CARBON SEQUESTRATION PILOT PROGRAM

Estimated Land Available for Carbon Sequestration in the National Highway System

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EXECUTIVE SUMMARY

The Federal Highway Administration (FHWA) established the Carbon Sequestration Pilot Program (CSPP) in 2008 to assess whether a roadside carbon sequestration effort through modified maintenance and management practices is appropriate and feasible for state Departments of Transportation (DOTs) when balanced against ecological and economic uncertainties. The purposes of the pilot were to:

- Develop estimates of the amount of revenue that DOTs could earn if they undertook a carbon sequestration effort using native vegetation;
- Determine the cost-effectiveness of a similar effort on a national scale; and,
- Create decision support tools that DOTs could use to determine the efficacy of programs in their states.

CSPP findings are expected to inform DOTs that may be considering the implications of future climate change legislation or that independently want to evaluate the cost effectiveness of using National Highway System (NHS) right of way (ROW) to generate revenue from the sale of carbon credits, offset their own emissions, or meet statewide greenhouse gas emissions objectives.

The project team used data from Minnesota and several other states to estimate the amount of unpaved NHS ROW available for carbon sequestration—marking the first time that a rigorous study has been conducted to quantify the amount of state DOT-managed soft estate acreage. In the first of two analytical approaches used, ROW widths at random locations in nine states were manually measured on property maps to provide a distribution of common ROW dimensions and observed vegetation types. A subsequent geographic information system (GIS) analysis of 1,000 random locations nationwide provided insight into the types of land cover in close proximity to the NHS.

Results indicate that there are approximately 5.05 million acres in the NHS nationwide, with a likely range of 1.4 to 8.7 million acres. Roughly 68 percent, or 3.4 million acres, is unpaved. Evidence shows that the land cover has undergone little change since 1992.

The project team estimates the NHS ROW has approximately 91 million metric tons (MMT) of carbon currently sequestered in vegetation and is currently sequestering approximately 3.6 MMT of carbon per year, or 1.06 metric tons of carbon per acre per year. This equals the annual carbon dioxide emissions of approximately 2.6 million passenger cars. At its carbon equilibrium, the entire NHS ROW is estimated to be able to sequester between 425 and 680 MMT of carbon. Using a hypothetical

NHS ROW Acreage	U.S. Estimate (in 000s of acres)
Total	1,400—8,700, likely ~ 5,000
Unpaved	400—6,400, likely ~ 3,400
Grassland	200—2,800, likely ~ 2,200
Woody vegetation	30—460, likely ~ 360
Grassland/woody vegetation mix	36—600, likely ~ 470
Shrub	30—500, likely ~ 390

carbon price of $20 per metric ton, this equates to a total potential value of $8.5 to $14 billion nationwide.

The availability of ROW property data was highly variable and, thus, was the major limiter in making these estimates. As discovered through this research, very few DOTs have had time, funding, or impetus to scan and geospatially reference their ROW property maps. The research here could have been vastly expedited had there been more DOTs with property maps in the needed electronic format and had their ROW data been easily accessible in a national GIS database.

In addition to this report, FHWA has developed a Highway Carbon Sequestration Estimator to help DOTs assess the return on investment for various carbon sequestration scenarios. The decision-support tool, which allows transportation officials to make estimates based on more state-specific considerations than possible here, is available upon request from carson.poe@dot.gov.

Even under the best scenarios, revenue generated from biological carbon sequestration will vary greatly from state to state based on carbon prices, management techniques, and ecological variability. However, considering the use of vegetation for living snow fences, landslide minimization, and other such human infrastructure protection may, in some cases, eventually be found to be more cost-effective than traditional engineering solutions, especially when all costs are included.

INTRODUCTION

The potential for land managers to generate revenue from biological carbon sequestration through sustainable forestry and replacing traditional ground cover with native grasses was the genesis of the Federal Highway Administration's (FHWA) Carbon Sequestration Pilot Program (CSPP). Federal statutes allow state Departments of Transportation (DOTs) to generate revenue from their land holdings. Since DOTs must retain unused buffers in their right-of-way (ROW) for safety, operations, and maintenance purposes, FHWA recognized that an opportunity might exist to shape the future of a burgeoning ecosystem service market.[1]

The National Highway System (NHS) is approximately 163,000 miles of roadway consisting of the Interstate Highway System and other roads important to the nation's economy, defense, and mobility.[2] The NHS includes only 4 percent of the nation's roads but carries more than 40 percent of all highway traffic, 75 percent of heavy truck traffic, and 90 percent of tourist traffic. In 2007, approximately 69 percent of the NHS was classified as being located in rural areas. FHWA developed the CSPP to assess whether a roadside carbon sequestration effort on the NHS through modified maintenance and management practices is appropriate and feasible for DOTs when balanced against the economic and ecological uncertainties.[3]

The goals of the pilot were to:

(1) Develop estimates of the amount of revenue that DOTs could earn if they undertook such a effort using native vegetation;
(2) Determine the cost-effectiveness of a similar effort on a national scale; and,
(3) Create decision support tools that DOTs could use to determine the efficacy of programs in their states.

