18:26	23:37	18:20	22:47	22:20	20:01	19:02
NB 16th Street H St to Crescent	7:14	6:53	6:54	Construction / No Data	9:35	6:26	6:22	5:35
SB 16th Street Crescent to H St.	11:40	10:42	6:24	Construction / No Data	6:30	5:37	9:25	7:44
NB 14th Street[1] Independence- Fla.	8:28	8:10	12:56	11:15	9:10	8:01	12:08	10:40
SB 14th Street[1] Fla.-Independence	10:19	10:31	12:21	12:09	13:57	12:10	8:53	7:59
EB Rhode Island Scott Circle to V St	9:39	9:15	8:20	8:15	10:13	9:05	To 6th St 5:12	To 6th St 5:26
WB Rhode Island V St to Scott Circle	13:09	12:16	9:53	9:02	10:22	10:14	From 6th St 5:35	From 6th St 5:46

Route	AM		Midday		PM		Saturday	
	"Before"	"After"	"Before"	"After"	"Before"	"After"	"Before"	"After"
EB Florida / U St Conn. to N. Cap	20:36	12:35	17:54	11:11	20:33	12:56	17:12	12:17
WB Florida / U St N. Cap to Conn.	15:36	11:42	17:24	9:48	17:30	14:40	16:12	13:03
L Street Penn. to 11th	11:28	10:22	13:20	11:51	14:27	11:46	9:08	9:12
EB K Street 27th to 11th	9:33	8:08	9:34	10:02	11:50	7:06	Construction / No Data	Construction / No Data
WB K Street 11th to 27th	8:05	8:22	7:29	7:09	12:36	12:06	Construction / No Data	Construction / No Data
NB 20th E St. to Q St.	10:00	6:15	8:08	4:33	7:00	5:08	8:03	6:11
SB 21st New Hamp to Const.	7:06	5:50	6:05	6:19	6:50	6:00	4:38	4:52
NB 23rd Const. to Wash. Cir	4:53	3:48	2:51	3:06	4:06	4:00	Construction / No Data	Construction / No Data
SB 23rd Wash. Cir to Const.	4:19	3:44	3:27	2:25	4:36	2:35	Construction / No Data	Construction / No Data
EB Penn 26th to 17th	3:46	3:07	5:51	4:44	5:46	3:12	No data	No data
WB Penn 17th to 26th	7:25	5:32	No data	No data	4:23	5:23	No data	No data
EB Penn 14th to 3rd	3:12	5:32	8:23	5:34	9:34	8:30	Road Closure / No Data	Road Closure / No Data
WB Penn 3rd to 14th	5:55	4:55	5:35	6:15	6:08	6:52	Road Closure / No Data	Road Closure / No Data
NB N. Cap La. to Randolph	6:39	4:46	Construction / No Data	Construction / No Data	9:48	6:28	To M St 4:11	To M St 3:00
SB N. Cap Randolph to La.	7:14	6:29	Construction / No Data	Construction / No Data	12:12	9:57	From M St 7:26	From M St 2:50

Route	AM		Midday		PM		Saturday	
	"Before"	"After"	"Before"	"After"	"Before"	"After"	"Before"	"After"
SB 9th St Sherman to Const.	8:58	7:47	11:21	8:23	13:52	11:48	11:01	9:10
NB 9th St Mass to Sherman	5:00	5:19	5:45	4:48	5:06	5:01	No Data	No Data
EB M St/ Georgetown MacArthur to 28th	5:20	5:11	No data	No data	10:24	7:40	No data	No data
WB M St/Georgetown 28th to MacArthur	No Data	No Data	7:38	6:04	10:14	5:18	No data	No data
NB Wisconsin M to Q St	2:36	1:45	No data	No data	No data	No data	No data	No data
SB Wisconsin Q to M St	3:37	2:05	No data	No data	No data	No data	No data	No data
EB H St 19th to 6th	6:52	6:32	12:20	12:49	9:26	8:53	12:30	7:19
WB H St 5th to New York Ave	5:50	4:26	6:00	4:50	5:04	4:32	5:03	2:58
Eye St 21st to 11th St	6:44	6:08	8:30	6:40	13:30	6:22	5:22	3:12
M St 18th to 26th St.	5:10	2:45	3:08	2:30	6:20	3:30	5:56	2:07
NB Conn./17th Constitution to Fla.	17:25	11:04	10:34	8:17	13:50	10:05	No Data	No Data
SB Conn./17th Fla. to Constitution	12:39	Before Phase Change 13:26	12:03	10:07	27:49	28:34	No Data	No Data
NB 12th St Penn to Mass	5:02	2:42	5:59	Construction / No Data	7:28	3:34	4:03	2:53
NB 15th St K to Florida	5:01	5:06	4:49	4:43	6:33	4:33	4:53	4:31
NB 6th St Const. to Rhode Is.	6:31	5:44	6:40	6:53	12:18	8:16	5:37	Special Event/No Data

Route	AM		Midday		PM		Saturday	
	"Before"	"After"	"Before"	"After"	"Before"	"After"	"Before"	"After"
SB 6th St Rhode Is. to Const.	10:21	6:55	8:04	7:07	11:04	9:49	6:55	Special Event/No Data
NB 18th St Const. to Conn. / M St	10:45	7:17	Construction / No Data	Construction / No Data	7:52	6:22	4:10	3:57
19th St M St to Const.	05:53	05:59	8:16	6:40	7:44	7:10	To E St 3:33	To E St 2:45
EB Mass. Ave[1] Rock Creek to N. Cap	14:10	12:38	14:47	13:54	16:17	13:43	12:10	13:43
WB Mass. Ave[1] N. Cap to Rock Creek	16:56	15:56	18:01	16:56	18:28	16:09	15:25	14:48
TOTALS[2]	**7 Hours 0 minutes**	**5 hours 56 minutes**	**6 hours 17 minutes**	**5 hours 20 minutes**	**8 hours 22 minutes**	**6 hours 50 minutes**	**4 hours 40 minutes**	**4 hours 6 minutes**
TOTAL TRAVEL TIME SAVINGS BY PEAK	**1 hour 4 minutes**		**57 minutes**		**1 hour 32 minutes**		**34 minutes**	

[1] - Travel Time data for selected routes derived from INRIX® Travel Time data. Absolute values are aggregated over entire peak periods and may be higher or lower than GPS-based travel time data which has fewer data points.

2 - Note that there is more data "missing" for the Midday and Weekend, and especially the Weekend, so the absolute numbers are lower. However, relative differences may still be used for "Before" versus "After" comparison, but not for a comparison between the other peak periods.

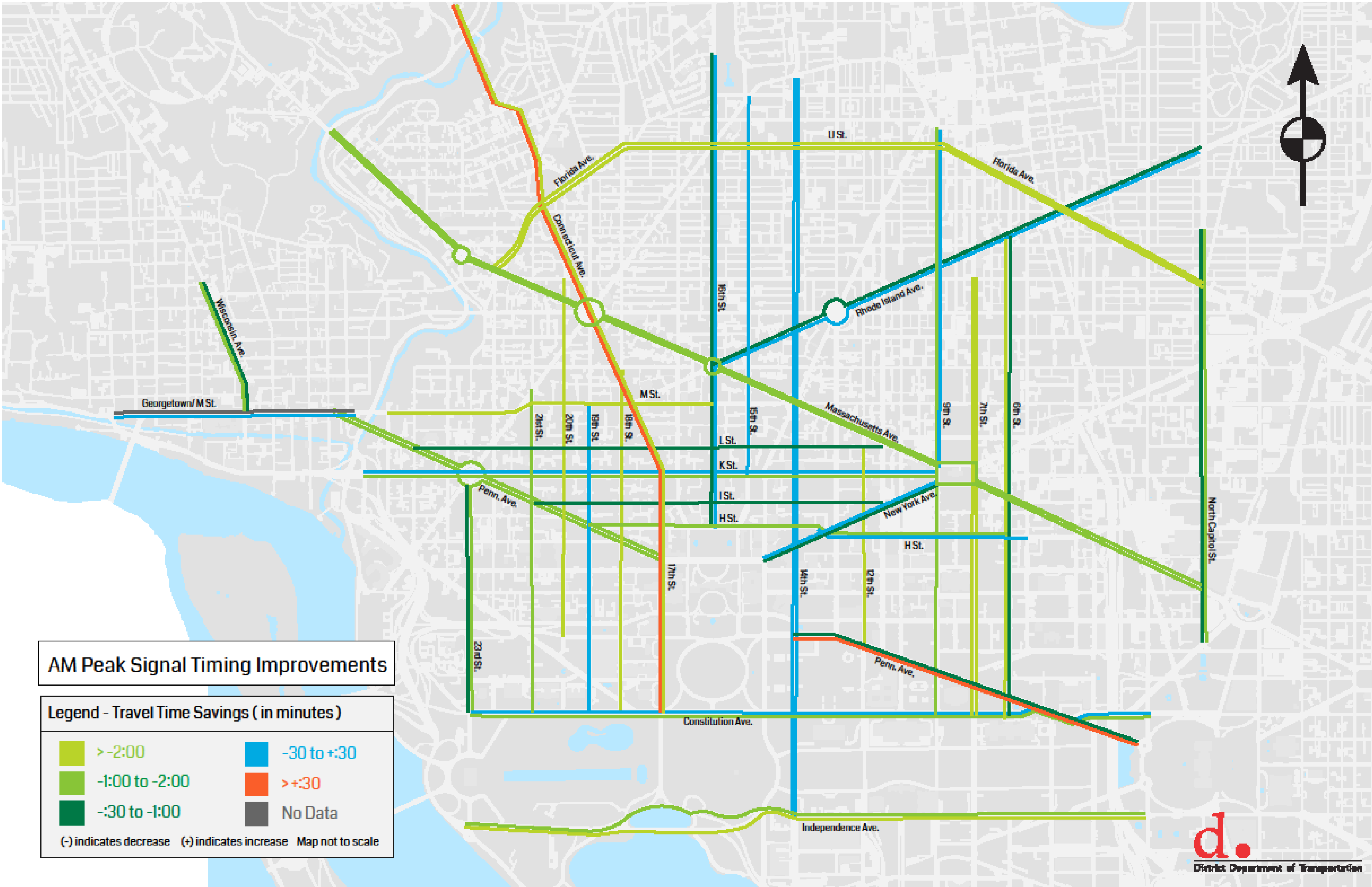

Figure 25: AM Travel Time Improvements Map

Note: SB Conn. Ave. travel time was reduced compared to "before" conditions by a signal phase optimization at Florida Avenue after this data was collected

