Low-Stress LTS: The District of Columbia's Innovative Approach to Applying Level of Traffic Stress

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ABSTRACT

Washington, D.C. (the District) has been a national leader in the adoption of innovative bicycle facilities. However, with much of the "low-hanging fruit" bicycle facilities already in place, the District Department of Transportation (DDOT) needs a mechanism for prioritizing future investments. As part of a Multimodal Congestion Management Study, DDOT used existing roadway information combined with an innovative GIS-based approach to prioritize and expedite the collection of supplemental roadway information to develop a bicycle Level of Traffic Stress (LTS) map for the District. The results both confirmed existing perceptions about the availability of bicycle facilities in the District, and identified previously unidentified gaps in the overall bicycle network. In addition, the methodology for developing the LTS network map provides a proof-of-concept for other jurisdictions looking to develop their own LTS network map. Using this information, DDOT is able to prioritize future bicycle infrastructure investments, while having a mechanism for updating the LTS map as additional data is collected and new facilities are constructed.

INTRODUCTION

The District Department of Transportation (DDOT), serving Washington, D.C. (the District), is nationally known as a leader in the planning, development, and implementation of innovative bicycle infrastructure. Across the District, DDOT has installed 75 miles of marked bicycle lanes, 6 miles of cycle tracks, deployed more than 3,000 bicycle racks, launched one of the first public bike sharing programs in the United States, and seen peak-hour cycling volumes nearly quadruple since 2004. While much of the success of the District bicycle program has come from taking care of the "low-hanging fruit" DDOT is now looking towards prioritizing future needs and identifying strategic investments that will complete missing gaps in the bicycle network. Towards that end, DDOT was able to leverage work being done on the council-mandated Multimodal Congestion Management study to complete a Level of Traffic Stress (LTS) analysis on all District roads, and begin the process of identifying strategic missing gaps in the bicycle network.

BACKGROUND AND LITERATURE REVIEW

In 2016, the Council of the District of Columbia tasked the District Department of Transportation (DDOT) with studying and reporting on "multimodal congestion" in the District. The Council Action (D.C. Code § 50-921.21) called for an assessment of the current state of congestion and recommendations for remedying existing congestion problems and an implementation plan. The ensuing Multimodal Congestion Management Study, led by DDOT, was responsive both to the Council's request and DDOT's own identified needs for monitoring and managing the transportation system.

The project team first sought to define "congestion." Defined traditionally, congestion impacts are limited to vehicular traffic and transit. In rare cases, pedestrians experience congestion related to overcrowded sidewalks. Bicycle congestion remains uncommon even on the District's busiest bicycle corridors. To more comprehensively characterize multimodal travel, DDOT's study focused on three areas related to congestion:

- Travel time reliability,
- Accessibility to modes of travel and to destinations, and
- Intensity of use

In addition to being largely free of congestion, bicycle transportation in the District is extremely reliable. Travel times are consistent and predictable, irrespective of time of day or day of the week. But this reliable form of transportation is only realistically available to District residents and visitors who can travel a safe route for their trips. As a result, the focus of the effort is on defining bicycle *accessibility* in the District.

Defining Accessibility

Transportation accessibility is broadly defined as "the ability to reach desired goods, services, activities, and destinations" (1). For automobile travel, access is considered to be the ability to reach destinations within a given time period. Basic conditions of safety and comfort are assumed, so the primary considerations for access are things like congestion (delay) and development patterns (land use) (2). For bicycles, however, the equation is more complex.

Bicycle travel is permitted on all but the few limited-access facilities in the District, such as interstates and parkways. But safety, comfort, and convenience concerns keep the majority of District residents, employees, and visitors from bicycling for most trips (3; 4). Therefore, understanding accessibility requires a more nuanced view of bicycle conditions. Only those streets on which people would be comfortable bicycling can be considered "accessible" (5).

Measuring Bicycle Accessibility

Defining bicycle performance measures has been a topic of much concentrated research in recent years. Researchers have developed numerous methods to quantify the quality of service or level of service for bicycling on streets (6; 7; 8; 9). Bicycle level of service methods have even been incorporated into the 2010 *Highway Capacity Manual* (10). DDOT has used bicycle level of service methodologies in prior planning efforts, such as its 2005 Bicycling Master Plan (11) and its 2014 *moveDC* long-range 1. multimodal transportation plan (12). Yet challenges persist with many of these methods. Data collection needs are significant, limiting the ability to apply the analysis across an entire roadway network. Moreover, the results are 2 ~~not~~ immediately meaningful. Level of service and level of comfort scores on a scale from A to F are used to characterize the diverse factors contributing to a cyclist's experience on a road, including traffic impacts and delay at intersections. And the methods contain imperfections and can produce counterintuitive results (13).