This paper addresses the first two purposes,[4] refining a coarse estimate of the unpaved NHS ROW available for carbon sequestration that FHWA had made when establishing the merits of a pilot program. Results from the analysis include more accurate estimates of several variables for each state and for the nation as a whole, including:

- Total acres of ROW owned in fee simple
- Total acres of unpaved ROW
- Total acres of paved ROW
- Total acres of ROW in woody vegetation
- Total acres of ROW in grassland
- Total acres of ROW that could be converted to native woody vegetation

An approximation of the carbon currently sequestered in NHS ROW is also

[1] Ecosystem services are defined as inherent functions of natural ecosystem's that benefit human populations at little or no additional cost. These functions include flood storage, water quality treatment, carbon sequestration, provision of wildlife habitat, genetic diversity, and landscape diversity. Human alteration of the natural environment often eliminates or disrupts natural ecosystem functions, and requires human intervention and investment (economic cost) to replace lost functions. Some functions, such as genetic diversity and landscape pattern diversity, are difficult, if not impossible, to replace.

[2] The NHS includes the Eisenhower Interstate System; other principal arterials; the Strategic Highway Network; major strategic highway network connectors; and intermodal connectors that provide highway access between major intermodal facilities and the other subsystems.

[3] After assessing all 50 states, Washington D.C., and Puerto Rico against a number of criteria, New Mexico DOT (NMDOT) and Minnesota DOT (Mn/DOT) were selected to participate in the pilot program. Details, methods, results, and lessons learned from the NMDOT pilot are documented in FHWA's February 2009 *CSPP Implementation and Next Steps Progress Report* and not reported here.

[4] Hatton (1982) studied a section of highway in Maine to estimate the state's total highway ROW acreage that could potentially be used for forestry purposes. Forman (2002) offers an approach for making a more rigorous estimate of total road surface and roadside areas. Other literature providing unpaved highway ROW acreage estimates was unavailable.

presented. It should be noted that estimates here for the amount of land that could be converted to management for carbon sequestration constitute an upper bound. Net availability will undoubtedly be less, due to considerations for safety, operations, and maintenance.

The findings can inform leadership at DOTs that are considering the implications of future climate change legislation and the transportation reauthorization bill or that might independently want to evaluate the cost effectiveness of using highway ROW for carbon sequestration and carbon offset trading.

METHODS

The geographic focus of this study is the 48 contiguous United States. Two analytical approaches were developed to generate estimates of ROW acreage at a state scale and for the nation as a whole. The first method—the transect analysis—requires that states have fairly detailed datasets in the appropriate electronic format and involves significant manual manipulation by an analyst. The second method—the polygon area analysis—uses widely available data, and, while GIS modeling competence is needed, overall requires less time to generate results.

Transect Analysis

Using ESRI's ArcMap GIS application, Minnesota's NHS roadway network was overlaid with a ¼-mile by ¼-mile grid across the entire state.

At every instance where a road crossed the grid (over 55,000 occurrences), a point was made and assigned a unique identification number. Random numbers were generated and then sorted in ascending order. The first 40 random points in the sorted list were used as the sample for analysis.

The sample was overlaid in the GIS on computer-aided design (CAD) drawings and scanned, geospatially-referenced ROW maps available in Minnesota DOT's (Mn/DOT) Right of Way Mapping and Monitoring application.[5] A transect line perpendicular to the highway and between property boundaries was then drawn at each random site (Figure 1). It was assumed that all land within the property boundaries was owned in fee simple, and no land was held in easement.

Figure 1. Example random site with transect and property boundary lines drawn

[5] Mn/DOT's Right of Way Mapping and Monitoring application: www.dot.state.mn.us/maps/gisweb/row/

Based on information in the underlying legal ROW property maps, the ROW widths were manually measured using the GIS application's embedded tool. Points were discarded in cases where the random site was positioned in the middle of a four-way intersection or where no ROW property map or CAD drawing was available to delineate property boundaries. In the analysis for Minnesota, this occurred twice.

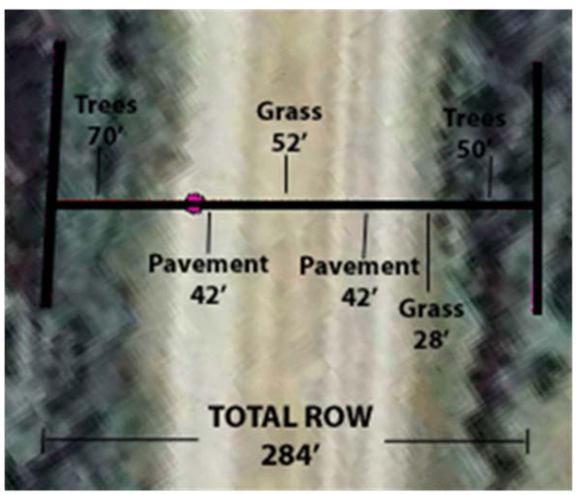
The project team also used National Agriculture Imagery Program (NAIP) aerial imagery[6, 7] to discern visually unpaved and paved areas and to estimate transect widths for grass, shrubs, trees, grass/trees within the ROW at the random sites.

The grass/trees category describes land cover where the project team observed both grass and woody vegetation in roughly equal proportions. Under a passive restoration land management approach either vegetation type might be expected to be prevalent. Here again, widths for paved and vegetated portions of the ROW were measured manually for all of the random points using the GIS application's embedded ruler tool (Figure 2).

This exercise resulted in a distribution of ROW widths for each of the categories mentioned above. The average value of each of these categories was then multiplied by the total number of miles of NHS in the state, and appropriate conversions were made to arrive at acreage estimates.