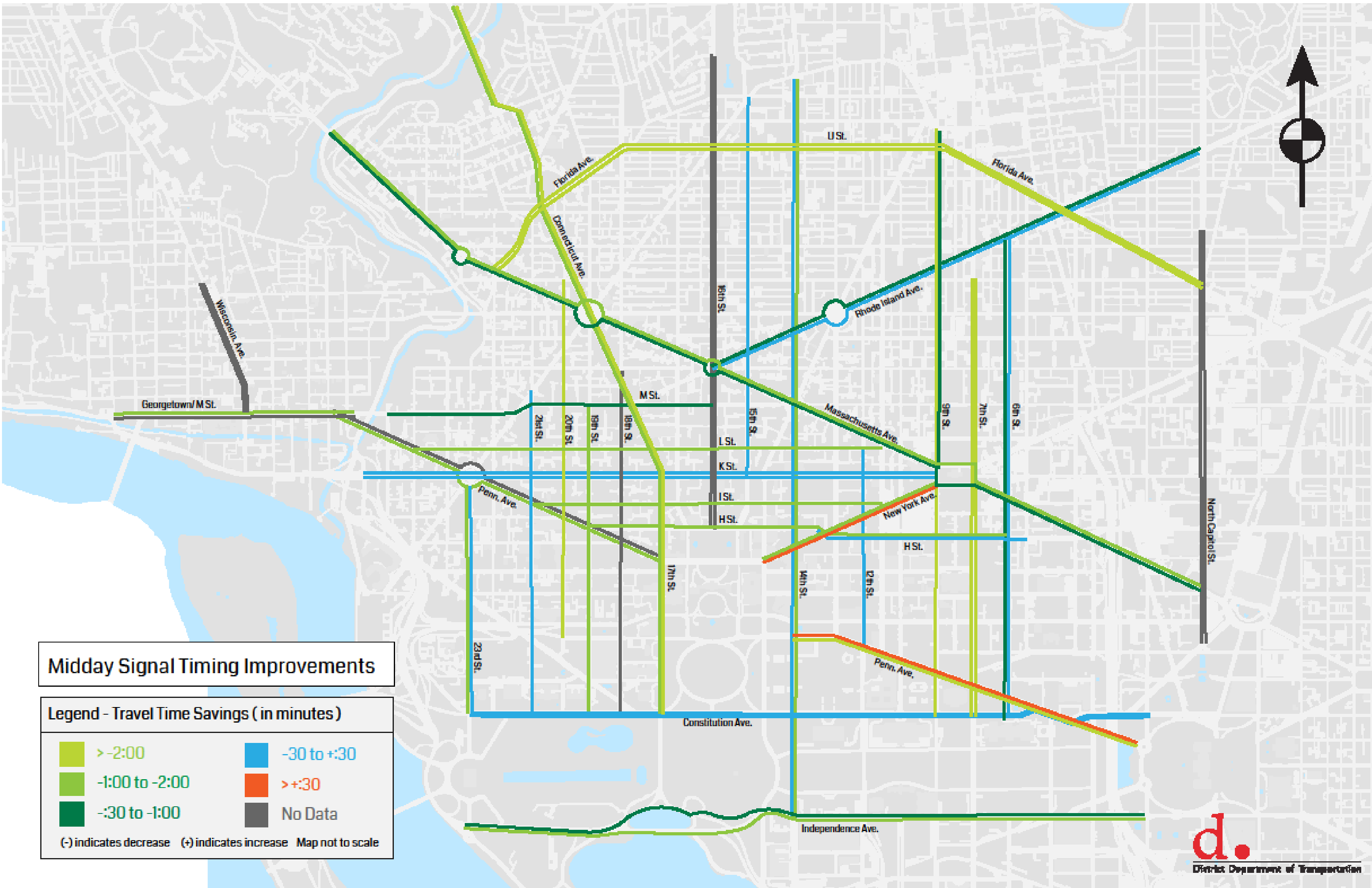

Figure 26: Midday Travel Time Improvements Map

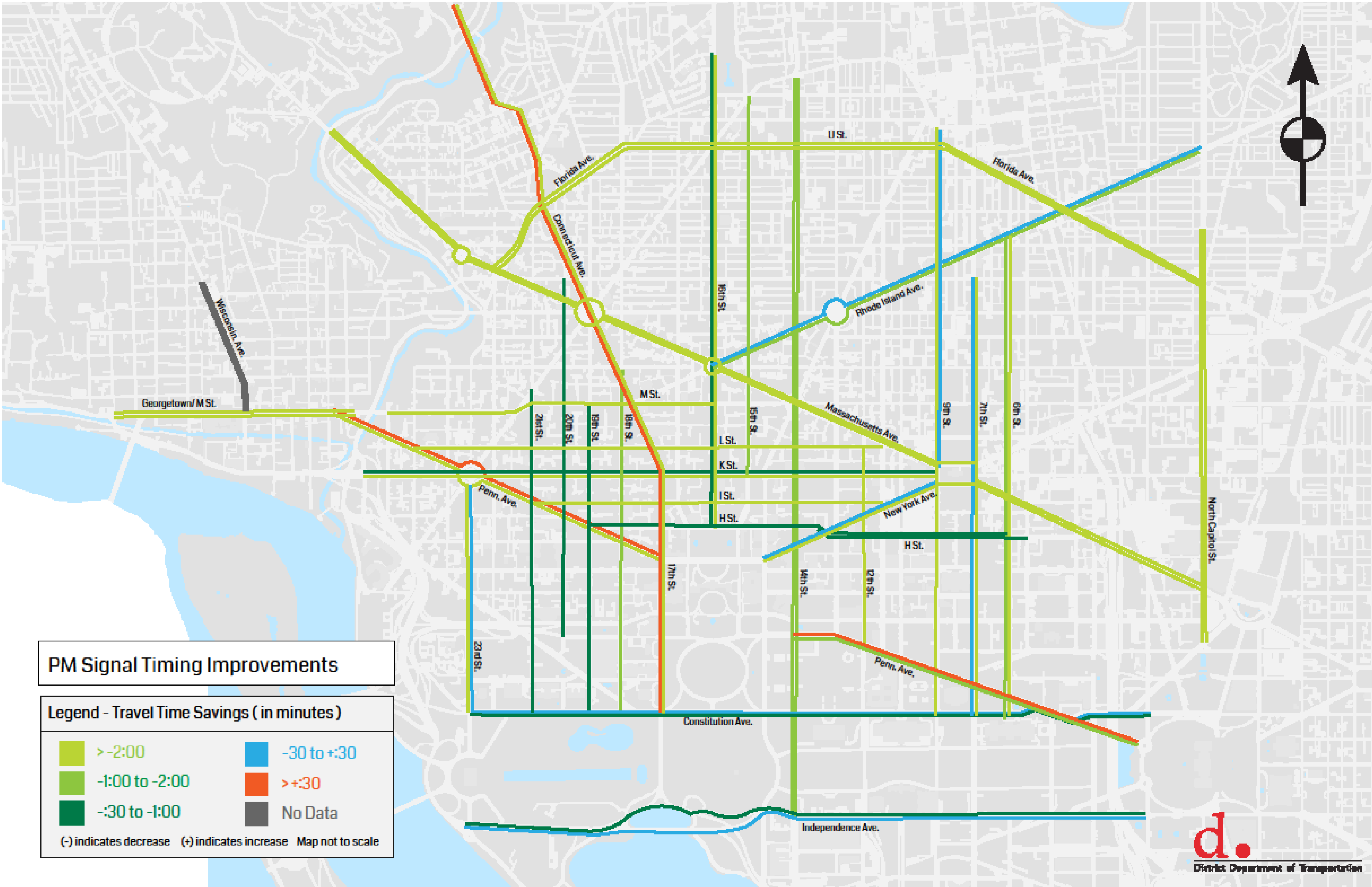

Figure 27: PM Travel Time Improvements Map

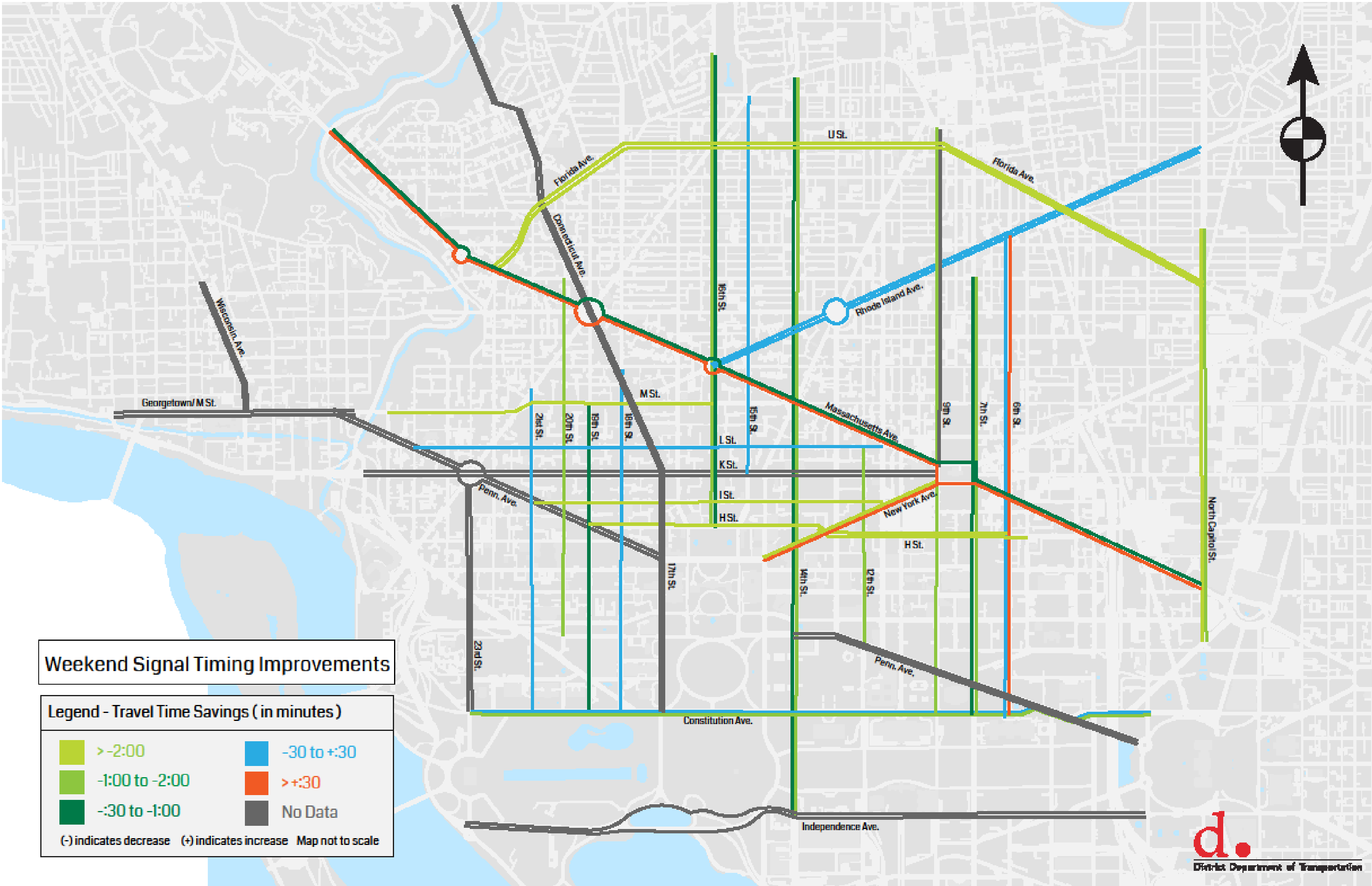

Figure 28: Weekend Travel Time Improvements Map

Some explanation of the "TOTAL TRAVEL TIME SAVINGS BY PEAK" data in **Table 3** is necessary. Consider this hypothetical example, which is based on data the collected from nearly 50 corridors throughout the City in terms of "Before" (signal timing optimization) travel times compared to "After" (signal timing optimization) travel times. "Before" the signal timings were optimized, if you drove each of these 60 corridors in the peak 60-minutes of the AM rush hour, it would take you 7 hours, or 7 days (drive one hour each day) to complete all of your trips. "After" the signal timings were optimized, if you drove these same 60 corridors during the same time periods, it would take you a less than 6 hours! Similarly, if you drove these same corridors in the most-congested portion of the Midday peak 60-minutes (around lunch time), the "Before" trips would take over 6 hours whereas the "After" trips would take just over 5 hours. And finally, for the peak 60-minutes of the PM rush hour, the "Before" trips would take almost 8 ½ hours whereas the "After" trips would take 6 hours and 50 minutes! This data is illustrated in **Figure 29.**

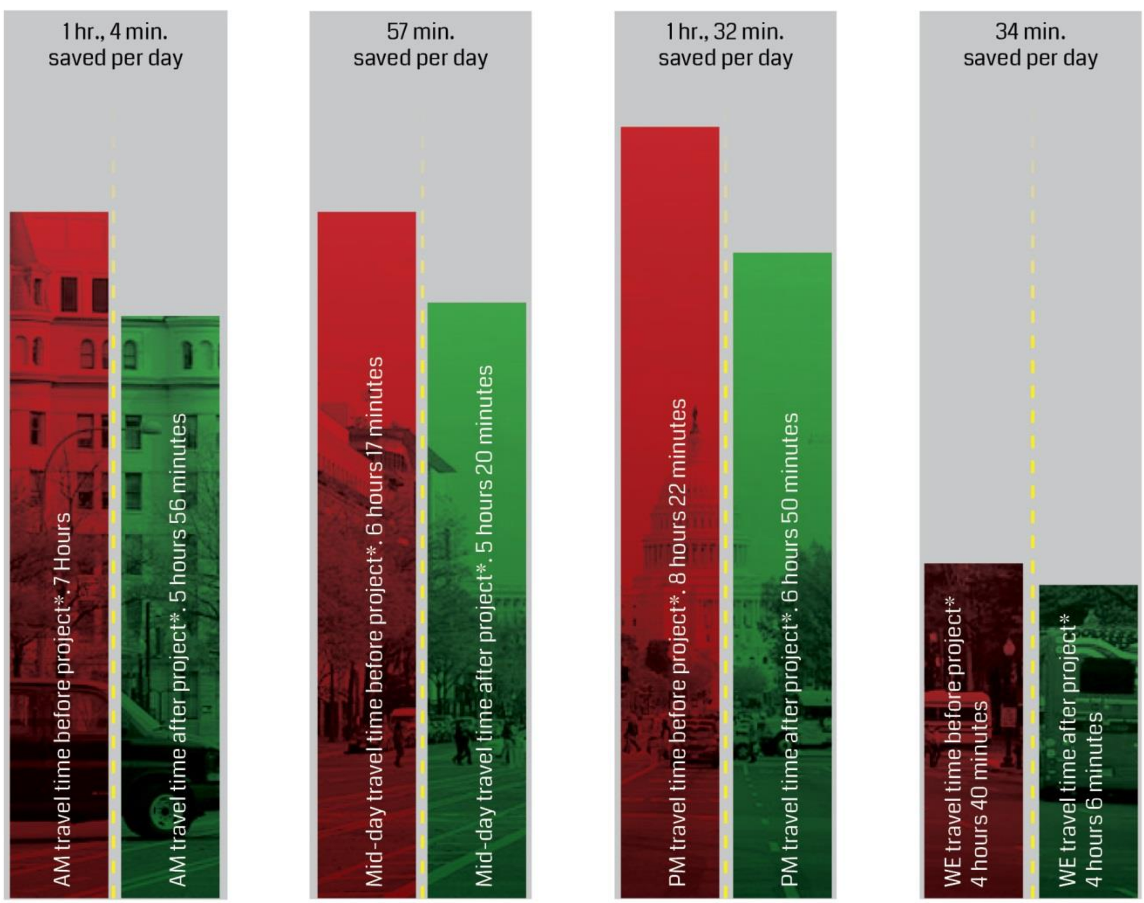

Figure 29: Cumulative Travel Time Comparison of Vehicle Travel Time over 49 Routes

E. Bus Travel Time Improvements

Improving bus running times and reducing bus delays was one of the goals of the optimization project. WMATA Metro Bus vehicles are equipped with Automatic Vehicle Locators (AVLs) which allow bus locations to be tracked and recorded, and bus delays and running times evaluated. Using this data, it is possible to compare bus route travel times within the study area “before” and “after” the signal timing optimization to determine if the project goal of improving bus running times and reducing bus delays was met.

AVL data was collected for WMATA Metro Bus routes operating in the Downtown Core area for 5 weekdays “before” optimization (4/20/2015 to 4/24/2015) and 5 weekdays “after” optimization (5/4/2015 to 5/8/2015). Travel time was analyzed for the weekday AM, Midday and PM peak periods for forty (40) routes (20 route numbers x 2 directions) consisting of over 21,000 data points within the Downtown Core. The selected routes and their average weekday ridership are listed in **Table 4**. These routes account for nearly 90,000 person-trips per day. Average “before” and “after” travel times for all routes during the AM, Midday and PM peaks are shown in

Figure 30**.** The overall Downtown Core bus system experienced significant improvements in travel times throughout the day. AM, Midday and PM Peak bus travel times have improved by 4% to 7% across the Downtown Core with an average reduction in absolute travel time over one (1) minute. Changes in individual bus route travel times range from a 7% increase to a 22% decrease. The largest increase in travel time was just under two (2) minutes while the largest decrease was just under ten (10) minutes. **Table 5** presents the average travel time data by route for each direction, for each peak period.

The previous sections of this report demonstrated considerable improvements for vehicular traffic. However, in a signal timing project, it is not a foregone conclusion that transit vehicles also experience similar travel time improvements since city bus operating speeds and ‘normal’ vehicular operating speeds are quite different. It may be that, if the signal timing project was designed for ‘normal’ vehicles, bus operations would be negatively affected. However, the analysis of bus travel time data showed that not only did overall travel times generally improve, but that peak period, peak direction travel times improved more than peak period opposite-direction travel times. In some cases, similar to vehicular experiences, transit line travel times did increase, but they were in the minority in terms of frequency of occurrence and magnitude.