Since the Multimodal Congestion Management Study required a District-wide analysis of travel by all modes on all District streets, researchers needed an analysis method that could be applied efficiently and used to measure bicycle accessibility. The Level of Traffic Stress (LTS) method (14) provides a network-level analysis with relatively little data. LTS evaluates the impact of traffic on a bicyclist's experience and its analysis results classify streets into one of four "stress levels" for bicycling. These stress levels are inspired by the "Four Types of Cyclists" popularized by the City of Portland (15) and correlated to the theorized comfort level of different types of bicyclists:

- LTS 1: a level of traffic stress that most children can tolerate
- LTS 2: the level that would be tolerated by the mainstream adult population
- LTS 3: the level tolerated by American cyclists who are "enthused and confident" but prefer dedicated space for riding
- LTS 4: a level tolerated only by those characterized as "strong and fearless"

The LTS method recognizes that cyclists are sensitive to traffic conditions and are likely to only choose to bicycle for transportation if their trip can be completed on streets at or below their individual stress comfort level. Conversely, providing better low-stress connections has the potential to attract more riders and improve bicycle accessibility (16). For a bicycle network to attract the broadest segment of the population, it must provide low-stress connectivity, defined as: "providing routes between people's origins and destinations that do not require cyclists to use links that exceed their tolerance for traffic stress, and that do not involve an undue level of detour" (14).

Data Requirements

A key benefit of the LTS method is that it requires less data than the other bicycle performance measure tools reviewed. And the data required are relatively easy to collect. Most of roadway characteristics included in the method are data many cities will already have collected, or are relatively simple to collect. The data requirements to conduct the LTS analysis and the availability of District sources are summarized in Table 1.

TABLE 1. LTS Data Requirements and Sources

Analysis Element	Data Requirement	District Mapping Source
Segments	Presence or absence of parking	None
	Presence or absence of bike lane	District Bike Layer
	Presence or absence of a centerline	None
	Street width (number of lanes)	District Centerline layer (partial)
	Width of bike lane and parking lane	None
	Speed limit or prevailing speed	District Centerline layer (partial); historic speed study results
	Frequency of vehicles parked in bike lane	Business District Layer*
Intersection Approaches	Presence of right turn lane(s)	None
	Length of right turn lane	None
	Turn lane configuration	None
Unsignalized Crossings	Width of cross street	District Centerline layer (partial)
	Speed limit of cross street	District Centerline layer (partial)
	Presence or absence of median refuge	District Street Right-of-Way layer

*In the absence of bike lane blocking data, the LTS method recommends identifying commercial areas to designate "frequent" blocking

While much of the data required for LTS were available on most major streets, some information was missing for most streets in the District. On a street-by-street basis, collecting this information would be relatively simple. But with over 1,500 centerline miles of street in the District, it would require several hundreds of hours to collect the remaining data.

Precedent Studies

The District study built on lessons learned through several precedent studies applying LTS. The first, in Montgomery County, Maryland, used a desktop-based audit of streets in downtown Bethesda (17). 1. Although most of the needed data to perform the LTS analysis had not previously been collected, the researchers leveraged readily available aerial and street-level photography to streamline data collection. Using this desktop review method, an initial LTS map was created relatively quickly. Some data that were not available or not clearly obtainable using this method were collected through field visits. The results of this analysis yielded street network maps for cyclists of different abilities and comfort levels with relatively minimal effort.

The next evolution of LTS analysis was pioneered by the City of Oakland, California. Building 2 off the LTS method, the City developed a citywide model of roadway conditions and how those conditions affect bicyclists (18). The model, which runs through a script within the City's geospatial mapping program, will produce a block-by-block LTS map for Oakland when it is complete. This allows the city to simply update and monitor its street layer, while allowing the model to make any necessary changes to LTS classifications.

1,2 -> this

Still, both of these methods required a complete set of data to be collected for the analysis to be performed. But a strength of the LTS method is that it applies a "weakest link" logic, wherein the stress level is assigned based on the lowest-performing attribute. For example, even if a segment has mostly low stress characteristics, the occurrence of one high-stress attribute (e.g. a narrow outside lane) dictates the stress level for the link. From an analysis perspective, this means it is not always necessary to collect all of the data on each street. Based on a subset of information, streets can be organized—or "triaged"—according to LTS analysis categories.

Figure 1 provides the LTS scoring method for mixed traffic streets, or those streets without any dedicated bicycle infrastructure. On these streets, the key variables are traffic speed and number of lanes (street width). No data about parking or bike facilities (which are necessarily absent) are needed to perform the LTS analysis.

Table 4. Criteria for Level of Traffic Stress in Mixed Traffic

Speed Limit	Street Width: 2-3 lanes	4-5 lanes	6+ lanes
Up to 25 mph	LTS 1[a] or 2[a]	LTS 3	LTS 4
30 mph	LTS 2[a] or 3[a]	LTS 4	LTS 4
35+ mph	LTS 4	LTS 4	LTS 4

Note: [a] Use lower value for streets without marked centerlines or classified as residential and with fewer than 3 lanes; use higher value otherwise.

FIGURE 1. LTS Scoring for Mixed Traffic Streets (14)

Still further triaging is possible. All streets with posted speed limits above 35 miles per hour are LTS 4, and no further analysis is needed. And any street posted 30 miles per hour with four lanes or more is LTS 4. On the other end of the comfort spectrum, most local neighborhood streets are easily classified. Assuming local streets are no more than two to three lanes wide, with speed limits 25 miles per hour or slower, the only variable needed is the presence or absence of a centerline. Leveraging this triage, detailed data collection is only needed for mixed traffic streets with 25 to 30 mile per hour speed limits and between two and five lanes of traffic.