Next, other state DOTs were contacted in random order to determine whether electronic and geospatially-referenced ROW property data similar to Mn/DOT's were

Figure 2. Example random site with pavement and vegetation measurements shown



[6] The NAIP acquires aerial imagery during the agricultural growing seasons in the continental United States. Imagery is available for all lower 48 states. Beginning in 2003, NAIP was acquired on a 5-year cycle. 2008 was a transition year, and a three-year cycle began in 2009: www.fsa.usda.gov/FSA/apfoapp?area=home&subject=prog&topic=nai.

[7] Minnesota's Department of Natural Resources offered more detailed Gap Analysis Program land cover imagery, which allows for identification down to the species level. These data are paid for by square mile and were not consulted due to the fact that this analysis required only distinguishing between forested and non-forested land covers.

available. The intent was to generate ROW acreage estimates for an additional 5–10 states, then extrapolate the results to all other states and the nation as a whole.

With the data from additional states in hand, the project team modified the methodology used for Minnesota by overlaying a 1-mile by 1-mile grid on the entire NHS network in the 48 contiguous United States. At every instance where a road crossed the grid, a point was made and assigned a unique identification number. Again, random numbers were generated, and the first 1,000 corresponding points were selected for inclusion in the sample. Points in states for which electronic and geospatially-referenced ROW property map data were available were used as locations where additional boundary to boundary measurements were made.

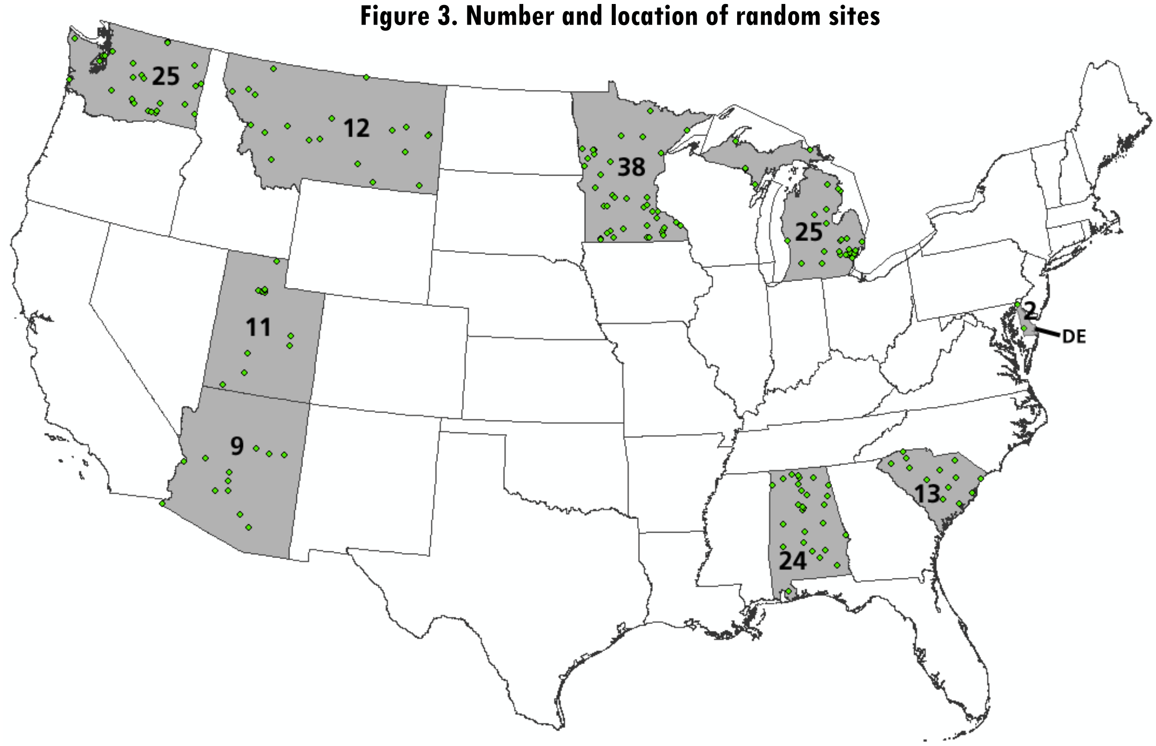
Using the available ROW and NAIP data, pavement and vegetation widths were manually made for all of the new sites. In total, 121 sites across 8 states were analyzed, in addition to those in Minnesota (Figure 3).

The resulting distribution of ROW widths was multiplied by the number of NHS miles in the U.S. to provide extrapolations of NHS ROW acreage. Specifically, the observed pooled average widths for all states' transect sites were multiplied by each individual state's NHS mileage to provide ROW estimates. In other words, no individual state's acreage estimate was derived solely from that state's own measurements:

> *ROW Acreage Estimate = (Observed Pooled Average Width * NHS mileage in ft by state)/43650 ft²*

The standard deviation for the widths at all transect sites was also added to and subtracted from each state's average width value to provide ranges of expected ROW widths. The upper and lower width values for each state were then multiplied by the respective state's NHS mileage to provide estimated ROW ranges.