Table 4: Selected Downtown Core Bus Route Weekday Ridership

Route #	Bus Line	2014 Weekday Ridership	Primary Routes
32,36	Pennsylvania Avenue	13,981	Penn. Ave, I St / H St, M St & Wisc. Ave
37	Wisconsin Avenue Limited	654	Wisc. Ave, Mass Ave, 21st/20th, Eye/H St, 13th, Penn Ave
39	Pennsylvania Avenue Limited	895	23rd St, Penn. Ave, Eye/H St, 13th, 7th, Independence Ave

Route #	Bus Line	2014 Weekday Ridership	Primary Routes
52,53,54	14th Street	15,527	14th St, Penn. Ave, 7th, D St, F St, 6th St, 11th St
70	Georgia Avenue-7th Street	10,625	Georgia Avenue / 7th Street
79	Georgia Avenue Limited	8,067	Georgia Avenue, 7th St / 9th St
80	North Capitol Street	7,097	North Cap., H St, K St, 18th/19th St, Virginia Ave
11Y	Mt. Vernon Express	452	14th,Eye/H St, 19th/18th St, 15th St
16X	Columbia Pike-Federal Triangle	977	Independence Ave, 7th St, 6th St, Penn. Ave
16Y	Columbia Pike-Farragut Square	1,718	18th / 19th St, K St
3Y	Lee Highway-Farragut Square	462	18th / 19th St, K St
G8	Rhode Island Avenue	4,221	Rhode Island Ave, 9th/11th St, Eye/H St
L1,L2	Connecticut Avenue	5,053	L1 - Connecticut Ave, Florida Ave, New Hamp. Ave, 23rd St, Constitution Ave L2 - Connecticut Ave
S2,S4	16th Street	14,274	14th, K St/ Eye St, H St, 11th St, 12th / 10th, Constitution Ave
S9	16th Street Limited	3,747	16th Street, K St, Eye St

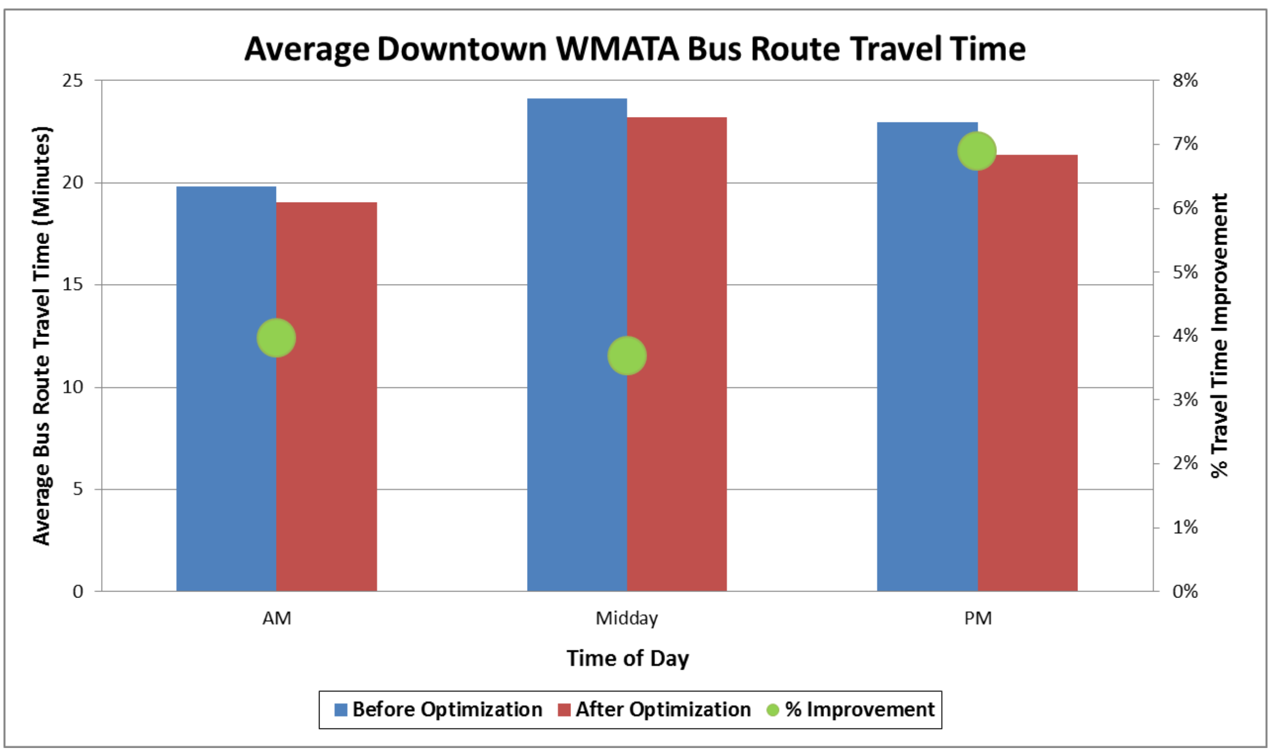

Figure 30: Average Downtown WMATA Bus Route Travel Time by Time of Day

Travel time data for the individual routes during the AM, Midday and PM peaks was also synthesized and is illustrated in **Figure 31**, **Figure 32** and **Figure 33**. It should be noted that data is not available for some routes due to limitations on operating hours, direction and/or data sample size.

Using the WMATA ridership and bus AVL travel time data, an aggregate measure of person-hours of delay savings was calculated. According to WMATA, approximately 60 percent of Metrobus ridership on a typical weekday occurs in the peak hours between 6am-10am and 3pm-7pm. Therefore, it was assumed that 30% of the average weekday ridership occurs during each of the AM and PM peaks. It was also assumed that approximately 15% of the average weekday ridership occurs during the Midday peak. For express routes which operate only during AM and PM peaks, it was assumed that 50% of the ridership occurs during each of the AM and PM peaks. The assumed peak ridership shares were multiplied by the total weekday ridership for each route; then the total ridership by peak for each route was then multiplied by the average peak travel time savings over all routes in the analysis and converted to person-hours.

The signal timing optimization reduced travel time on Metro buses, resulting in:

- 359 person-hours of delay reduction in the AM peak hour,
- 185 person-hours of delay reduction in the Midday peak hour,
- 718 person-hours of delay reduction in in the PM hour.
- A daily savings of 1,262 person-hours.
- An annual savings of over 315,000 person-hours.

The annual savings is based on 250 weekdays per year.

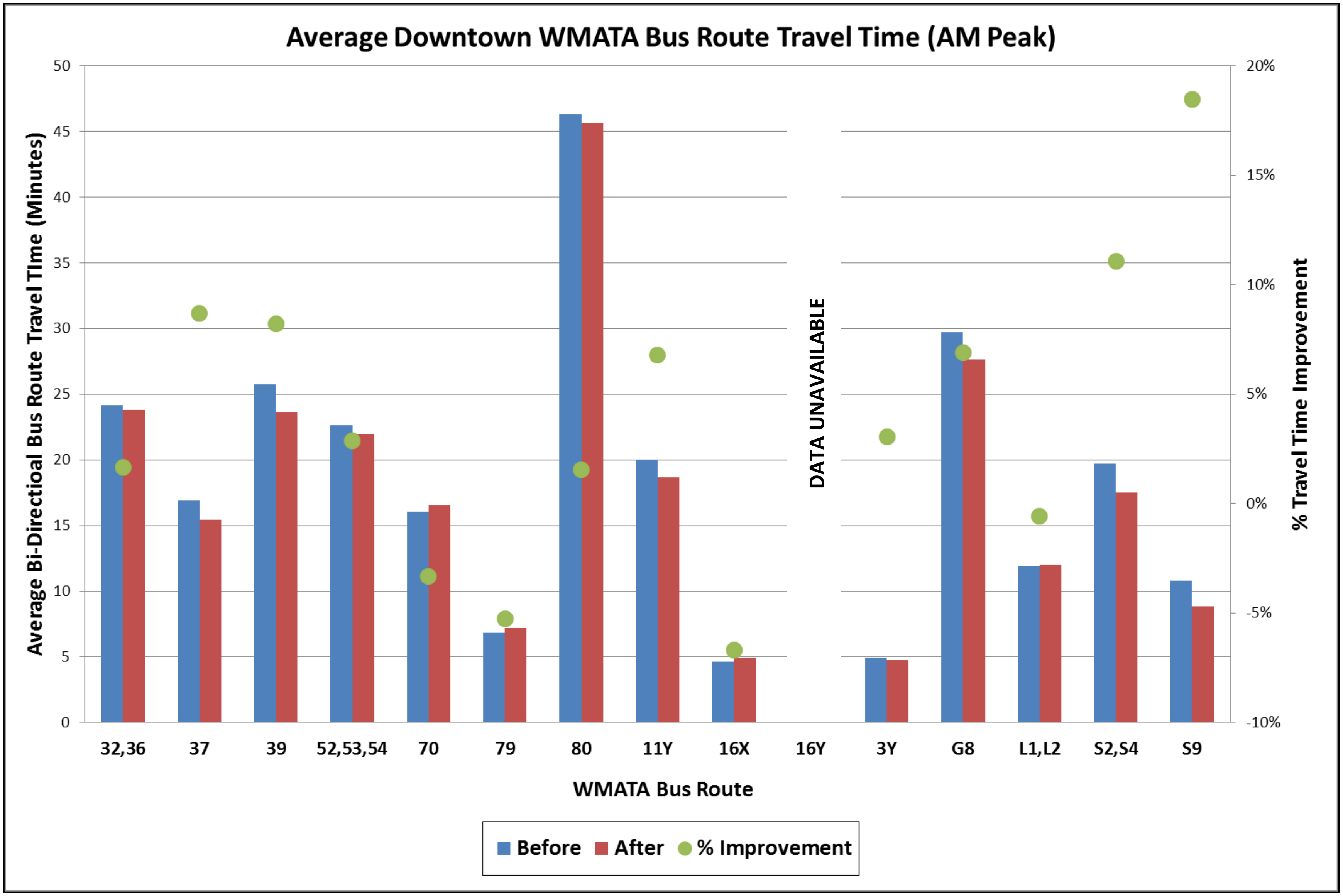

Figure 31: Average AM Peak Downtown WMATA Bus Route Travel Time by Individual Route

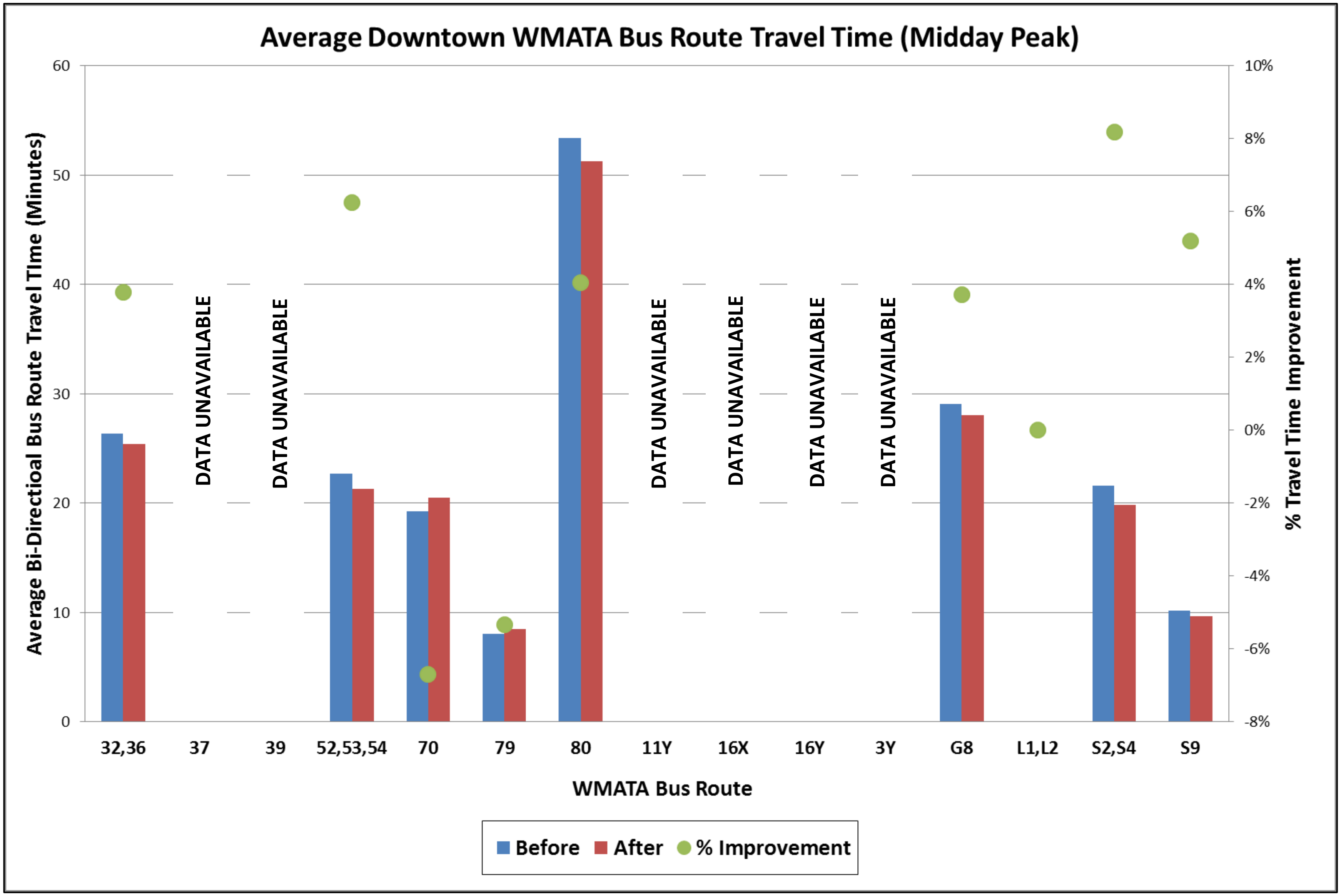

Figure 32: Average Midday Peak Downtown WMATA Bus Route Travel Time by Individual Route