The advantages of this analysis method were first realized in Baltimore City in 2016, where analysts categorized LTS data collection needs on Baltimore streets (19). First, the local street network was filtered out from the analysis using the functional classification designation. As a policy, Baltimore City does not stripe double yellow centerlines on its local streets, so all local streets were classified as LTS 1. And many of the city's main arterials are well above the LTS 4 threshold, making them easy to classify without conducting a block-by-block data inventory. Since the majority of streets in Baltimore are local, as in most cities, this substantially reduced the data collection effort needed. Eliminating local streets and principal arterials from the analysis reduced the person-hours needed to collect the remaining data.

These precedent studies provided the groundwork for the analysis in the District, and created the opportunity to refine the method even further. In addition to automatically classifying the "easy to identify" LTS 1 and LTS 4 streets, the remaining streets could be organized in terms of what data are needed.

DATA FILTRATION

The project team's approach to assigning LTS scores to DC roads significantly expanded upon the data filtration process used in Baltimore. Roads that could be filtered out using the "weakest link" principle were identified using publically available GIS data from DC's Open Data website, pre-existing GIS data from a DDOT speed study, the institutional knowledge of DDOT's Bicycle Program Specialists, and key assumptions regarding roadway functional classification and speed. By strategically applying existing data to the District's roads and trails with GIS, the project team was able to assign LTS scores to 81% of all roads and trails in the District. The triaged and remaining streets to be analyzed are illustrated in Figure 2 and Figure 3, respectively.

LTS scores assigned to mixed-traffic roads (roads without bike facilities) are based on street width and speed limit. DDOT and the project team developed assumptions regarding roadway functional classification, speed limits, and street width to filter out mixed-traffic roads. All local roads were assumed to have a maximum street width of 2-3 travel lanes and a speed limit of 25 mph. In the absence of a District-wide speed limit dataset, GIS data from a DDOT speed study was assumed to have identified all collector and arterial roads in the District with a listed speed of 35 mph or higher. Based on this assumption, an assumed speed limit of 30 mph was applied to all remaining collector and arterial roads. All roadways with a functional classification of highway, interstate or freeway were removed from the

LTS network. High-speed, high-volume roads such as highways and interstates are assumed to be off-limits to cyclists, and thus fall out of the LTS network entirely.

Given the assumptions established by DDOT, all mixed-traffic, local roads could be assigned a score of LTS 1 or LTS 2. The LTS methodology generally assigns an LTS score of 1 to local roads classified as "residential," and an LTS score of 2 to all other local roads. Local roads were identified in GIS using the functional classification field in DDOT's street centerline shapefile. A 100' buffer was applied to all commercial and industrial parcels in DDOT's existing land uses shapefile. Local roads located within the 100' buffers were classified as "non-residential" and were assigned an LTS score of 2. All remaining local roads were assigned an LTS score of 1.