Figure 3. Number and location of random sites



Polygon Area Analysis

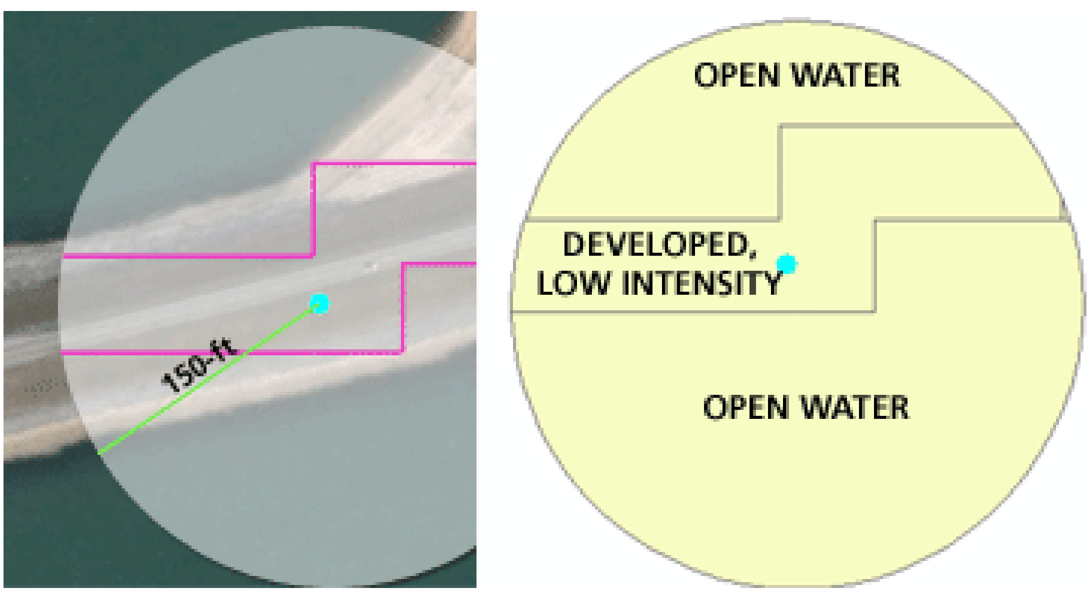
Using ESRI's ArcMap GIS application, 300-foot diameter circle polygons were centered on each of the same random points included in the transect analysis (40 for Minnesota and 1,000 for the 48 contiguous states). Land cover data from the Multi-Resolution Land Characteristics Consortium's (MRLC) 2001 National Land Cover Database (NLCD) were extracted from each polygon providing percent cover for several land cover types in each polygon (Figure 4).[8] The land cover distributions were compared with the land cover estimates from the transect analysis to determine the degree to which the polygon area analysis method is a suitable substitute to manual transect measurement in corroborating land cover types.

Land cover data from the MRLC's Retrofit Land Cover Change Data were also extracted from each polygon in order to discern any changes in land cover that might have occurred at the 1,000 random points between 1992 and 2001. Results from the polygon area analysis consist of distributions for (1) each land cover type found in 2001 and (2) cover changes that occurred from 1992 to 2001.

RESULTS

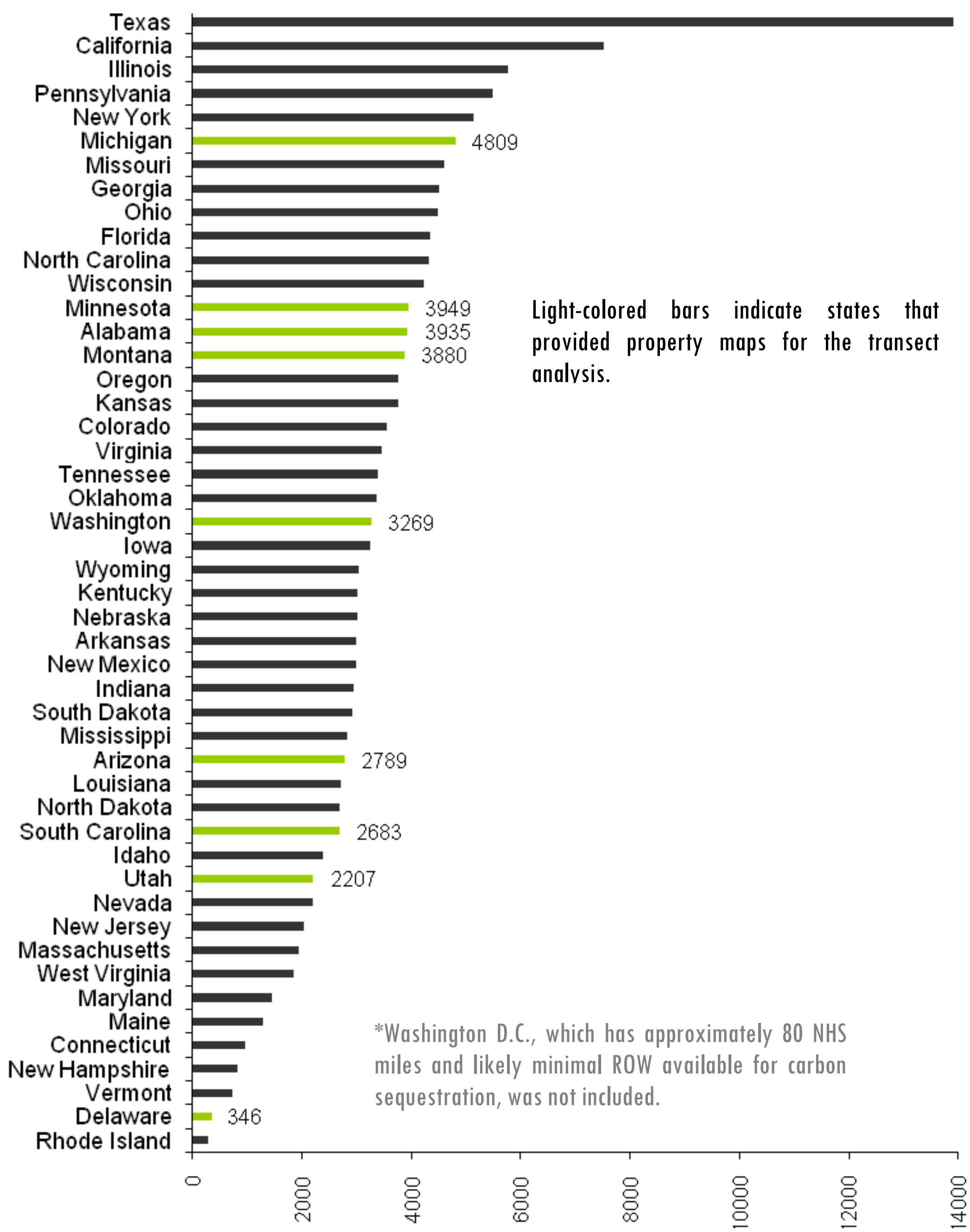
There are approximately 163,000 miles of roadway in the NHS of the contiguous U.S., with Texas having the most mileage and Rhode Island having the least (Figure 5).