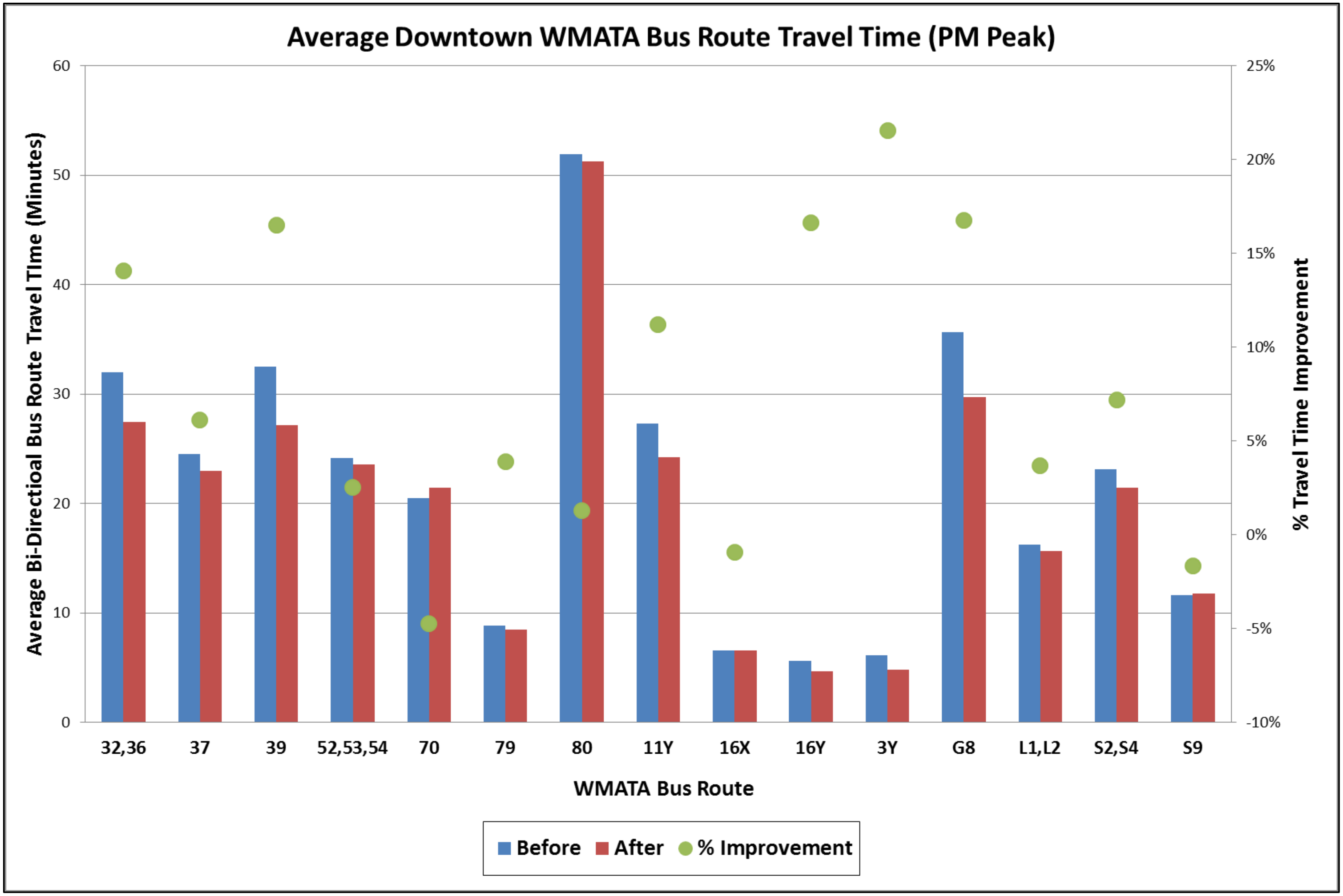

Figure 33: Average PM Peak Downtown WMATA Bus Route Travel Time by Individual Route

Table 5: Summary of Bus Travel Time "Before" and "After" Signal Timing Optimization

Bus Route		Peak Period											
		AM				MD				PM			
		Before (Min.)	After (Min.)	Change (sec.)	% Improved	Before (Min.)	After (Min.)	Change (sec.)	% Improved	Before (Min.)	After (Min.)	Change (sec.)	% Improved
53	North	10.0	10.7	44	-7%	13.2	11.8	-83	11%	14.6	13.5	-67	8%
	South	11.1	10.1	-63	9%	10.8	10.3	-29	5%	11.8	12.0	14	-2%
S9	North	10.8	8.8	-120	18%	12.9	10.4	-155	20%	12.1	12.0	-10	1%
	South	8.6	9.7	64	-12%	10.2	9.7	-32	5%	11.1	11.6	33	-5%
37	North	--	--	--	--	--	--	--	--	24.5	23.0	-88	6%
	South	17.0	15.4	-92	9%	16.8	17.5	46	-5%	--	--	--	--
39	East	--	--	--	--	--	--	--	--	32.5	27.2	-323	17%
	West	25.8	23.6	-127	8%	--	--	--	--	--	--	--	--
11Y	North	20.0	18.7	-82	7%	--	--	--	--	--	--	--	--
	South	--	--	--	--	--	--	--	--	27.3	24.3	-184	11%
16X	East	5.3	5.4	5	-2%	--	--	--	--	5.8	6.2	24	-7%
	West	4.0	4.5	32	-13%	3.8	4.2	22	-10%	7.3	7.1	-17	4%
16Y	East	3.1	3.8	37	-19%	--	--	--	--	--	--	--	--
	West	--	--	--	--	--	--	--	--	5.7	4.7	-56	17%
3Y	East	4.9	4.8	-9	3%	--	--	--	--	--	--	--	--
	West	--	--	--	--	--	--	--	--	6.1	4.8	-79	22%
79	North	6.8	6.6	-11	3%	9.0	9.2	9	-2%	9.4	9.1	-19	3%
	South	6.9	7.8	55	-13%	7.1	7.9	43	-10%	8.2	7.8	-23	5%
70	North	16.0	16.6	31	-3%	20.4	22.0	100	-8%	21.5	21.7	13	-1%
	South	16.0	16.6	34	-3%	18.1	19.1	56	-5%	19.5	21.3	104	-9%
52	North	24.9	25.5	35	-2%	29.2	27.5	-100	6%	30.6	30.1	-32	2%
	South	23.5	22.3	-73	5%	24.7	23.4	-78	5%	26.1	26.5	25	-2%

Bus Route		Peak Period											
		AM				MD				PM			
		Before (Min.)	After (Min.)	Change (sec.)	% Improved	Before (Min.)	After (Min.)	Change (sec.)	% Improved	Before (Min.)	After (Min.)	Change (sec.)	% Improved
54	North	29.6	29.9	17	-1%	32.8	30.2	-152	8%	33.2	32.4	-49	2%
	South	23.9	22.1	-111	8%	25.5	24.4	-66	4%	28.9	27.1	-109	6%
80	North	45.0	45.0	3	0%	59.3	58.5	-49	1%	54.5	54.7	11	0%
	South	47.8	46.3	-89	3%	47.5	44.0	-211	7%	49.3	47.8	-91	3%
G8	East	24.7	23.8	-55	4%	28.9	27.0	-110	6%	37.4	29.9	-447	20%
	West	34.7	31.5	-191	9%	29.3	29.0	-20	1%	34.0	29.5	-271	13%
S2	North	21.3	19.1	-134	10%	21.9	21.1	-52	4%	24.9	24.3	-38	3%
	South	17.4	16.3	-66	6%	20.2	18.3	-114	9%	23.5	19.0	-271	19%
S4	North	22.6	18.4	-255	19%	23.4	20.9	-149	11%	23.2	22.4	-48	3%
	South	17.5	16.3	-68	7%	21.0	19.2	-110	9%	20.9	20.2	-43	3%
32	East	17.7	17.5	-10	1%	25.0	23.1	-114	8%	32.2	30.8	-84	4%
	West	30.0	29.8	-12	1%	26.9	27.2	15	-1%	31.8	25.5	-377	20%
36	East	18.1	18.4	22	-2%	24.4	23.5	-55	4%	31.3	30.0	-73	4%
	West	31.1	29.8	-77	4%	29.4	28.1	-76	4%	33.0	23.8	-551	28%
L1	North	--	--	--	--	--	--	--	--	28.1	28.1	2	0%
	South	22.4	22.7	16	-1%	--	--	--	--	--	--	--	--
L2	North	6.8	6.7	-8	2%	9.3	10.2	50	-9%	11.2	10.2	-60	9%
	South	6.5	6.6	4	-1%	6.8	10.1	197	-48%	9.6	8.7	-50	9%
Average (Minutes)		19.81	19.03	4%		24.1	23.2	4%		23.0	21.4	7%	
TOTAL TRAVEL TIME SAVINGS PER PEAK (Hours)		10.5	10.2	0.35		10.1	9.8	0.34		13.0	12.1	0.90	

The last row in **Table 5** above is similar to the vehicular "TOTAL TRAVEL TIME SAVINGS BY PEAK" vehicular data. Again, some explanation may be necessary. The following is based on bus travel time data the collected from 40 bus lines throughout the downtown area in terms of "Before" (signal timing optimization) travel times compared to "After" (signal timing optimization) travel times. "Before" the signal timings were optimized, if you rode each of these 40 lines on a bus in the peak 60-minutes of the AM rush hour, it would take you 10 ½ hours, or 10 ½ days (ride one hour each day) to complete all of your trips. "After" the signal timings were optimized, if you rode these same 40 lines during the same time periods, it would take you just over 10 hours. Similarly, if you rode these same lines in the most-congested portion of the Midday peak 60-minutes (around lunch time), the "Before" trips would take over 10 hours whereas the "After" trips would take just under 10 hours. And finally, for the peak 60-minutes of the PM rush hour, the "Before" trips would take 13 hours whereas the "After" trips would take just over 12 hours! This data is illustrated in **Figure 34.**

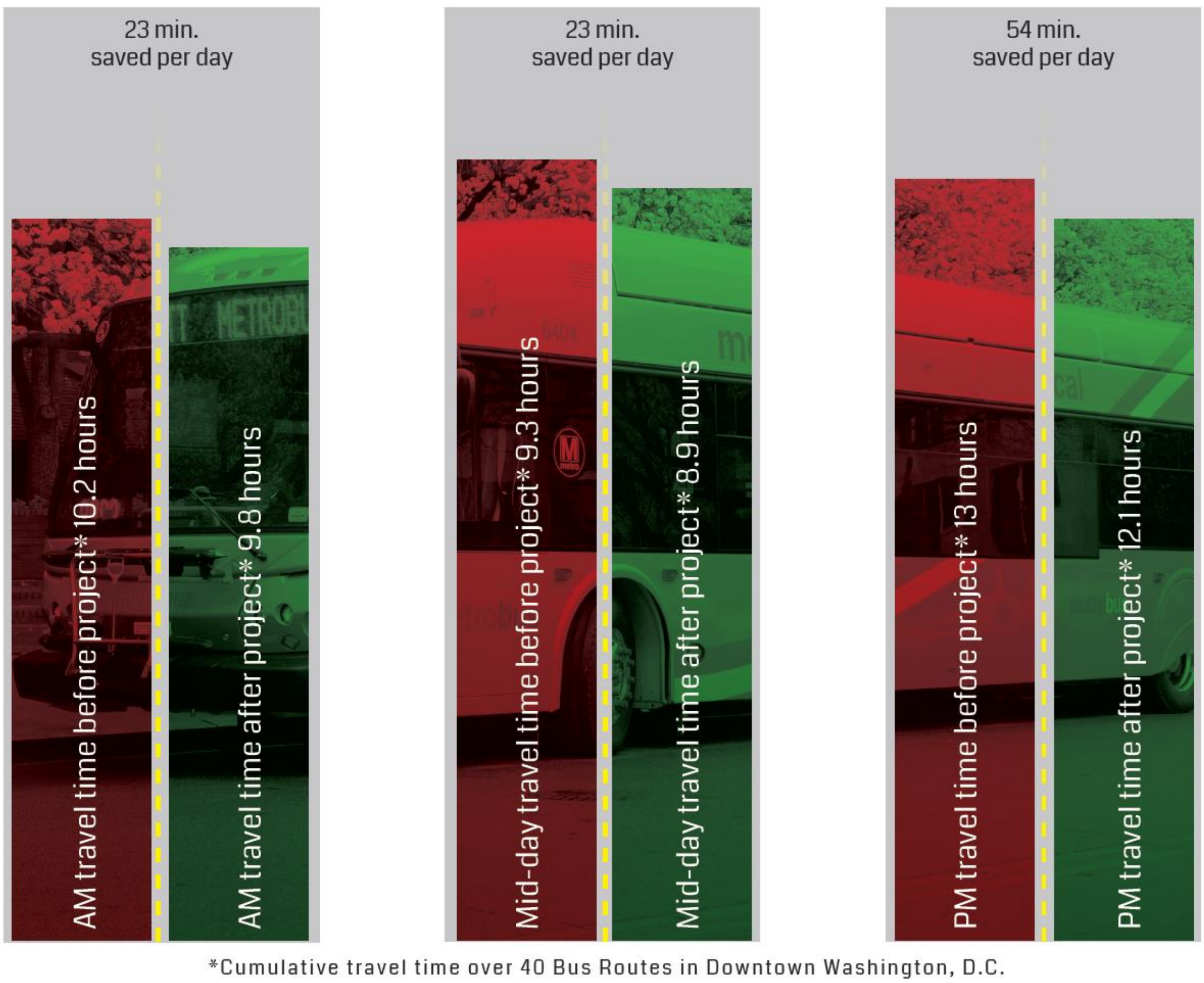

Figure 34: Cumulative Travel Time Comparison of Bus Travel Time over 40 Bus Lines

F. Intersection Level of Service and Delay Improvements

The Synchro™ software models were used to evaluate Level of Service (LOS) and overall intersection delay changes between the "before" and "after" optimization conditions. The *Highway Capacity Manual* defines the methodology for the determination of LOS, which is based on the intersection delay calculation (see inset for a comparison of values). LOS is based on a weighted average of delay calculations for each approach to the intersection, and by itself it not a significant concept for coordinated signal timing, in that coordination focuses on the corridor as whole and not individual intersections. Furthermore, intersection delay calculations are a function of many variables that do not change with signal timing such as geometry, grades, traffic composition, etc. In general, the intersection LOS did not change between "before" and "after" signal timings, as is expected.

LOS	Intersection Delay Per Vehicle (seconds)
A	≤10
B	>10 and ≤20
C	>20 and ≤35
D	>35 and ≤55
E	>55 and ≤80
F	>80

Level of Service vs. Control Delay

However, overall intersection delays did change. These changes provide a high-level view of the project benefits. Generally, intersection delays decrease with shorter cycle lengths, and increase with longer cycle lengths, which would lead to the conclusion that cycle lengths should be as low as possible. However, to provide coordination through groups of signals, a longer cycle length is preferred, and would lead to the opposite conclusion, namely that cycle lengths should be as high as possible. As discussed previously, determination of cycle length is a balancing act, and is its selection is dependent upon the objectives of each corridor.

In order to present an overall snapshot of the area, the overall findings in terms of the number of intersections that experienced changes in intersection delay from this analysis are summarized in **Table 6.**

Table 6: Level of Service and Delay Comparison between Before and After Conditions

Measure of Effectiveness	Number of Intersections (Data is number of 589 total intersections)				
	AM	Midday	PM	Late Night	Weekend
Significant Delay Reduction **(> 3 second reduction)**	**222**	**204**	**245**	**99**	**208**
Insignificant Change **(between 3 second increase and a 3 second decrease)**	**295**	**305**	**271**	**466**	**293**
Significant Delay Increase **(> 3 second increase)**	**72**	**80**	**73**	**24**	**88**

The following are noteworthy:

- Delays significantly decreased at 33% of the intersections over all peak periods. Significance is defined as more than 3 seconds decrease in overall intersection delay.
- Delay significantly increased at 11% of the intersections. Significance is defined as more than 3 seconds increase in overall intersection delay. Less than 1% of the intersections that experienced a significant increase in delay were operating at LOS D, E or F. A majority (99%) of the significant delay increases were at LOS A, B or C intersection, and were a natural consequence requirement of cycle length increases along an entire corridor. It should be noted that while delays increased slightly at individual intersections, the overall corridor travel times were reduced significantly as demonstrated in the previous section.
- The changes in delay at the remaining 56% of intersections were insignificant (+/-3 seconds delay change).