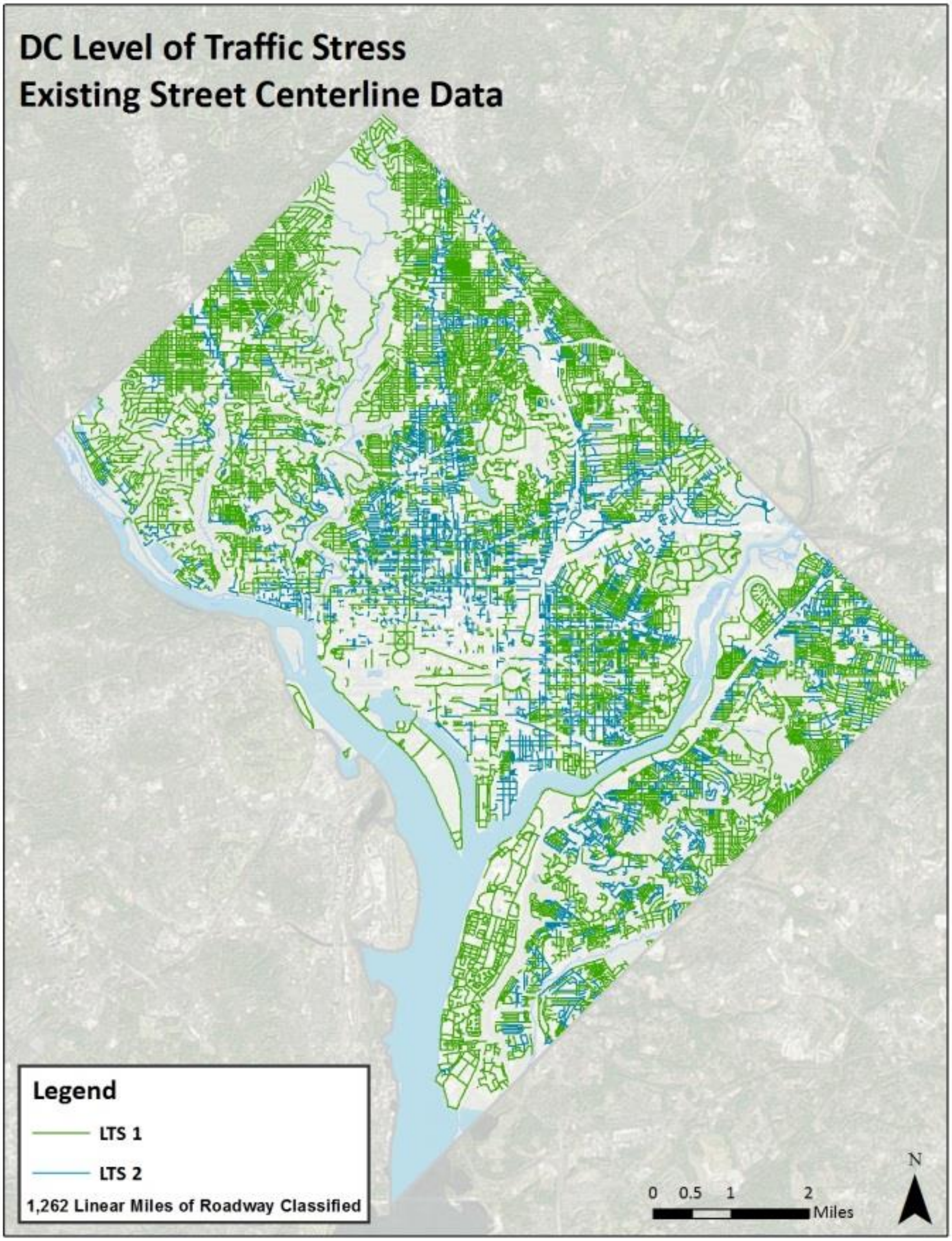

FIGURE 2. Categorically classified Washington, DC streets from the LTS triage

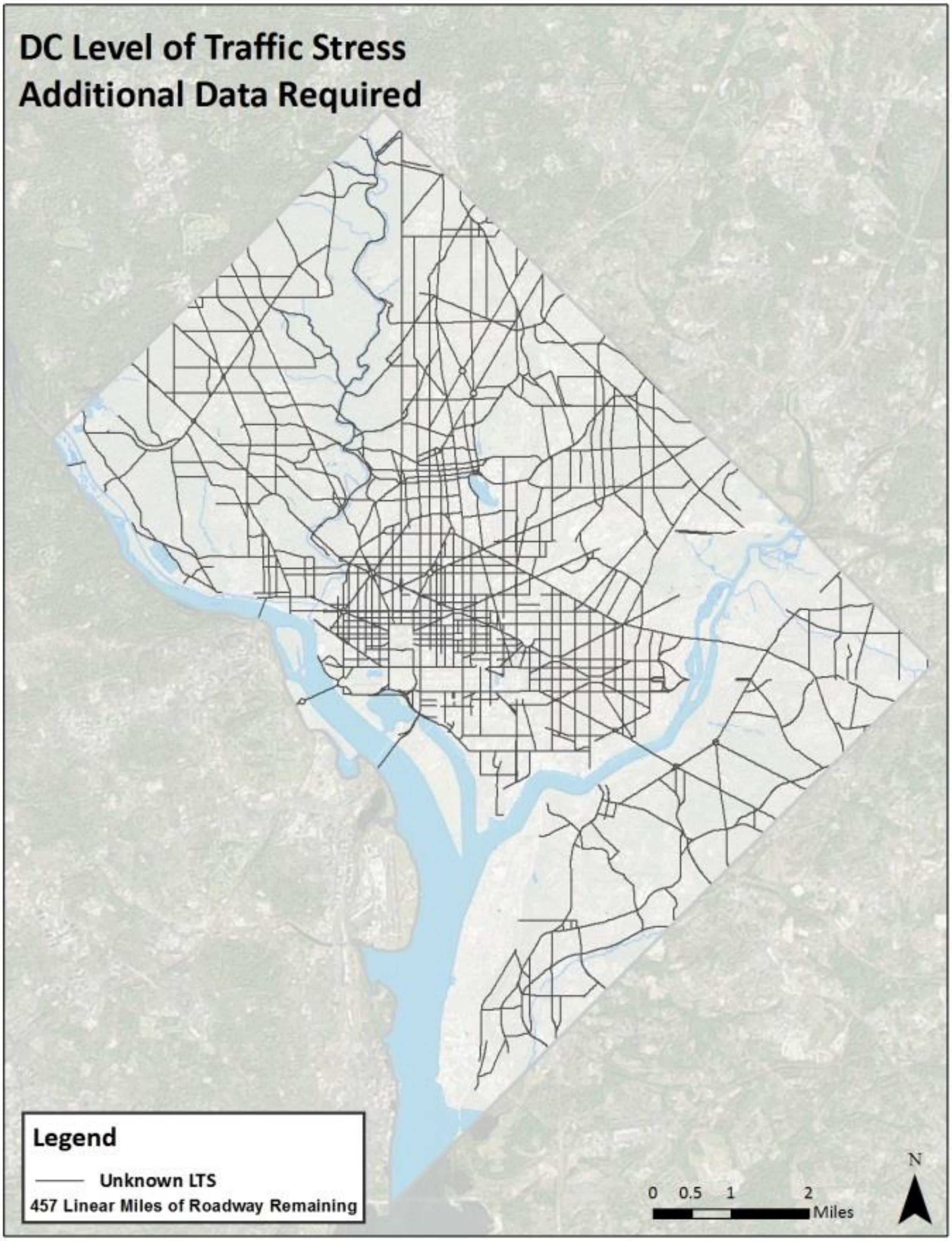

FIGURE 3. Remaining Washington, DC streets needing data for analysis after initial LTS triage

GIS data from DDOT's speed study were used to identify all mixed-traffic arterial and collector roads with observed operating speeds of 35 mph or higher. Per the LTS criteria, these roads were all assigned an LTS score of 4. All remaining mixed-traffic arterial and collector roads were assigned an assumed speed limit of 30 mph, and could not be scored without additional roadway width data. The observed speed data included several local roads originally assigned an LTS score of 1 or 2. These roads were reviewed, and the roads were re-classified if observed speeds exceeded 25 mph. Local roads were otherwise assumed to have limited speeding issues thanks to the narrow street widths and the high density of four-way stop controlled intersections in most residential areas.