Figure 4. Example random site with circle polygon drawn and land cover extracted



[8] For NLCD land cover class definitions, see www.mrlc.gov/nlcd_definitions.php.

Figure 5. NHS mileage, by state*



Right-of-Way in the National Highway System

Transect widths were measured at 159 random sites across 9 states. The sample showed a total ROW range from 60 ft to 1,295 ft with an average of 257 ft. Unpaved ROW ranged from 0 ft to 1,047 ft with an average of 175 ft. A majority of the ROW was observed to be grass (Table 1 and Figure 6).

It is estimated that there are approximately five million acres of NHS ROW nationwide. Adding and subtracting one standard deviation results in a range of 1.4 to 8.7 million acres. Approximately 68 percent of those acres (3.4 million) are estimated to be unpaved, with grasses expected to comprise the largest unpaved ROW portion (Table 2).

Table 1. Descriptive statistics for random site transect measurements

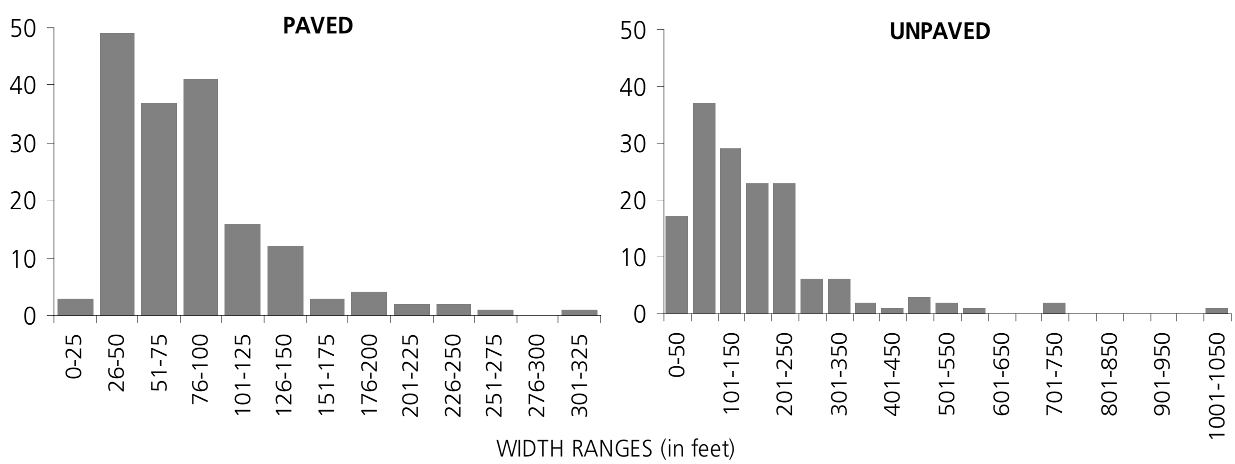
AVERAGE TOTAL ROW	257 ft
Average paved	32 %
Average unpaved	68%
Average grass	64%
Average trees	11%
Average grass/trees	14%
Average shrubs	11%
MEDIAN TOTAL ROW	**202 ft**
Median Paved	70 ft
Median Unpaved	144 ft

Table 2. Estimated Total NHS ROW acres*

	Acres (in thousands)
TOTAL	1,400–8,700, likely ~ 5,000
Unpaved	400–6,400, likely ~ 3,400
Grass	200–2,800, likely ~ 2,200
Woody Vegetation	30–460 likely ~ 360
Grass/Woody Vegetation	38–600, likely ~ 470
Shrub	30–500, likely ~ 390

*Total ROW and unpaved ROW acreage estimates for individual states are in Appendix A.

Figure 6. Frequency of observed widths at random sites**



**Note: The x-axes' scales differ for the two histograms.

Land Cover in the National Highway System

Land cover data were collected at 1,000 random sites across the contiguous United States. The sample showed that the main land cover types in the vicinity of the NHS are "developed, open space" and "developed, low intensity." The most common land cover types not characterized as "developed" are "cultivated crops" followed by "deciduous forest" (Table 3). When disaggregated, the land cover results show "developed, open space" as the most prevalent land cover type near the NHS in 29 of 48 states.