G. Pedestrian Improvements

Making DC traffic signals safer and friendlier for pedestrians was one of the goals of the optimization project. This goal was met by providing appropriate and sufficient pedestrian clearance (Flashing Don't Walk) intervals, adding All Red intervals, and changing pedestrian traffic signal operations to conform to the 2009 Federal Highway Administration (FHWA) *Manual on Uniform Traffic Control Devices* (MUTCD) which improved both pedestrian safety and mobility. Specifically, the following were accomplished.

a) FDW Intervals Increased

Flashing Don't Walk (FDW) intervals were re-calculated based on a slower pedestrian walking speed of 3.5 feet per second to provide pedestrians more time to cross the street. Per the MUTCD, a FDW signal means that "a pedestrian shall not start to cross…but that any pedestrian who has already started to cross…shall proceed to the far side of the highway." It is a safety-critical interval that serves to facilitate the safe transfer of right-of-way between different modes of travel. It is important to note that the FDW should not be excessively long. If it were too long, pedestrians would be prohibited from entering the intersection before it is necessary to require such a prohibition, thereby impairing pedestrian mobility. In other words, if a FDW value is too high, pedestrians are instructed to refrain from entering the crosswalk even when it would be perfectly safe to do so.

An analysis was performed at each intersection to determine how many crosswalks experienced an increase in FDW and how many experienced a decrease in FDW. The results showed that FDW intervals increased or remained the same at 82% (1,342) of the crosswalks and decreased at 18% (290) of the crosswalks. The locations where FDW times decreased had inappropriately high values, whereas the locations where FDW times increased had insufficient time for pedestrians to cross prior to the traffic signal optimization. In both cases, the re-calculated values are fully compliant with the FHWA MUTCD.

b) All Red Intervals Added

All Red intervals were added at 42 intersections. Previously the pedestrian walk indications would start immediately upon termination of the conflicting approach's yellow indication. Adding All Red Intervals improved pedestrian safety by introducing a factor of safety into the crossing time.

c) Solid Walk Intervals Added

Flashing Walks at 217 intersections were changed to solid Walks in compliance with the MUTCD, which notes a uniform display is necessary for traffic control devices in general to be effective.

H. Cyclist Improvements

Bikes are one of the fastest growing transportation modes across the country and in the District in particular. Between 2011 and 2012, cyclist traffic in DC increased by nearly 21% to over 7,000 trips per day. With the continued success of the Capital Bikeshare program, the ongoing installation of dedicated cycle facilities, and increased awareness as a result of various programs including Towards ZERO Deaths DC, these numbers have continued to grow. Recent counts along the 15th Street Cycle Track show a peak hour bicycle volume of over 350 bikes per hour – as much or more than the vehicular traffic on many small to medium sized streets. While many cyclists choose to share vehicular lanes, it is apparent that the relative safety and convenience of Cycle Tracks drives increased ridership. **Figure 35** shows the increase in peak hour bike traffic that was induced as a result of the installation of the Pennsylvania Avenue Cycle Track as compared to the citywide average. This graphic illustrates the need to dedicate particular attention to Cycle Tracks when performing Traffic Signal Optimization.

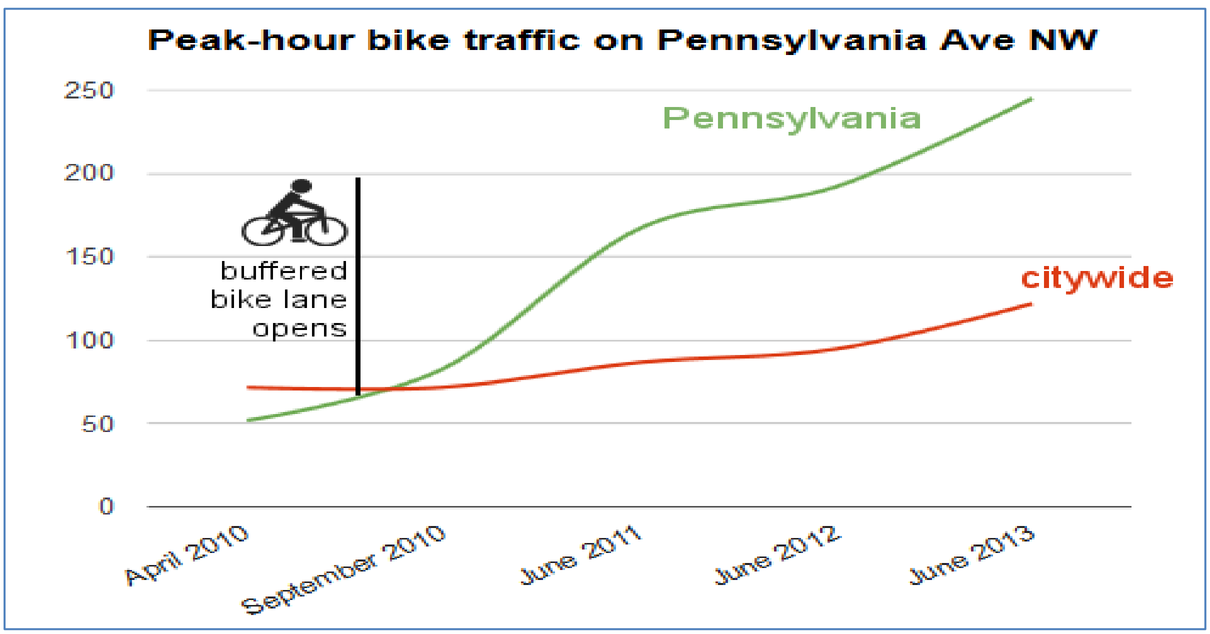

Figure 35: Pennsylvania Avenue Peak Hour Cycle Track Volume (Source: StreetsBlogUSA)

While cyclists often use the same traffic signal equipment as passenger vehicles, they have very different characteristics which must be accounted for when performing a Traffic Signal Optimization project. One of the key differences between passenger vehicles and cyclists is travel speed. Passenger vehicle travel speed is fairly consistent and is generally at or somewhat above the 25 mph speed limit in the Downtown core. Conversely, cyclist speed is much more variable depending on the characteristics of the rider, the slope of the road and the purpose of their trip (e.g. a courier would be expected to travel much faster than someone out for a sightseeing ride).

As a result of this difference in speeds, traffic signal timings designed for 25 mph that provide a smooth ride for motorized vehicles may be disruptive or cause excessive stops for cyclists. During the fine tuning phase of this project, signal timing engineers worked with DDOT bicycle planners and input from the cycling community to modify the signal timings along major bicycle routes to ensure smooth flow for cyclists as well as passenger vehicles.

One of the most prominent cycling corridors in the Downtown Core is Pennsylvania Avenue, NW between 3rd Street and 15th Street which has a two-way “cycle track” in the center of the travel lanes. Along this corridor, dedicated bicycle signals are not installed and cyclists are required to obey the vehicular traffic signals. During the initial field observations, signal timing engineers noted that vehicular traffic was progressing very well while bicycle traffic seemed to be experiencing numerous arrivals during the yellow clearance or solid red. Comments from the cycling community confirmed these observations.

In coordination with DDOT bicycle planners, signal timing engineers surveyed the bicycle travel patterns during the AM, Midday and PM peak periods on bicycles and in passenger vehicles at low speed and made numerous fine tuning adjustments to provide improved progression for cyclists. The bicycle travel time and stops before and after these adjustments are shown in **Table 7.** It should be noted that this data is based on one run in each direction during each peak period before and after the changes. Bicycle travel times, as noted above, are highly variable depending on the characteristics of the cyclist and therefore may vary significantly from what is shown in the table.

Table 7: Pennsylvania Avenue Cycle Track Travel Time and Stops Before and After Fine Tuning

	Before		After	
	Travel Time	Stops	Travel Time	Stops
AM Eastbound	7:30	5	6:20	5
AM Westbound	8:30	7	7:30	3
MD Eastbound	8:10	8	7:20	5
MD Westbound	8:20	7	8:10	6
PM Eastbound	10:30	8	10:10	7
PM Westbound	7:45	7	8:10	5

While the highly variable characteristics of cyclists pose a challenge to the conventional methods of traffic signal optimization, DDOT was able to leverage their extensive signal timing expertise, internal bicycle planning resources and input from the active DC cyclist community to improve operations for cyclists while balancing the needs of all users including pedestrians, transit vehicles and vehicular traffic.

IV. Benefit-Cost Analysis

A. Methodology

The benefits of a signal timing optimization project are estimated in terms of delay savings, reduction in vehicle operating costs (measured in stops per vehicle), fuel consumption savings, and emissions reductions. Each of these values are calculated and then compared between the "Before" and "After" scenarios to determine the overall benefit. For this project, the overall benefits were derived from Synchro Traffic Models, which are based on pedestrian & traffic volumes, signal timing data, and roadway characteristics.

Benefits are calculated for each of the AM, Midday, and PM peak hours, and then multiplied by the number of hours in each peak period (2 hours) to estimate the benefits per peak period. The sum of the AM, Midday and PM peak periods (6 hours) represents one weekday. Weekend benefits are calculated based on a Saturday peak period (3 hours) and a Sunday peak period (2 hours). The annual benefit is based on multiplying one weekday by 250 weekdays per year (the 250 weekday assumes 10 holiday days per year) plus one weekend by 52 weekends per year. It should be noted that benefits were not estimated for non-peak periods (i.e. only 6 hours per day were measured; not 24 hours), thus the calculations should be considered conservative.

B. Benefit-Cost Analysis

To determine whether or not the signal timing optimization was successful from an environmental and economic standpoint, a benefit-cost analysis was performed. The purpose of the analysis is to determine whether or not the cost of signal timing improvements exceeded the benefits derived from these improvements. In this Benefit-Cost analysis, the public gains societal and environmental benefits and the government incurs costs.

Benefits are measured in terms of the monetary value of delay savings, reduction in vehicle operating costs (measured in stops per vehicle), fuel consumption savings, and emissions reductions. Costs include traffic data collection, consulting fees for developing new timing plans, and labor costs associated with DDOT review of timing plans, uploading the new timing plans into the signal controllers, and fine-tuning. Benefits are estimated for a period of one year. The following monetary values were used:

- $27.03 per hour of delay[3]

[3] The average wage rate in the District of Columbia of $37.04, multiplied by a 50% reduction factor (recommended by FHWA when converting wage rates into values of time to account for non-work trips), and a 1.46 occupancy rate were applied to determine the cost of time per person in a passenger car of $27.03. The average hourly wage rates

- $0.014 per each stop[4]
- $3.00 per each gallon of gasoline[5]
- $7.011/kg of Carbon monoxide[6]
- $14.192/kg of Nitrogen Oxide[4]
- $7.38/kg of Volatile Organic Compounds[4]

Table 8 summarizes the benefits and costs for retiming the entire network, as derived from the Synchro™ traffic model for a one-year period. It should be noted that Synchro results are typically conservative as compared to field measured results. Therefore, the benefits derived from this analysis may be underestimated.

Based on the Benefit-Cost analysis, the signal timing optimization benefits outweigh the costs by a factor of 45:1 in the first year. The total annual benefit of the Downtown signal timing optimization is estimated at $96 Million per year, or just under $400,000 per day. With a total project cost of $2 Million, this benefit represents a payback period of less than 6 days.

The analysis shows that the Downtown signal timing optimization project reduced vehicular carbon emissions by over 167,000 kg per year, and fuel consumption by over 2.3 million gallons per year, meeting the project's goal to reduce vehicular emissions.

Table 8: Annual Benefits Based on Synchro Traffic Model: Network Wide

MOE	Delay (hours)	Stops	Fuel Consumption (gal)	CO Emissions (kg)	NOx Emissions (kg)	VOC Emissions (kg)
"Before"	12,043,080	843,614,040	18,957,840	1,325,660	257,800	307,500
"After"	9,299,640	751,443,180	16,570,280	1,158,400	225,400	268,580
Improvement	2,743,440	92,170,860	2,387,560	167,260	32,400	38,920
% Improvement	23%	11%	13%	13%	13%	13%
Annual Benefit	$74,155,183	$12,903,920	$7,162,680	$1,172,660	$ 459,821	$ 287,230
Total Annual Benefit	$96,141,494					
Cost	$2,150,658					
Benefit-Cost Ratio	40:1					

were determined from the United States Department of Labor, Bureau of Labor Statistics Occupational Employment Statistics (May, 2013) http://www.bls.gov/oes/current/oes_dc.htm#00-0000

[4] Texas Transportation Institute Study

[5] Reasonable assumption based on the current price of gasoline

[6] "Evaluation of the Benefits of a Real-Time Incident Response System", presented at the 9th World Congress Conference on ITS, Chicago, Illinois, October 14-17, 2002.

V. Future Recommendations

A. Improve Curb Space Management

In the Downtown area, space is at a premium, not just for land, but also in the transportation network. The traveled way must be shared between both those in transit, or moving, such as personal vehicles, bicycles, pedestrians, transit vehicles; and those that are stationary, such as parked cars and trucks, construction vehicles and equipment, and delivery trucks. Delivery vehicles were frequently observed blocking through lanes during the critical peak hours of the day (7-9 AM and 4-6 PM).

a) Loading and Unloading / Delivery Trucks

- Based on multiple observations of travel time data on a corridors where the right lane was blocked with a delivery vehicle and when the same section was available for moving traffic (not blocked), travel time due to a delivery vehicle blocking a through lane in a high volume section of roadway can increase travel time significantly. For example on a 1 ½ mile section of L Street, travel time in the PM peak increased approximately 5 minutes due to loading vehicles blocking lanes on a critical section of the roadway. Alternatively, in some cases, the presence of a delivery vehicle blocking a through lane had no impact on congestion or delays.
- DDOT should consider identifying critical sections of the network where rigorous enforcement of the no stopping or standing rule should be applied to provide for the mobility of the travelling public and the efficiency and safety of the roadway system.

Photo: Looking south on 19th Street north of K Street, NW. The delivery truck is illegally parked blocking the left lane (note the sign in the photo prohibiting loading here). The right lane (not shown in the photo) is also blocked by legally parked vehicles and delivery trucks. Numerous violations were observed along 19th Street from N Street to K Street during the midday time period, reducing 19th Street to a single lane and causing cycle failures and long delays.

Photo: Looking west on H Street at 14th Street, NW, the truck is changing out a trash bin during the AM peak hour, blocking two of the travel lanes on H Street (H Street is on-way eastbound).

Photo: Looking east on K Street at 14th Street, NW during the AM rush hour. This delivery vehicle blocked the right lane for nearly 45 minutes causing AM traffic delays to extend into the tunnel below Washington Circle.