LTS scores assigned to roads with bike facilities are based on the type of facility, the combined width of the facility and its adjoining parking lane, street width, and speed limit. DDOT maintains publically-available GIS shapefiles for all cycle tracks, bike lanes and bike trails in the district. The data stored in these shapefiles was joined to the District's street centerline shapefile to identify off-road trails and roads with bicycle facilities. Per the LTS methodology, all off-road trails and roads with cycle tracks were automatically assigned an LTS score of 1. All remaining roads with bike facilities could not be scored without data on the combined width of each facility and its adjoining parking lane.

The project team capitalized on the institutional knowledge of DDOT's Bicycle Program specialists to catalogue bike lane and parking lane widths for all remaining roads with bike facilities. Per DDOT, the District's standard 5' bike lanes typically adjoin 8' parking lanes, for a combined width of 13'. DDOT's Bicycle Program specialists provided the project team with a comprehensive list of all known exceptions to the standard parking and bike lane widths, including bike and parking lane width measurements for each unique facility. All other roads with bike facilities were assigned DDOT's standard combined width of 13'.

Armed with information on bike lane and parking lane widths, along with established assumptions regarding speed limits and lane widths for local, collector and arterial roads, the project team classified all remaining roads with bike facilities. Local roads with bike facilities were assigned an LTS score of 1 if the sum of bike lane and parking lane widths amounted to 15 feet or more. All remaining local roads with bike facilities were assigned an LTS score of 2. Collector and arterial roads with bike facilities were assigned an LTS score of 3.

By using readily available GIS data, institutional knowledge and educated assumptions, the project team assigned LTS scores to 81% of all roads and trails in the District. The remaining District roadways could not be assigned an LTS score without collecting data on street widths. Figure 4 provides a concept illustration of the streamlined data collection approach.

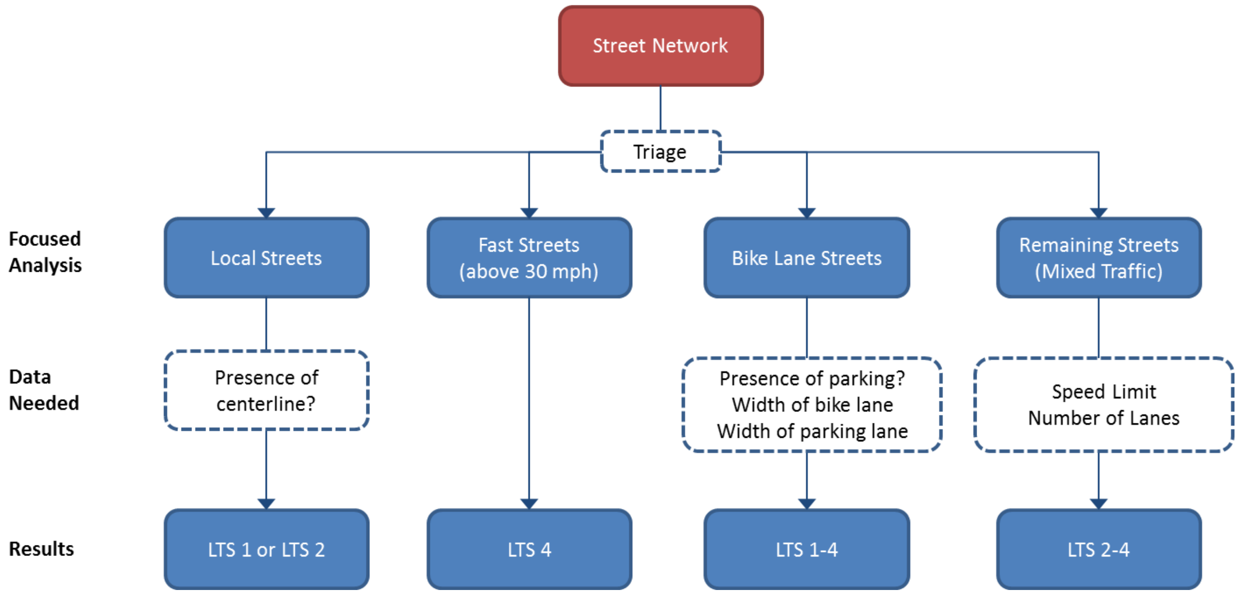

FIGURE 4. Streamlined Data Collection Process

DATA COLLECTION

The project team's data filtration process reduced outstanding unclassified roads and trails to 19% of the District's bicycle network. All remaining unclassified roads fell under the mixed-traffic roadway classification, so the data points needed to assign LTS scores to these roads were restricted to speed and street width. Through discussions with DDOT, an assumed speed limit of 30 mph was assigned to all unclassified collector and arterial roads in the District. Consequently, roadway data collection requirements were reduced to one data point: street width.

The LTS methodology defines street width as the number of travel lanes spanning a street. Street cross-sections were catalogued to provide the project team with accurate street widths for all remaining roadways. The project team discussed various methods for efficiently recording street cross-sections, and settled on digitizing roadway information using DDOT's new linear reference system.