Less than four percent of the land cover in the polygons changed categories from 1992 to 2001 (Table 4). A majority of the change was from a vegetated cover type to the "Urban" cover type, which consists of primarily developed, open spaces and some low, medium, and high intensity lands.[9] Forested portions of the polygons experienced a net loss of approximately 1.6 percent over the same time period. The grassland/shrub land cover segment of the polygons experienced a net loss of roughly 0.5 percent between 1992 and 2001.

Table 3. Polygon area analysis land cover percentages, nationwide

Land Cover Classification	Percent
Developed, Open Space	32.39%
Developed, Low Intensity	25.92%
Developed, Medium Intensity	14.22%
Cultivated Crops	4.95%
Developed, High Intensity	4.43%
Decidous Forest	3.81%
Shrub/Scrub	3.58%
Hay/Pasture	3.33%
Herbaceuous	2.55%
Evergreen Forest	2.34%
Woody Wetlands	1.06%
Emergent Herbaceuous Wetlands	0.47%
Mixed Forest	0.43%
Barren Land	0.34%
Open Water	0.18%

Table 4. Land cover change at polygon area analysis random sites, 1992—2001

Type of Land Cover Change	Percent of Circle Buffers Changed
Forest to Urban	1.545%
Agriculture to Urban	1.183%
Grassland/Shrub to Urban	0.479%
Wetlands to Urban	0.150%
Forest to Agriculture	0.120%
Grassland/Shrub to Agriculture	0.090%
Agriculture to Forest	0.067%
Agriculture to Grassland/Shrub	0.056%
Forest to Grassland/Shrub	0.050%
Agriculture to Wetlands	0.037%
Grassland/Shrub to Forest	0.015%
Agriculture to Barren	0.013%
Agriculture to Open Water	0.013%
Wetlands to Agriculture	0.007%
Grassland/Shrub to Barren	0.005%
Forest to Barren	0.002%
Grassland/Shrub to Wetlands	0.001%

[9] NLCD 1992/2001 Retrofit Change Data definitions: www.mrlc.gov/changeproduct_definitions.php

DISCUSSION

This discussion consists of three sections: ROW Estimates; Carbon Sequestration in the NHS; and, Conclusions. Recommendations for repeating or customizing the methods developed here are presented, as well as estimates of carbon sequestration rates and potential on NHS ROW.

ROW Estimates

The project team assumed that ROW acreage estimates for all 50 States could be generated from a multi-state distribution of ROW widths based on the known miles of NHS roads in each State; it was understood that acreage estimates for states where data were not collected would potentially be subject to more error if the sample of states was not sufficiently representative.

The transect analysis, which was used to develop the ROW distribution, was particularly valuable because it allowed the project team to use maps to quickly discern property boundaries, providing a means to take precise and accurate ROW measurements. It offered a degree of certainty likely not possible by any means other than taking surveys in the field. However, the reliance on electronic property maps was also the transect analysis principal drawback. The ability to perform the transect analysis was (and remains) contingent upon the availability of easily accessible, electronic and geospatially-referenced ROW property maps. It became apparent during the transect analysis that most state DOTs do not have maps in this format readily available, indicating an area where future federal funding might be directed. For the state DOTs that *did* have and were able to provide electronic property maps, there was an implicit assumption that all lands delineated as NHS ROW were owned in fee simple, rather than in easement. This, too, is a possible concern due to questions regarding how ownership rights to lands a state DOT manages might affect the process for selling carbon credits generated on those lands (FHWA 2009).

These realities, along with the fact that transects require time-intensive manual interpretation, led the project team to develop the polygon area analysis methodology to complement and potentially be a proxy for the transect analysis. The project team hypothesized that the percent land cover in the polygons would not be substantially different from that measured manually in the transect analysis. Thus, the project team used only the transect method for developing an estimate of acres of ROW across the US, and both the transect and polygon area methods for determining land cover types.

The polygon area analysis relied on the 2001 NLCD and polygons centered on the roadway used to extract land cover data. The 2001 NLCD has 29 different land cover classifications, 15 of which occurred in some quantity in the polygon area analysis. Four of those land covers describe varying intensities of development: high, medium, low, and open space. Observation of a random subset of 200 circle polygons indicated that paved NHS areas were most commonly classified as “developed, low intensity,” while “developed, medium intensity” typically referred to places where bridges or interchanges were located. “Developed, high intensity” NHS areas were usually in very urbanized areas near parking lots, dense building development, and other impervious surfaces. “Developed, open space”—the predominant land cover found in the polygon area analysis—generally captured unpaved portions of NHS ROW. From a carbon sequestration standpoint, open space and low intensity developed areas are generally expected to have the most carbon sequestration potential. This should not, however, suggest that medium and high intensity development areas are not suitable for carbon sequestration. In fact, some of the widest ROWs the project team observed were at interchanges in locations predominately developed with high-intensity; the diameter of the circle polygon may have extracted only a portion of the land cover types identified at the same location in the transect analysis. In other words, areas of medium- and high-intensity development may also be able to accommodate vegetation as open- and low-intensity development areas would be expected to do so. A difference would be that alternative vegetation management practices in the former may require the balancing of more factors.

Paved NHS areas—those classified as "developed, low intensity" or "developed, medium intensity"—were predicted to account for roughly 35 percent of each circle polygon.[10] This proportion corresponded to what the transect measurements showed. There, 32 percent of the observed ROW was paved. Furthermore, it was assumed the polygons would have a uniform bias toward vegetation that is closest to the road. Assuming most woody vegetation is located further from the road, this might result in a disproportionately high percentage of grass relative to woody vegetation. However, the polygon area analysis indicated that grasses, forests, and shrubs respectively comprised 43.5 percent, 6.6 percent, and 3.5 percent of the unpaved area in the vicinity of the random points—nearly matching results from the transect analysis (43.9 percent grasses, 7.2 percent trees, and 7.7 percent shrub) (Table 5).