Photo: Looking south on 19th Street at E Street, NW during the PM rush hour. This delivery vehicle blocked the right turn lane for 30+ minutes causing significant traffic delays. The right turn volume at this intersection is higher than the through volume.

b) Construction Lane Closures

- During the fine tuning effort, the team frequently observed construction lane closures starting during the AM rush hour and often into the PM rush hour. In order to minimize congestion, DDOT should strictly enforce non-emergency work-zone lane closures.
- In addition, DDOT should observe and enforce that all contractor equipment that is blocking lanes is removed. Several times, contractor's equipment was left in the roadway during the peak hours, blocking travel lanes and causing congestion.

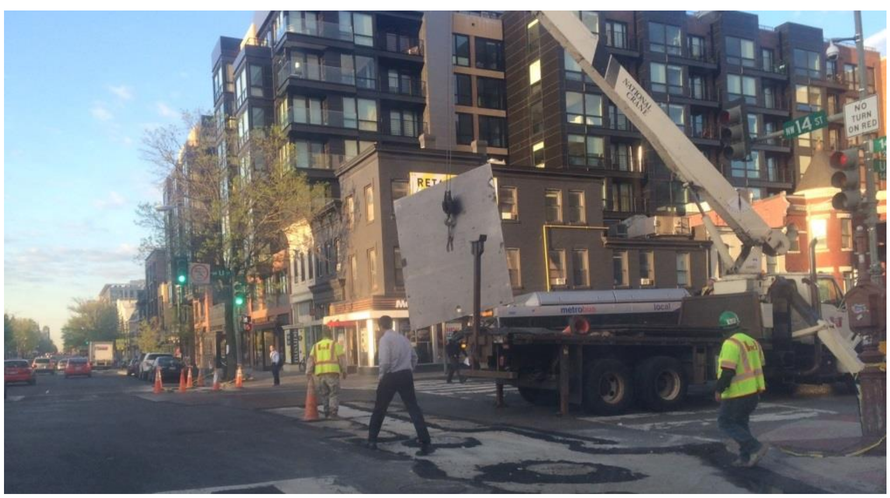

Photo: Looking south on 14th Street at U Street, NW as the right lane is closed on both 14th Street and on U Street during the AM rush hour. In this case, DDOT was notified and the contractor was shut down, however congestion from these lane closures impacted travel conditions on both routes

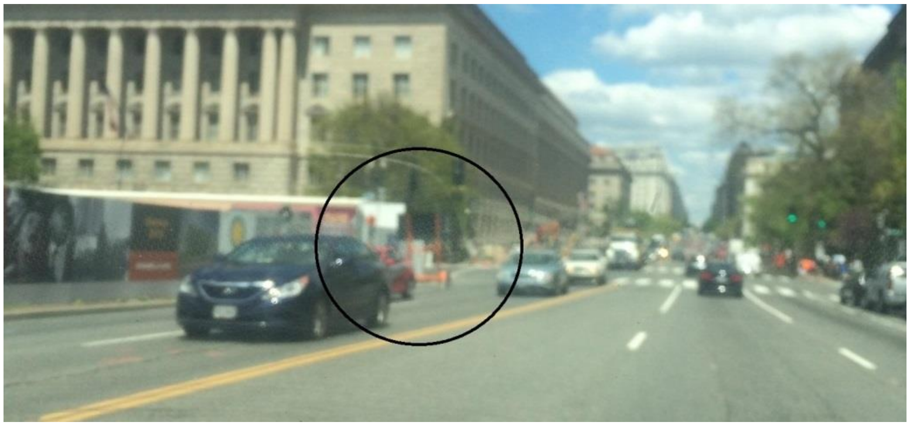

Photo: Looking north on 14th Street at Constitution Avenue, NW. This portable arrow board (circled) had the 3rd southbound lane closed for the Monday PM peak and throughout Tuesday for no reason (i.e. there was no construction activity). The Contractor apparently did not remove the lane closure. In this case, DDOT was notified and the arrow board was removed and all 3 lanes were open to traffic by the PM rush hour by the second day (Tuesday). The lane closure caused a nearly 10 minute increase in travel times on southbound 14th Street when comparing travel times with (on Monday) and without (on Tuesday) the lane closure during the PM peak.

Photo: Looking south on 17th Street north of Pennsylvania Avenue, NW the right lane is blocked during the AM rush hour by a truck dropping off concrete slabs. The slabs were most likely for some off peak construction and lane closures occurring on 17th Street in this area. Although during observations the lane closures only affected the outer lane where parking is allowed.

c) Illegally Parked Vehicles

- Similar to loading vehicles illegally blocking lanes, there were numerous observations of illegally parked vehicles, many of them in Tow Away zones.
- Illegally parked vehicles were consistently observed during the AM and PM peak hours along major routes such as Constitution Avenue, 14th Street, and M Street.
- The National Mall, being a prominent destination for tourists draws a significant amount of traffic via Constitution and Independence Avenues. Peak hour parking restrictions are in place along these corridors. However, vehicles were observed to remain parked in violation of the restrictions on all days, especially during the afternoon peak period. Vehicles were routinely found to remain parked even after 5 PM (parking is restricted between 4 – 6:30 PM). This effectively reduces the number of travel lanes available and is a major contributor to traffic congestion. It is recommended that parking restrictions be aggressively enforced to mitigate this issue.

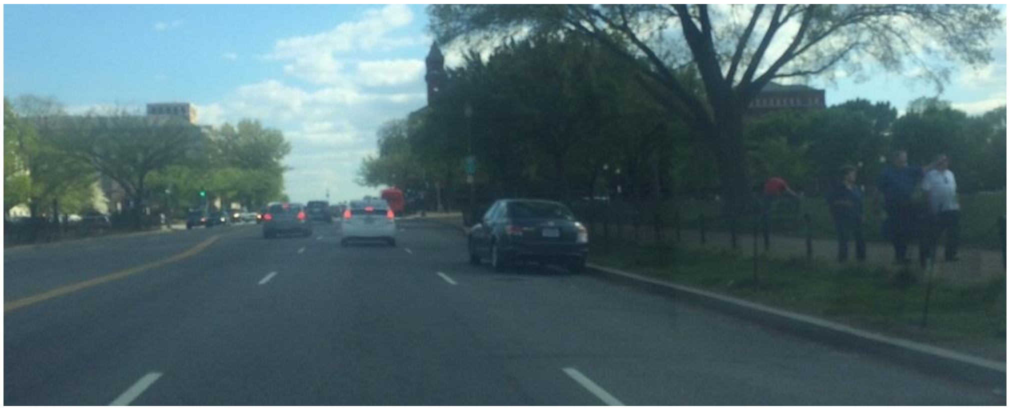

Photo: Looking south on 14th Street, north of Independence, NW as the right lane blocked by an illegally parked vehicle.

B. Traffic Engineering Recommendations

a) K Street, NW

- Left turns are prohibited during the peak periods at almost every intersection on K Street from 12th Street NW to 21st Street NW. However, left turns into the midblock service road access driveways are not prohibited. These midblock left turns create congestion, especially since the left turns block the left thru lane and the right lane is typically blocked by buses. DDOT should consider installing flex posts down the center of K Street between intersections to prohibit these maneuvers, similar to the photo below of New York Avenue.

Photo: Flexible tubular post on New York Avenue. These are recommended on K Street NW to prohibit midblock left turns into the service road access points

- Traffic Control Officers, when stationed at intersections along K Street are very effective in enforcing the No Left Turn prohibitions. However, after multiple weeks of observations on the corridor, they are not deployed consistently. When they are not consistently deployed, motorists often disobey the turn prohibition signs, and as a result, congestion increases due to illegal left turns blocking the left through lane.
- Loading / Unloading by delivery vehicles often block the right through lanes, leaving one effective lane. When this occurs during the middle of the day when left turns are permitted at the signalized intersections, this leaves only 1 effective lane. Some delivery vehicles do utilize the service road; however, there is no always adequate space for the larger trucks on the service road. Trucks loading / unloading and blocking the right through lane occurs during the peak hours as well. Increased enforcement of the curbside space, particularly on K Street, which is a primary corridor, would alleviate congestion.
- The westbound left turn on K Street to southbound 27th Street is very heavy and the left turn bay too short. As a result, the left turn queue blocks through traffic in the left lane, leaving only one of the three allocated lanes for traffic heading towards K Street and the Whitehurst Freeway. Implement a twice per cycle left turn to manage the queues. Change the lane configuration on westbound K Street to a double left towards southbound 27th. There are 2-3 through lanes, but there is only one effective through lane as the left turn queue blocks the inside through lane. There appears to be space to provide two receiving lanes on 27th Street.
- Eastbound K Street west of 27th is very congested in the PM peak period. To help in alleviating some of this congestion and to improve pedestrian safety, do not operate the east-west pedestrian phase with eastbound K Street. There are a lot of right turns from eastbound K Street, and the rights speed up to round the corner as the distance to the crosswalk is relatively far from their starting location. Also, the pedestrians hold up turning movements on this very congested approach.
- Westbound On Ramp at 25th Street - In order to increase efficiency of the ramp, add overhead lane use signs (reverse curve through arrows) to indicate there are two through lanes on this ramp in the PM; currently the outside lane is underutilized.

- Westbound K Street at 19th Street – buses only are allowed to turn left here. This causes congestion on K Street. DDOT may consider evaluating the benefits of a bus only signal phase. However, it would have to be a transit-type signal indication as otherwise all motorists would use it.

b) L Street, NW

- The left lane has a lot of conflicts with the bike lane. Motorists generally yield to bikes (which is good and safe behavior) but this causes left turns to stop in the through lane when crossing the bike lane. Also, left turns crossing the sidewalk often have to yield to pedestrians.
- The left turn pockets/ turn bays are generally too short for the left turn volume and the queues of left turning vehicles back up into the through lane.
- As a result of the above two issues, during the peak period, the left-through lane functions as a left turn lane, particularly in the section between 21st and Connecticut. It appears, from multiple observations, that it would be safer to have vehicles cross the bike lane at an intersection rather than midblock. This movement could be controlled (via a signal) as opposed to the merge 200 feet back where motorists have to look over their shoulder to see an approaching cyclist. The disadvantage to this option (bikes left of vehicles) is that a bike signal would be needed, and the cyclists would receive less green time.
- The section of L Street between Pennsylvania Avenue and New Hampshire is a critical section on which to maintain two lanes. At 6:30 PM, parking restrictions are lifted and this section becomes one lane. However, peak hour traffic lasts until 7 PM, and often beyond. As a result, the travel time in this 3 block section increases from a typical 2-3 minutes from 4 to 6:30 PM, to a 8-9 minute time immediately after 6:30 PM. Consider prohibiting parking on the south side curb lane until 8 PM.
- L Street from 13th to 11th: This section of L Street frequently has the right lane blocked by loading vehicles. In the section between 12th and 11th Streets, when vehicles are blocking the right lane the problems at Massachusetts 11th and L are exacerbated. The left lane on L Street, is queued because of the lack of storage space between L and Massachusetts, and is often blocked as queued vehicles block the left/ through lane. When the right lane is blocked, the right turning traffic uses the middle through lane. Since right turn traffic yields to pedestrian during the first portion of the green interval, the middle/ through lane is stopped. As a result, both lanes are blocked on L Street, causing congestion in this section.
- As noted above, the intersection of L at 11th at Massachusetts is a congested / bottleneck intersection. Consider prohibiting left turns from eastbound L Street to northbound 11th Street.

c) M Street, NW in Georgetown

- At Wisconsin Avenue and M Street it is very difficult for southbound right turning traffic to make the turn due to pedestrian conflicts while southbound traffic has a green ball. A right turn overlap phase could be added to run with the eastbound left turn phase. This would provide a protected movement for the rights and greatly improve the intersection operation. This is especially critical on the weekends when there are even greater pedestrian volumes. This would also provide additional incentive to divert traffic off of 34th Street if motorists could depend on this as being a reliable and more efficient travel route. It is recommended that the north south phase sequence be reversed so that the southbound movement would immediately precede the eastbound left so as to provide a continuous movement when the overlap is implemented.

- The signal controller at Key Bridge is currently running interval operation. Converting this controller to phase based operation would allow more flexibility and make it much easier to implement phase changes and other operational strategies. One potential strategy would be to lag the eastbound M Street traffic. This would provide better coordination with the 34th Street intersection. Having the ability to force off the Key Bridge right turns prior to the left turns would allow much greater capability to manage the short spacing between Key Bridge and 34th Street. This would help prevent the space from getting jammed up and restricting the flow of eastbound M Street traffic from this signal.
- At Potomac and M Street implement a dummy phase so that the start of the east and west movements can be separated. This would provide smoother coordination with the left turn phase at the 33rd Street intersection.
- The Traffic Control Officers should be provided with more focused instructions as to how best manage the traffic in this area. The locations where they could be most beneficial are:
  - M Street and 33rd Street. Because of the all-way stop on 33rd at Prospect and the short block length, left turns from M Street can often back out into the intersection. Once the pedestrian crossing on the north side starts vehicles that were not able to clear are stranded and create a major impediment to the westbound traffic. TCO presence would be most beneficial from 4:00 to 6:30 p.m. weekdays. Their focus would be to prevent east bound left turns from blocking westbound movement, and if a vehicle did get stranded near the crosswalk to hold the pedestrians so the vehicle could clear the intersection.
  - M Street and 34th Street. Positioned on the northwest corner of the intersection to ensure that pedestrians do not attempt to cross on the west side where there is no crosswalk, and also to ensure they do not try and cross when the right turn arrow is up for 34th Street. Because pedestrian see crossings occurring on the south side with the leading eastbound movement they assume they can start on the north as well. This was witnessed on numerous occasions and impacted the right turning traffic on 34th Street. TCO presence recommended from 4:00 to 6:30 p.m. weekdays.
  - M Street and Key Bridge. One TCO positioned in the channelizing island separating the Key Bridge left and right turns. Their primary focus would be to ensure the Key Bridge traffic stops at the stop bar and not in front of the bar. Also any right turning traffic that is not able to enter on green and is between M Street and the stop bar should be prevented from making a right turn on red which is not allowed. This will help keep the short space between Key Bridge and 34th Street open to accept eastbound M Street traffic. TCO presence is recommended from noon until 5 p.m. on Saturdays.

d) 14th Street, NW

- At C Street install 3-section left turn signal heads for protected-only southbound left turn and 3-section signal heads for through traffic (similar to westbound). Southbound signal heads are currently 4-section heads with upward through arrow and lagging left turn arrow.
- At 14th and I Street, NW, convert the northbound lagging left turn movement to a leading left turn movement. This will help address queue spill back from this left turn movement that extends into and affects the operation of 14th Street at H Street, NW.

e) 15th Street, NW

- There are no lane markings along 15th Street between Massachusetts Avenue and P Street; pavement markings should be added to separate the travel lanes.

f) 17th Street Southbound at Constitution Avenue, NW

- Prohibit parking for 150 to 200 feet along the right curb lanes during the weekend and midday time periods and provide space for a separate left and through lane. During the weekend and midday peak period, left turns are allowed and the left turning traffic completely blocks the approach as it is only a single lane, resulting in cycle failures.

g) 18th Street, NW

- The pavement makings for the inside through lane "disappear" between D and E Streets, NW, and G and K Streets, NW. The road should be marked with skip lines to indicate a though lane, and not a parking lane. This will help left turns stay in their lane and allow through vehicles to bypass.
- There are no crosswalks across Constitution Avenue at 18th Street, NW. However, when the eastbound signal turns green, westbound traffic stops and pedestrians think that it is safe to cross. Pedestrians either get stuck in the middle of the road or they delay traffic. DDOT should post signs to alert pedestrians to use the crosswalks at 19th and 17th Streets.
- There is a Tour Bus driveway on the south side of the intersection of Constitution Avenue at 18th Street, NW that has a small amount of green time. However, the phase is recalled to the maximum and should be actuated. During the peak hours, the signal for this movement is relatively pointless since queues extend through the entrance.

h) 19th Street, NW

- There are numerous illegal parking and loading / unloading along 19th Street, particular between L Street and M Street, NW. This occurs during all times of day, but creates congestion during the AM and PM peak hours, reducing 19th Street to a single through lane. During the peak hours, even a single illegally parked vehicle can cause bottleneck conditions and back-up the entire block. The other blocks aren't as heavily affected by parked vehicles, since past K St, it becomes 4 lanes instead of 3. Vigorous enforcement is needed, particularly during the PM peak hours.
- On 19th at E Street, NW, there is a very heavy right turn towards E Street and the expressway. The inside lane of this double right turn lane was often blocked by either express buses (such as Loudoun County Transit) and/or by loading trucks. As a result, all turns were performed from

the shared right/through lane; through traffic generally utilized the outer (east side curb lane). Since only one lane was generally being utilized for through traffic, DDOT should perform a study at the intersection to identify whether or not it would be more efficient to designate this west side lane for bus loading and unloading and designate the middle lanes as “Right Only” and “Right / Through.” The study should include lane utilization counts and the Level of Service impact of lane utilization changes. The two alternatives are illustrated below.