Linear reference systems offer an elegant alternative to traditional data storage methods. Unlike traditional GIS, linear referencing stores data using a relative position along existing line features. The location of GIS data is usually mapped with x, y coordinates, while data stored using linear referencing can be mapped based on a known linear feature and a position, or measure, along it. Linear referencing allows multiple attributes to be associated with any portion of an existing linear feature, independent of its beginning and end. Linear reference systems are particularly useful to organizations that maintain detailed data on linear features, such as urban roadway networks. DDOT's Office of Information Technology and Innovation (OITI) added a dynamic digitizing tool to its linear referencing system in 2016, so the LTS project provided DDOT with an opportunity to test the digitizing capabilities of its linear referencing application.

DDOT uses linear referencing to store roadway data in a "Roads and Highways" route feature class. That feature class is similar to a standard line feature class, but it stores an m-coordinate along with x- and y-coordinates as part of the linear referencing system. Roads and Highways is composed of linear features for all roads and highways in the District, which are overlaid with linear "lane events" that store characteristics of individual roadway lanes. Any given roadway segment in DDOT's Roads and Highways feature class can be associated with multiple lane events that describe the unique characteristics of the roadway lanes in that roadway segment. Existing lane events can be overlaid with new lane events to reflect changes in lane characteristics. Consequently, the linear referencing capabilities of DDOT's GIS provided the project team with an opportunity to simultaneously record roadway cross-sections and detailed lane characteristics for all unclassified roads in the LTS network.

Researchers established data entry requirements for digitizing roadway cross-section information in DDOT's Roads & Highways route feature class. OITI provided the project team with specific data entry guidelines to ensure the accuracy of lane event digitization and characterization. Required roadway digitizing directions differed in the District based on roadway location, specifically District quadrants (NW, NE, SE, SW). Certain roadway characteristics were required to be catalogued with each new lane event, including lane side (relation to roadway centerline), lane type and lane width. Through discussion with DDOT, the project team established default lane widths for each lane type in order to increase the efficiency of the digitizing process. Figure 5 further defines the lane event digitizing and data entry requirements that were established by OITI for the Roads and Highways route feature class.