Based on these results, the project team believes that that the polygon area analysis serves as a relatively robust surrogate to the transect method for determining land cover types. Similarly, it is expected that the land cover types the polygon area analysis identified can be used to refine the more coarse land cover categories of the transect analysis, thereby potentially providing more precision in state-level estimates for carbon sequestration potential. However, at this time the transect method remains our only available method for developing rigorous estimates of ROW acreage.

The following are recommended steps for state DOTs interested in repeating or customizing either of the analyses described:[11]

Table 5. Comparison of predicted land cover types from two analytical approaches

	Polygon Area Analysis	Transect Analysis
Paved areas	34.8	32
Grasses	43.5	43.9
Woody vegetation	6.6	7.2
Shrubs	3.5	7.7

[10] Equation: 70,650 sq ft polygon area / 24,600 sq ft predicted NHS pavement area [300' road length per polygon x 82' average pavement width from transect analysis] = 34.8%

[11] The spreadsheets used to record the manual transect measurements, as well as more detailed instructions for repeating the polygon area analysis, are available upon request. Contact Carson Poe at carson.poe@dot.gov for more information.

Transect Analysis

- Work with the office responsible for managing the DOT's property maps to locate as many of maps associated with randomly selected locations as possible. Assuming field surveys are not an option, the transect analysis is not possible without property maps or some other legal delineation of property boundaries.
- Use the highest resolution aerial imagery available to estimate paved and unpaved ROW, and then work with biologists to determine species types for the unpaved areas
- Save a GIS new file for each transect measurement point so that any point can be quickly accessed again at a later time.

Polygon Area Analysis

- Clip raster images from the NLCD using a larger circle polygon than the final buffer diameter desired. For example, if 300-ft diameter circle polygons will be the unit of analysis, then the raster image should be clipped with a larger (e.g., 500-ft diameter) circle polygon. This will ensure that data are not lost due to pixel size once the raster image is converted to a polygon for analysis.
- Convert the clipped raster image layer into a polygon layer before clipping with the smaller polygon buffer.
- Use the GIS program to aggregate the attribute of choice (e.g., land cover area)

Carbon Sequestration in the NHS

The project team assumed that ROW acreage estimates could be used to assess:

- Current carbon sequestration rates on the NHS;
- The amount of carbon already sequestered on the NHS; and,
- The amount of carbon the NHS might be able to sequester in the future.

A variety of factors affect the long-term storage potential, or carbon stock equilibrium,[12] of vegetation and soil. Considerable variations in sequestration rates have been demonstrated depending on geographic region, plant species (Stavins and Richard 2005, Birdsey 1992), management practices, and natural disturbance regimes such as fire.

The Chicago Climate Exchange (CCX)[13] addresses this variation in part by crediting sequestration of grasslands between 0.4 and 1.0 metric tons of C/ac/yr, depending on location. Here, the project team used the average of these values, 0.7 metric tons of C/ac/yr, for grasses and shrubs. Representative carbon sequestration for reforestation activities in the U.S. have been estimated to be between 1.1 and 7.7 metric tons C/ac/yr over 120 years (Birdsey 1996) and up to 172.1 metric tons C/ac/yr for avoided deforestation[14] (U.S. Government 2000). CCX has more

[12] Congressional Budget Office. The Potential for Carbon Sequestration in the United States. 2007. www.cbo.gov/ftpdocs/86xx/doc8624/09-12-CarbonSequestration.pdf

13 CCX operates North America's only cap and trade system for all six greenhouse gases. GHG reductions achieved through CCX are the only reductions made in North America through a legally binding compliance regime, providing independent, third party verification.

[14] Avoided deforestation (AD) refers to the protection of existing forests by reducing deforestation and forest degradation rates. Carbon sequestration rates for AD are higher than those for reforestation because its alternative – deforestation – creates significant emissions itself; it has been estimated that tropical deforestation accounts for as much as 25 percent of global human-caused GHG emissions (Houghton 2005). Sedjo and Sohngen (2006) note "[n]ot only is carbon lost to the atmosphere from net reductions in forest cover, but newly afforested or reforested lands store far less carbon per hectare (currently) than mature stands being deforested. In addition, the geographical variation in forest cover trends has important implications for carbon emissions because of the large differences in carbon stock per hectare across regions. In general, the tropical areas experiencing net deforestation have higher carbon stocks in forest biomass per hectare than temperate regions experiencing net afforestation." Recent data have indicated that a market for AD carbon offsets is highly desirable among industry sectors: www.ecosecurities.com/Registered/ECOForestrySurvey2009.pdf

refined sequestration rates for a variety of tree species. For these purposes, the project team averaged CCX sequestration rates for 21 to 25 year-old coniferous (2.21 metric tons C/ac/yr) and deciduous species (2.16 metric tons C/ac/yr)—the expected representative age of trees on the NHS, then applied them to calculate the estimates below. It should be noted that carbon sequestration rates for afforestation activities[15] in the U.S. have been shown to be higher than reforestation sequestration rates—between 2.2 and 9.5 metric tons of C/ac/yr (ROW 1996). However, afforestation often requires significant inputs of labor, water, and fertilizer that would render the project cost prohibitive. For this and other reasons, FHWA strongly encourages native, self-sustaining vegetation.