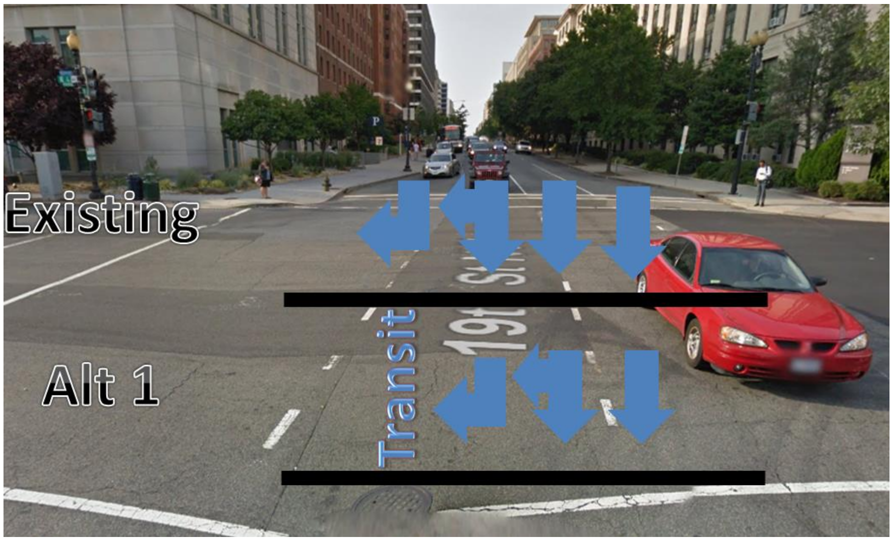

Photo: Looking north on 19th Street at E Street, NW. DDOT should study lane configuration changes.

- On southbound 19th Street at Pennsylvania Avenue, NW prohibit parking for at least 100-feet in advance of the intersection along the left (east side) curb lane to allow left turns to queue in this space. Currently, left turns block the through lanes while waiting for pedestrians to cross.
- On southbound 19th Street at Constitution Avenue, NW there is a triple left turn. The inside left turn lane have pavement marking that guide vehicles to the left-most lane on eastbound Constitution Avenue, which is a LEFT ONLY lane towards 18th Street. Vehicles that want to go through on Constitution Avenue often get trapped in this lane and attempt to drive through (rather than left) at 18th Street, either blocking the lanes, or cutting off traffic turning left from the second lane on eastbound Constitution Avenue. DDOT should restripe the puppy tracks from southbound 19th Street to Constitution Avenue so that the inside left turn lane is directed towards a through lane on Constitution Avenue.

i) 23rd Street, NW

- Southbound 23rd Street from Eye to G Street is not very well marked; it appears that there should be three lanes on this section, but only the curbside lane is stripped leaving the two center lanes ambiguous. Northbound 23rd on this same stretch is clearly stripped for three lanes. The ambiguity causes drivers to alternatively use it as one or two lanes, often forming one lane, until someone attempts to turn left, then breaking into two lanes to get around the turner.

j) Washington Circle, NW

- Vigilant enforcement of current parking restrictions on approaches into and out of the circle. The following are the most critical:
  - K St. Westbound Ramp, PM Peak – parking is restricted which provides two lanes for traffic leaving the circle. With the heavy Westbound flow on K St./Whitehurst Freeway there is no opportunity to provide more time for the K St. ramp so if illegal parking occurs it reduces the ramp to a single lane, cutting capacity in half and can cause traffic to back up into the circle. If this occurs, the Pennsylvania Avenue traffic entering the circle is impacted as well as traffic trying to leave the circle onto westbound Pennsylvania Avenue.
  - 23rd Street PM Peak – Since the only way we have been able to improve the flow leaving the circle in the PM is by reducing the split for 23rd Street entering the circle, it can often take three to four cycles for northbound 23rd Street traffic to enter the circle after stopping at I Street. With the significant bus operations on northbound 23rd Street just north of I St. the parking that is allowed on the east side significantly degrades northbound 23rd Street. Implementing parking restrictions throughout the evening rush hour between I Street and the circle on the eastside would greatly improve flow on 23rd Street and could provide an opportunity to provide more time to the circle movements.
  - 23rd Street PM Peak south of the circle. – There are peak period parking restrictions along 23rd Street southbound which provides for two lanes of travel southbound. When illegal parking occurs it can often impact traffic and cause 23rd Street traffic to back up all the way into the circle. If 23rd Street is unable to fully receive all the traffic that is leaving the circle then it backs up the circle and significantly impacts the overall operation.
  - 23rd Street AM Peak – The parking restrictions on the east side of 23rd Street between I Street and the circle end at 9:30 and cars are often beginning to park along this stretch between 9:00 and 9:30. Prior to any illegal parking 23rd Street flows smoothly and there is generally little to any backup. Once an illegal parked car appears 23rd Street is reduced to a single lane and it takes multiple cycles for vehicles to enter the circle. The backup will extend for two to three blocks south of the circle. Since the AM volumes continue to be high up until 10:00 it would be very beneficial to extend the parking restrictions on the east side of 23rd between I Street and the circle until 10:00 a.m. and ensure the restrictions are enforced.

k) Thomas Circle, NW

- In order to help alleviate congestion in the westbound direction along the portion of the circle between the ramp from westbound Massachusetts Avenue, and the spur ramp to westbound M Street, install a southbound overlap phase at 14th Street and the ramp from eastbound Massachusetts Avenue (ACISA # 1365). The overlap phase would allow the separation of critical movements, allowing additional green time for traffic circulating around the top portion of the circle. Also, DDOT should also investigate re-phasing of the circle to improve flow, particularly for the NB 14th Street and westbound Massachusetts Avenue approaches on the north and east sides of the circle.

l) DuPont Circle, NW

- The following improvements should be made to discourage illegal left turns through the crosswalks at the east and west side outlets from the inner circle, as illustrated in the graphic below and as follows:
    - Restripe channelizing pavement markings and install flex posts;
    - Install yellow dash line extensions from the stop bar across intersection;
    - Install far side R3-2 signs.

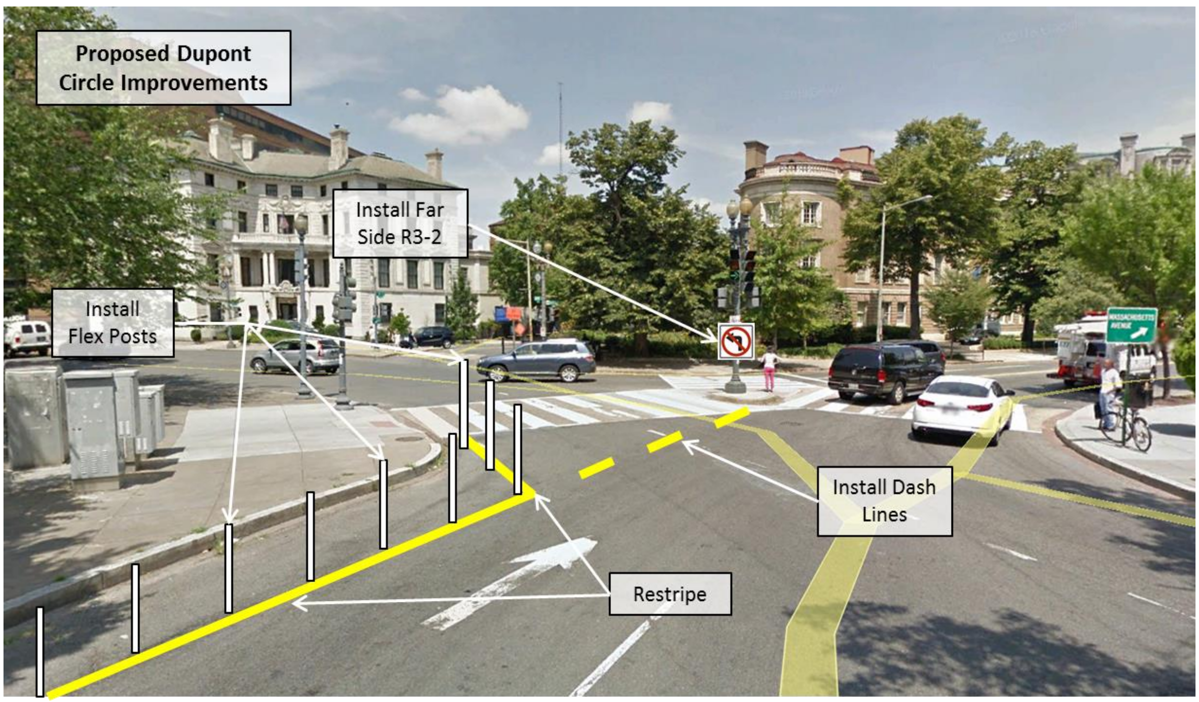

Photo: east from DuPont Circle towards Massachusetts Avenue. The sketch illustrates recommended improvements.

m) Rhode Island Avenue, from 10th St, NW to V Street, NE

- Install pedestrian detection at the 10th Street, NW pedestrian crossing.
- At 1st Street, install 3-section left turn signal head for protected-only eastbound left turn and 3-section signal head for through traffic (similar to westbound). Eastbound signal head is currently a 4-section head with upward through arrow and lagging left turn arrow.
- At North Capitol Street, consider restricting eastbound left turns starting at 3:00 PM instead of 4:00 PM. Backups from this movement and curb lane parking until 4:00 PM effectively reduce the available through capacity to one lane, resulting in long queues and cycle failures along eastbound Rhode Island.

- Install vehicle and pedestrian detection at V Street/Summit Place, NE intersection. Side street and pedestrian traffic was minimal during all peaks.

n) Florida Avenue, NW

- Install signage along westbound Florida Avenue prior to Florida Avenue/18th Street to indicate proper lane alignment. Appropriate signage may include “Left Lane to Florida Avenue Only” or similar. Install puppy tracks through intersection at Florida Avenue to channelize left turning vehicles to through lane at 18th Street.
- At 21st Street, convert westbound left turn only lane to a shared through/left lane.
- At Connecticut Avenue, restrict parking along Florida Avenue eastbound receiving lanes during the PM peak for approximately 130 feet to allow 2 through lanes to merge after clearing Connecticut Avenue.
- At Florida Avenue at Georgia Avenue and 7th Street, NW, convert the existing southbound “lagging” left turn to “leading” left turn movement. During all peak periods traffic from eastbound on T Street that wants to turn left to go north on 7th St./Georgia Ave. is basically "blocked" by the queue that extends from the Florida Ave. intersection. It is not a "blocking the box" issue; it's a queuing issue in the short block of 7th St. between Florida and T Street. There is a southbound "lagging" left turn movement on 7th St. at Florida Ave. The offsets between Florida Ave. and T St. are set up so that while the lagging southbound left turn is up at Florida the main street green is up at T St. This keeps southbound traffic moving between the two signals. Unfortunately, this allows northbound 7th St. traffic to continue flowing at the T St. intersections which in turn fills up the block between T St. and Florida Ave. Hence, T St. traffic has no room to turn onto northbound 7th St. If we adjust the offset at T St. to provide room for traffic coming from T. St. we would end up jamming southbound 7th St. between the two intersections in much the same way, with traffic from Florida Ave. that wanted to go south on 7th St. having no room to turn into in the short block. Converting the lagging left turn to a leading left turn will allow us to adjust the offsets so that the main streets shut down at the same time at both intersections, creating a little bit of clearance (and storage space) between the two intersections, giving T St. traffic some room to turn into, without impacting traffic coming from Florida Ave.

o) North Capitol Street

- Left turns are prohibited in the peak direction at almost every intersection on North Capitol Street from Louisiana Avenue to Randolph Place. However, left turns in the off-peak direction cause significant delay since there are no turn lanes and through vehicles get stuck behind these turning vehicles. Consider prohibiting left turns in both directions during both the AM and PM peak hours.
- The most problematic location, where serious consideration should be given for prohibiting left turns is at H Street. Restrict southbound left turns from 4:00-6:30 PM Monday through Friday. Currently, southbound left turns cause excessive queues and cycle failures for through traffic.
- At Lincoln Road it would be beneficial to separate the northbound and southbound movements so that southbound could be held to coincide with the start of green at Florida while allowing

northbound to be green and better accommodate the right turns coming off of Florida. Lincoln Road requires minimal green time

p) Pennsylvania Avenue, NW

- Heading northbound on 12^{th} Street at Pennsylvania Avenue, the approach lanes are not aligned with the receiving lanes. Vehicles were observed ending up occupying two lanes and at time very close to vehicles in adjacent lanes. Skip lines or re-aligning the approach lanes would help guide vehicles into the appropriate lanes.
- Evaluate installation of Bike Signals along Pennsylvania Avenue cycle track between Constitution Avenue and 15^{th} Street. Under present conditions, intersections with protected left turns cannot operate with their adjacent through movements because bicyclists are required to obey the through vehicular signal heads. Allowing the through vehicular signal heads to show green simultaneously with a left turn green arrow presents a conflict because the cycle track is in the center of the roadway cross-section and left turns would pass directly through the path of the cyclists. Dedicated Bike signals would allow the cycle track traffic to be held during the left turn movements while permitting through vehicular traffic to proceed. This operation would have no operational impact on the cycle track while providing improved operations for vehicular traffic. Issues related to cycle track safety and compliance should be studied under this evaluation.
- Evaluate a separate bicycle signal head at Pennsylvania Ave at Constitution Ave, NW. Eastbound Pennsylvania Avenue traffic must stop during the entire left turn phase due to bicycles having to be held. There is no pedestrian crossing on Pennsylvania Avenue at this location so eastbound through traffic could have 100 percent green time.

q) Independence Avenue, SW

- Introduce a protected left turn phase for westbound traffic along Independence Avenue at 23^{rd} Street/Ohio Drive. A substantial portion of the left-turning traffic at this location comprises of tour buses that require longer gaps in opposing traffic in order to make the permitted turn from Independence Avenue onto Ohio Drive. With opposing traffic being heavy even outside of peak periods, these vehicles were observed to experience lengthy delays and therefore resorted to making risky maneuvers including turning after the light has turned red. A protected phase improves safety and operational efficiency.