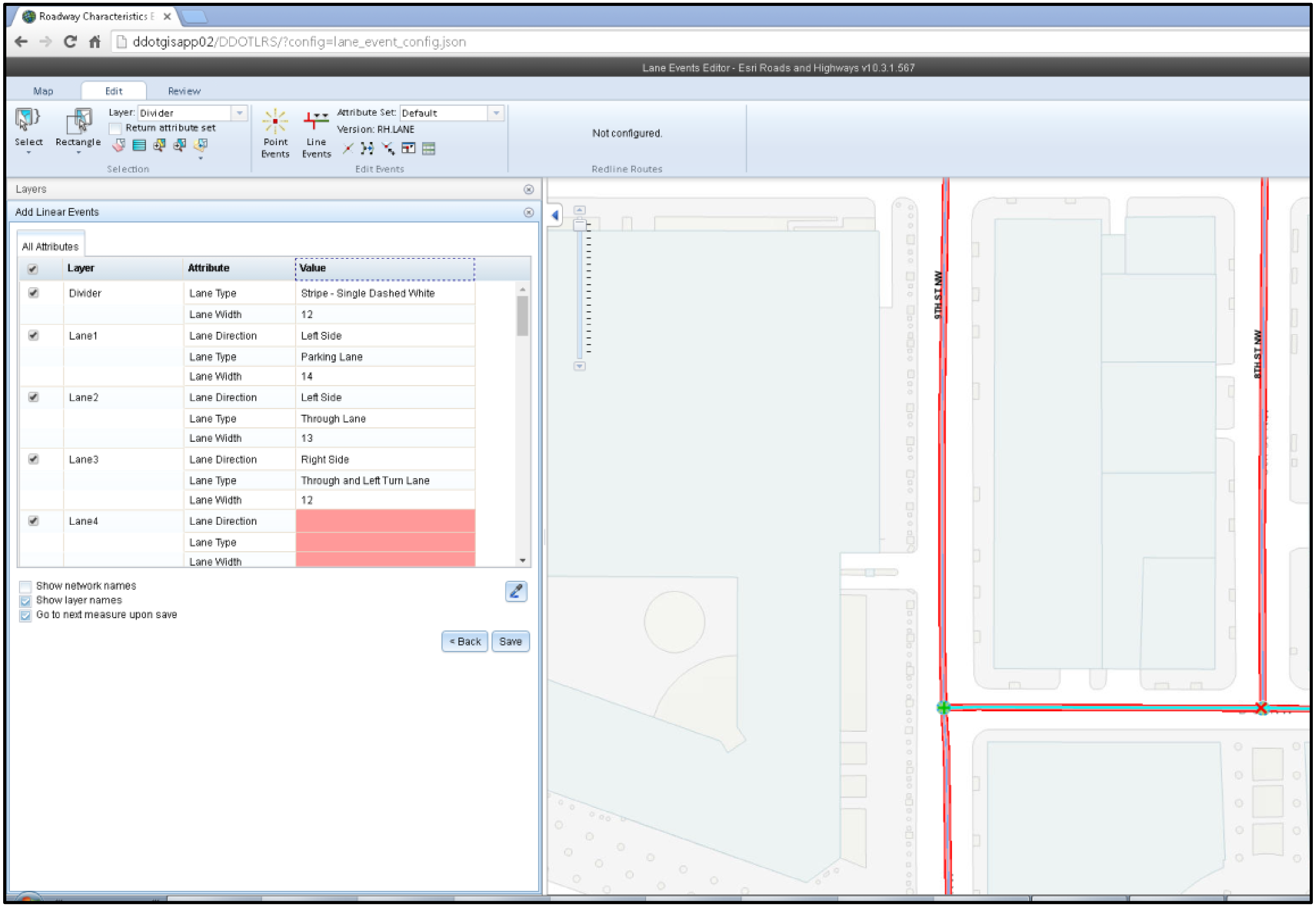

FIGURE 5. Example lane event digitizing entry window

Lane event data was digitized for all unclassified roads in the LTS network within three weeks. Time required for digitization was significantly reduced due to the data filtration process and the data collection process was further condensed by the data storage efficiencies of DDOT's linear referencing system. Ultimately, the data collection effort generated a record of the number or roadway lanes associated with all unclassified roadway segments in the District, while providing DDOT with a detailed catalogue of roadway characteristics associated with each roadway segment.

ANALYSIS

The lane event data collected by the project team was exported from DDOT's linear referencing system in a series of polyline shapefiles. Each shapefile contained roadway characteristics for a single lane event, so additional processing in GIS was required to calculate the number of travel lanes associated with each segment. Although the line features in the lane event shapefiles mirrored the line features in the LTS shapefile, the separate features could not be joined based on shared attributes. Since individual records in the lane event shapefiles were created using linear referencing, the records within each shapefile did not match up with individual records within the LTS shapefile. Spatial joins were used to associate the lane event data with the LTS shapefile, and to ultimately determine the number of travel lanes in each roadway segment.

Several steps were needed to incorporate data from the lane event shapefiles into the existing LTS shapefile. First, eight new short integer fields were created in the LTS shapefile, one for each exported lane event. Each new field would be populated with values of 0 or 1 to represent the presence or absence of a travel lane along each roadway segment in the LTS shapefile.

The individual records in each lane event shapefile included a detailed description of the type of lane associated with each record. Possible lane types ranged from parking lanes to through lanes. A definition query was applied to each lane event shapefile to single out individual records with the lane type equivalent of a travel lane. The use of the definition query ensured that erroneous lanes such as parking lanes were not counted as travel lanes in the LTS shapefile.

Once the LTS shapefile and lane event shapefiles were prepared for joining, a two-step join was applied to each lane event shapefile. First, a single lane event shapefile was joined with the LTS shapefile using a spatial join. This process created a new, combined shapefile which associated roadway segment IDs from the LTS shapefile with data from the lane event shapefile. The new, combined shapefile was joined to the original LTS shapefile based on roadway segment ID number, a shared attribute.

When the LTS shapefile was joined with data from the lane event shapefile, the "select by attribute tool" was used to identify all roadway segments that were associated with lane type data. The definition query that had been applied to the lane event shapefile ensured that all selected roadway segments were associated with a single travel lane. The field calculator was applied to the field for the lane event in question, and was used to assign a value of 1 to all selected roadway segments, indicating that a travel lane was associated with those roadway segments. The two-step join and field calculation process was applied to each lane event shapefile, so that all eight lane event fields in the original LTS shapefile were populated with binary values indicating the presence or absence of a travel lane.

Once the lane event fields in the LTS shapefile were populated, an additional short-integer field was added to the LTS shapefile. The field calculator was applied to the new "SumLanes" field to sum up the number of travel lanes associated with each roadway segment, thus creating a record of street width for all remaining unclassified roads in the District.

In addition to the three week data collection process, it took the project team around three hours to develop, test and apply the process to associate lane type data with the LTS shapefile. The newly calculated street widths and assumed speed limit of 30 mph were then used to apply an LTS score to all unclassified District roads. The completed LTS map was shared with DDOT so that agency staff could use their pre-existing knowledge of District roads to begin assessing the accuracy of the LTS scores. The review process is still underway, and may unearth road segments where a higher or lower LTS score is deemed appropriate by DDOT. The results of the LTS analysis are depicted in Figure 6.