- It is also recommended that vehicle and pedestrian detection devices (i.e., detectors and push buttons) be installed on side streets, and on the westbound left turn lane (to operate in conjunction with the proposed protected left turn phase). Side street traffic, especially from Ohio Drive is minimal; and detection allows any unused split time to be transferred to the main line.

- Left turns from Independence Avenue on to 14th Street are prohibited for all vehicles except buses and taxis. However, multiple instances of private vehicles violating these turn restrictions were observed. Vehicles waiting to make an illegal turn block the travel lane for the through traffic and thereby reduced the lane utilization. It is recommended that DDOT consider replacing the old No-Left Turn (NLT) signs with newer LED signs may improve visibility of turn restrictions. In addition, the existing NLT sign is located on the signal pole on the far right side. Relocating the signs onto the existing poles in the medians (as illustrated in the sketch below) improves the visibility of the sign by bringing it into the cone of vision of left turning vehicles. Automated enforcement of turn restrictions should also be considered.

- Install side street vehicle and pedestrian detection at the intersection of First Street and Independence Avenue, SW. Minimal traffic was observed from the side street at this intersection. Detection allows any unused split time to be transferred to the main line.
- Install side street vehicle and pedestrian detection at the intersection of Independence Avenue and 10th Street/L'Enfant Plaza, NW.
- At the intersection with 12th Street NW, evaluate removal of the shared through and left turn (as illustrated in the sketch below) lane along westbound Independence Avenue and convert it to a through-only lane. Vehicles were observed attempting to make a permissive turn from the shared lane and ended up blocking the through traffic. At the same location, evaluate removal of shared through and right turn lane along northbound 12th Street (as illustrated in the sketch below) and convert it to a through-only lane. Observations in the field indicated that the number of vehicles utilizing the shared lane to turn right is very low. However, vehicles were spotted attempting to turn right on red creating a safety hazard for pedestrians in the adjacent crosswalk. Therefore, it is recommended that the existing shared through and right-turn lane be re-striped to a through-only lane.

Photo: aerial view illustrating lane configuration changes recommended at 12th and Independence.

- Evaluate the feasibility of converting the phase sequence at Independence Avenue and Raoul Wallenberg Drive from a split-phase to concurrent operation with protected left turns. Install vehicle detection to run the proposed protected left turns from Independence Avenue onto Raoul Wallenberg Drive.

r) Constitution Avenue, NW

- Install vehicle detection for the westbound left turn movement on Constitution Avenue at 23rd Street, NW.
- Convert the existing lagging protected phase for the northbound left turn movement at the intersection of 15th Street and Constitution Avenue NW to a leading phase. In addition, install vehicle detection for the northbound left turn movement. The northbound left turn movement conflicts with a significant amount of pedestrian traffic. Pedestrian movement runs concurrent with the north and southbound through movements (permitted left turns allowed). However, observations indicated that pedestrians continue to enter the crosswalk even after the display changes from FLASHING DON'T WALK to a DON'T WALK indication. This puts the pedestrians in direct conflict with the northbound lagging protected left turn movement. Unable to complete the turn because of the illegal presence of pedestrians, vehicles were observed to wait 2 to 3 cycles to complete the turn. Converting it to a leading operation eliminates the conflict with the pedestrians.

- Install side street vehicle and pedestrian detection at the following intersections along Constitution Avenue:
  - 22nd Street, NW,
  - 21st Street, NW,
  - 20th Street, NW
  - 16th Street, NW,
  - New Jersey Avenue, NW,
  - Delaware Avenue, NW, and
  - First Street, NE.
- At the intersection of Constitution Avenue and 17th Street NW evaluate removal of existing shared through and right-turn lane along eastbound Constitution Avenue (as illustrated in the sketch below) and convert it to a through-only lane. Observations in the field indicated that the number of vehicles utilizing the shared lane to turn right is very low. However, vehicles were spotted attempting to turn right on red creating a safety hazard for pedestrians in the crosswalk. The proposed lane modification is anticipated to improve flow on Constitution Avenue and remove a potential safety hazard for pedestrians.

Photo: looking eastbound on Constitution Avenue. Red circles show recommended lane configuration changes at 17th Street

s) South Capitol Street and Virginia Avenue, SW

- Install side street vehicle and pedestrian detection at this intersection. Minimal traffic was observed from the side street at this intersection. Detection allows any unused split time to be transferred to the main line.

C. Recommendations to Reduce Pedestrian-Vehicle Conflicts

The following recommendations are intended to reduce pedestrian-vehicle conflicts and improve traffic operations. At these intersections with both heavy pedestrian traffic, and heavy turning traffic, turning traffic cannot proceed during the green interval as pedestrians are blocking the path. Frequently, vehicles are only able to turn during the end of the green interval and during the yellow interval and the result is a cycle failure (not all queued traffic is able to turn).

a) 19th Street at L Street, NW

- Southbound 19th Street traffic turning left onto L Street experiences recurring cycle failures since vehicles are not able to turn across the heavy flow of pedestrian traffic. DDOT should add a lagging dummy phase to stop the east side pedestrian movement to allow the left to move.

b) Eye Street at 17th Street, NW

- Westbound Eye Street traffic turning left onto southbound 17th Street experiences recurring cycle failures since vehicles are not able to turn across the heavy flow of pedestrian traffic. DDOT should investigate options to shut down the pedestrian interval to allow traffic to turn.

c) L Street at 15th Street, NW

- Eastbound L Street traffic turning left onto northbound 15th Street experiences recurring cycle failures since vehicles are not able to turn across the heavy flow of pedestrian traffic. DDOT should investigate options to shut down the pedestrian interval to allow traffic to turn.

d) L Street at 16th Street, NW

- Eastbound L Street traffic turning left onto northbound 16th Street experiences recurring cycle failures since vehicles are not able to turn across the heavy flow of pedestrian traffic. DDOT should investigate options to shut down the pedestrian interval to allow traffic to turn.

e) Constitution Avenue at 17th Street, NW

- Eastbound Constitution Avenue traffic turning right onto southbound 17th Street experiences recurring cycle failures since vehicles are not able to turn across the heavy flow of pedestrian traffic. DDOT should investigate options to shut down the pedestrian interval to allow traffic to turn.

f) Wisconsin Avenue at M Street, NW

- At Wisconsin Avenue and M Street it is very difficult for southbound right turning traffic to make the turn due to pedestrian conflicts while southbound traffic has a green ball. A right turn overlap phase could be added to run with the eastbound left turn phase. This would provide a protected movement for the rights and greatly improve the intersection operation. This is especially critical on the weekends when there are even greater pedestrian volumes. This would also provide additional incentive to divert traffic off of 34th Street if motorists could depend on this as being a reliable and more efficient travel route. It is recommended that the north south phase sequence be reversed so that the southbound movement would immediately precede the eastbound left so as to provide a continuous movement when the overlap is implemented.

D. Develop Special Event Signal Timing Plans

Special event signal timing plans should be developed for the corridors around Verizon center area and for high-draw, recurring special events, such as Fourth of July, and the Cherry Blossom Festival.

E. Develop Shoulder-of-the-Peak Offset for Oversaturated Corridors

As noted previously, several corridors were designed with a reverse offset pattern to clear the downstream queue before releasing the upstream traffic. This pattern is very effective during the peak 60 to 90+ minutes of the rush hours. However, the AM and PM pattern operates for 5 to 6 hours per day, and a progressive offset pattern may be more efficient during the "shoulder" periods of the AM and PM peak patterns. This is referred to as an Offset A (reverse) and Offset B (progressive) pattern; A and B are used to distinguish that the same pattern is running, but a different set of offsets is used by time of day. The following is a list of corridor where an offset A and B pattern may improve operations during the shoulder time periods:

- Westbound Constitution Avenue from 15th to 23rd Street in the PM peak
- Southbound 14th Street from F Street to Constitution Avenue in the PM peak
- L Street from 16th to 13th Street in the PM peak
- Eye Street from Connecticut Avenue to 17th Street in the PM peak
- 17th Street from Independence Avenue to K Street in the AM peak
- Westbound Rhode Island Avenue approaching Florida Avenue in the AM peak

F. Intersections to Study for Geometric Improvements

a) 16th Street at U Street, NW

- The recurring congestion at this intersection is not due to, or able to be significantly mitigated by signal timing optimization. Additional measures are necessary. During the before period southbound 16th Street experienced consistent cycle failures at the intersection with U Street Even after the timing optimization the cycle failures remain. The signal timing at this intersection remains constrained by the exclusive "bike" phase present at this intersection.

b) 7th Street at Rhode Island Avenue, NW

- The recurring congestion at this intersection is not due to, or able to be significantly mitigated by signal timing optimization. Additional measures are necessary. During the before period southbound 7th Street experienced consistent cycle failures at the intersection with Rhode Island Ave. Even after the timing optimization the cycle failures remain.

G. Develop Construction Activity Signal Timing for Large Impact Projects

The following is a list of observed construction activity that negatively affected the signal timing optimization. The point of compiling this list is to illustrate the fact that there is significant construction activity that creates non-recurring types of congestion at all times of day. It is important to note that not every construction project requires a change in signal timing. However, signal timing changes should continue to be made, along with general improvements in curb space management (meaning that DDOT manages construction permits to not allow construction during peak hours, expect for large projects). There is still a significant amount of work to be done on a day-to-day basis to manage construction-related lane closures, detours, etc. which may now be accomplished much easier than before this project started, using the signal timing model developed for this project.

Weekdays (Observed during the time period from Tuesday, April 28th through Thursday May 7th)

- 23rd Street (both directions) 1 lane closed in each direction to repaint crosswalk during Midday and PM hours; southbound traffic backed up to N St.
- Southbound 17th street north of Pennsylvania Avenue lane closed during the AM peak hour
- 21st Street at N Street – closed for gas emergency
- 20th Street at F Street – lane blocked by construction vehicle
- Road closures on Constitution at 17th, Henry Bacon and Independence at 23rd and 17th.
- North Capitol Street had ongoing construction occurring in the northbound direction between P Street and Randolph Pl. North Capitol Street was restricted to one lane between the AM and PM peak hour.
- Massachusetts Avenue between 6th Street and 7th Street building construction vehicles often stop/block the westbound curb lane prior to 7th Street.
- Massachusetts Avenue between 17th Street and 18th Street flaggers sometimes stop traffic to allow loading and unloading.
- Florida Avenue between 19th and 20th Street construction restricts eastbound traffic to one lane rather than two lanes.
- 7th Street, south of Rhode Island Ave. to south of T St. lane closures
- 14th Street, northbound from south of Vermont Ave. to Thomas Circle, right lane closed for utility emergency on April 27th and April 28th.
- 16th St. southbound between K St. and I St. ongoing right lane closure
- 9th Street and F Street Intersection lane closures
- 6th Street between G Street and H Street lane closures.
- 15th Street and K Street Intersection lane closures
- 15th Street at Massachusetts Ave Intersection lane closures
- 15th Street between K Street and Massachusetts Ave lane closures
- M Street between 21st Street and New Hampshire Avenue with lane closure
- Eye Street from 16th Street and 17th Street. This work zone was periodically present during the midday to PM peak hour, which caused congestions and multiple cycle failures.
- H Street work zones were present between 14th Street and NY Avenue periodically during mid-day to PM peak hour, which caused major congestions and multiple cycle failures. There was major construction at the intersection of H Street and 3rd St with various lane closures and detours.
- Westbound Constitution Avenue between 10th and 12th Streets NW: Construction cones were placed around data collection tubes in the curbside lane thereby reducing the number of travel lanes available from 4 to 3 in this segment.

- Westbound Constitution Avenue between 12th and 14th Streets NW: A portable DMS sign was left in the curbside travel lane during the morning peak thereby reducing the number of travel lanes available from 4 to 3 in this segment. In addition, parking attendants at the Andrew W. Mellon Auditorium blocked the curbside lane in preparation for receiving valet parking vehicles during the afternoon peak thereby reducing the number of travel lanes available from 4 to 3 in this segment.

Weekend (Observed during the time period from Saturday April 25th to Sunday May 3rd)

- 14th and U Street intersection lane closures
- 15th Street between I and Mass Avenue lane closures
- 6th Street SB between D street and Penn Ave lane closures
- 15th Street and I Street lane closures
- Mass Ave east of 5th Street lane closures
- 9th Street SB at F Street lane closures
- 21st Street was closed between M and L Streets
- K Street, several traffic signals were “dark” and under police control. K Street was also closed through several intersections on Sunday May 3rd on the east side of the corridor.
- 9th St. at F St. construction resulted in a single lane on 9th
- I St. west of 15th shut down for crane dismantling combined with NB 15th between I and K being shutdown caused tremendous backups and cycle failures along I and 15th in this area.
- M St. WB between Thomas Jefferson and 31st reduced to one lane due to construction.
- Wisconsin Ave., French Market was impacting traffic, curb lane NB blocked off for pedestrians so shops could set up displays on sidewalk. TCOs directing traffic along Wisconsin between Reservoir and Q.
- N. Capitol St. utility work around FL Ave. had traffic backed up all the way to L St. by the midafternoon.
- Penn. Ave between 12th and 14th shutdown for event
- Eye Street from 16th Street and 17th Street was fully closed and traffic was detoured to K Street or H Street.

DISTRICT DEPARTMENT OF TRANSPORTATION

Downtown Traffic Signal Optimization

June 2015

PREPARED FOR:

District Department of Transportation

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