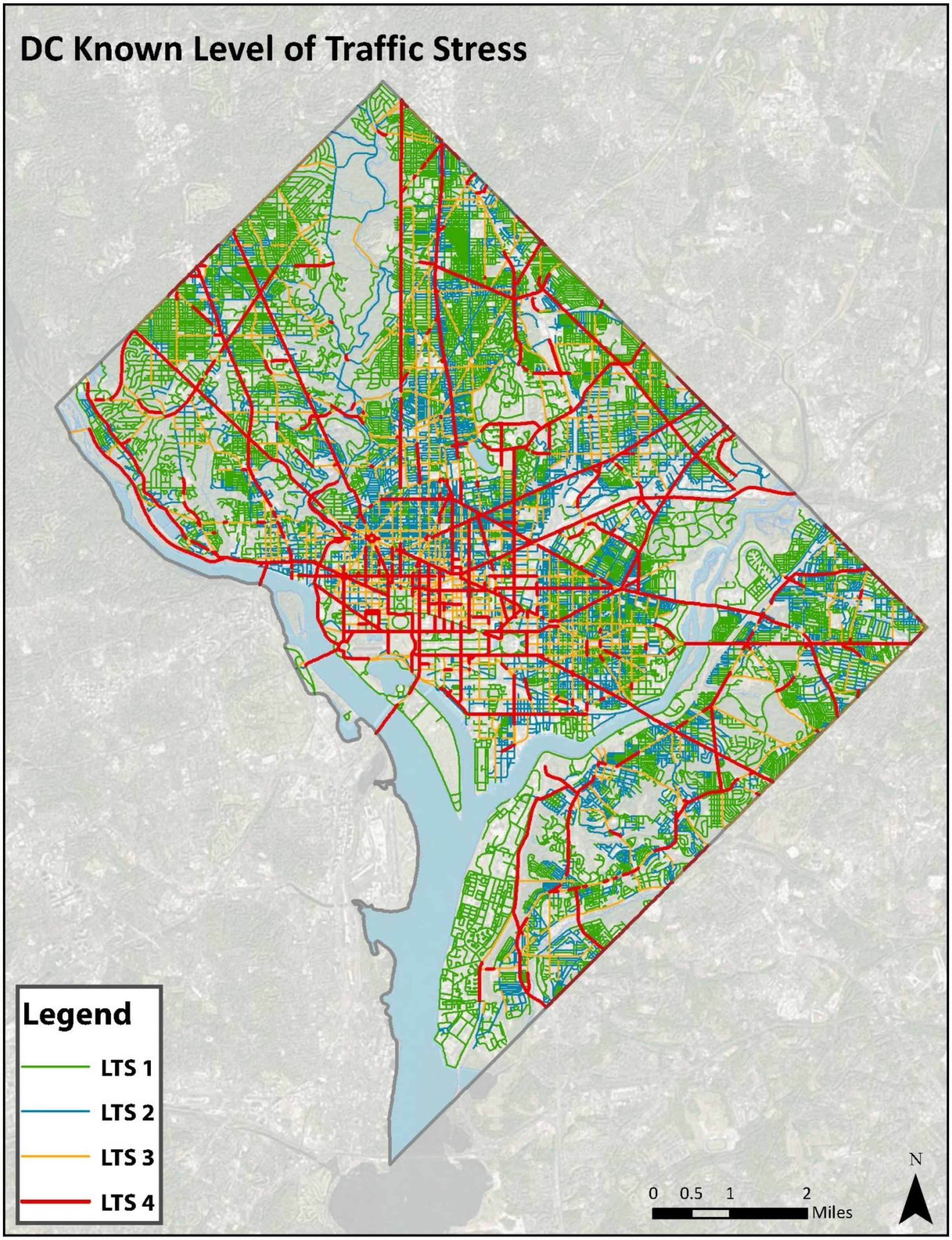

FIGURE 6. Preliminary results of DC LTS analysis

CONCLUSION

By applying the LTS method to District roads, the project team met a key goal of DDOT's Multimodal Congestion Management Study: to efficiently measure bicycle accessibility on all District streets. The LTS mapping effort has provided DDOT with a data-driven means of defining the effective bicycling network in the District, and an input to prioritizing future needs and investing strategically in efforts that will fill gaps in the network. DDOT will also be able to easily update the LTS data as changes are made to the network, ensuring the data will remain current in the long term.

Lessons Learned

The efforts of the project team confirmed that the LTS methodology can be efficiently applied to a large city in a condensed period of time. The data filtration, collection, and analysis processes required to develop a complete LTS map for the District took around just under a month to complete. By strategically filtering out streets that could be classified with existing information, the project team drastically cut down on the most time-consuming process in the LTS mapping effort: data collection. The data collection process was completed in three short weeks due to the advanced digitizing capabilities of DDOT's linear referencing system.

The project team's data filtration, collection, and analysis processes highlighted the value of institutional knowledge to LTS mapping efforts. DDOT provided the project team with critical data points regarding District speeds, bike lane and parking lane widths. Without DDOT input on these data points, the data collection process would have taken much longer. DDOT's understanding of local streets and communities within the District also helped to expedite the map review process. The project team's efficient approach to LTS mapping, combined with DDOT's invaluable input, proved that a process that usually takes several months to complete can be finalized in less than one month.

Opportunities for Future Research

Due to the condensed timeframe for completing the LTS mapping effort, the project team did not fully apply the traffic stress criteria for intersection approaches detailed in the LTS methodology. As an interim measure, those using the final LTS map for the District were asked to assume that all cross-streets reflect the highest stress level present. This does not take into account intersection treatments that have been incorporated into certain District intersections, and represents an opportunity for future refinement of the District's LTS map. Opportunities to apply streamlined data filtration and collection efforts to District intersections should be investigated and implemented as a part of future research efforts.

With a complete LTS map for the District, DDOT can also begin examining the theorized relationship between the LTS categories, and the stated and revealed preferences of bicycle riders on District streets. Besides testing the hypotheses of the LTS methodology, such research can help identify the most critical data gaps or changes that would further enhance the District's LTS map.

DDOT's linear reference system offers additional untapped opportunities to further streamline the LTS mapping process. The digitizing capabilities of the linear referencing system provide DDOT with the ability to dynamically update the roadway attributes of its Roads and Highways feature class. Changes to the District's roadways should be reflected in the District's LTS map. Opportunities to automatically integrate dynamic changes to the Districts Roads and Highways feature class with DDOT's LTS system should be evaluated during future research efforts.

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