Assuming trees can sequester carbon for 120-years and grasses up to 50 years (U.S. EPA) and portions of the NHS have been around for 50 years, the project team expected the *oldest* trees on the NHS to be nearly at their sequestration mid-points and grasses to be at their maximums.

Given that areas of the NHS remain under construction today, the project team further assumed the "average" NHS vegetation to be roughly 25 years old. Using the results from the transect and polygon area analyses and the sequestration rates described above, it is estimated that currently the total annual uptake of carbon on the NHS is approximately 3.6 million metric tons (MMT), or 1.06 metric tons of C/acre/year (Table 6). This equates to the annual carbon dioxide emissions of approximately 2.6 million passenger cars.[16] The project team also estimates that NHS ROW has sequestered approximately 91 MMT of carbon over its existence.

It is worth noting that the project team assumed portions of the NHS ROW identified as "grass/trees" in the transect analysis could be managed toward being trees and thus treated them as trees in making these estimates. The project team recognizes this will not be ecologically appropriate in some cases. It also should be noted that these estimates assume that all unpaved NHS ROW could be used for

Table 6. Estimated annual carbon uptake on the NHS

	Estimated Acres	Carbon Sequestration Rates *(metric tons C/ac/yr)*	Metric Tons of C/year
Deciduous	477,820	2.16	1,032,091
Coniferous	294,096	2.26	664,657
Mixed	54,608	2.21	120,684
Grasses	2,207,596	0.70	1,545,317
Shrub	389,393	0.70	272,575
Total Unpaved	3,423,513		3,635,325

[15] The IPCC defines afforestation as the "planting of new forests on lands that, historically, have not contained forests. EPA defines afforestation more broadly as "the establishment of trees on lands that were without trees for some period of time." According to EPA, [d]iffering interpretations of this time period will dictate whether the establishment of forest cover is considered to represent afforestation or reforestation." www.epa.gov/sequestration/pdf/ghg_part3.pdf

[16] This calculation assumes average passenger car emissions are 5.0292 metric tons of CO_2-eq per car per year (U.S. EPA 2010), or 1.371463 metric tons of carbon/car/year. *3.6 MMT estimated annual sequestration potential of NHS / 1.371463 MT/C/car/year = 2.6 million passenger cars*.

carbon sequestration of appropriate vegetation type. For example, the clear zone[17] would continue to be managed for grasses but might be mowed less frequently[18] or converted from an introduced species such as annual rye grass to native perennial species that store more carbon underground (Cox *et al.* 2006).

Pasture, rangeland, and agricultural land that is reserved for conservation purposes store carbon at equilibrium levels ranging from 73 to 159 metric tons of C/acre and average 113 metric tons. Mature, never harvested forests have higher equilibrium levels per acre, varying from 286 to 1,179 metric tons of C/acre and averaging 465 metric tons (Birdsey 1992 and CBO 2007). While harvesting forests can decrease the equilibrium level of carbon (Ruben *et al.* 2005), it was assumed that trees are not harvested on highway ROW—though harvesting timber presumably could be a DOT land management activity. Keeping these figures in mind, the point of carbon saturation on the NHS ROW is expected to be between 425 and 680 MMT (Appendix C). At current sequestration rates, carbon saturation on the NHS is not expected to occur for at least 75 years, and perhaps longer for areas of woody vegetation. That said, sequestration rates are expected to decline over time, and the actual carbon saturation point may be sooner if NHS vegetation is older than assumed. Using a hypothetical carbon price of $20 per metric ton, the estimated carbon volume equates to a total potential value of $8.5 to $14 billion nationwide. It is not unreasonable to conceive of even higher carbon prices (Benítez et al. 2006 assumes $50 per metric ton), as some modeling studies, consistent with attaining certain emissions goals during this century, show carbon prices rising to as high as $80 per ton of CO_2-equivalent by 2030 and $155/ton of CO_2-equivalent by 2050 (IPCC 2007).

The project team's estimated carbon sequestration maximum is based on the assumption that grasses are not converted to a different land cover. However, U.S. Forest Service data on both total historical forested land and total grassland pasture and rangeland suggest that many states could sequester additional volumes of carbon if alternative land management activities were undertaken. For example, from 1953 to 2002, forested land in Minnesota decreased by 6 percent. Presumably, some of the previously forested land is located the NHS ROW and could be shifted to a forest management strategy, increasing the estimated volume of carbon potentially sequestered in the state. This does not include other possible gains from restoring grassy areas to native grassland communities. Although some states may be more forested now than at other times during the past century, it is assumed that land along the NHS has been cleared, and thus the potential for additional carbon sequestration elsewhere is likely similar to that described in this example.

It should also be noted that these values represent calculations from aggregated data. Specific numbers will vary widely from state to state, and states are strongly encouraged to use FHWA's Highway Carbon Sequestration Estimator (or other appropriate tool), which allows transportation officials to assess the return on investment for various carbon sequestration scenarios based on more state-specific considerations than possible

[17] The American Association of State and Highway Transportation Official's Roadside Design Guide, 3rd Edition defines a "clear zone" as the total roadside border area, starting at the edge of the traveled way, available for safe use by errant vehicles. The desired minimum width is dependent upon traffic volumes and speeds and on the roadside geometry. Simply stated, it is an unobstructed, relatively flat area beyond the edge of the traveled way that allows a driver to stop safely or regain control of a vehicle that leaves the traveled way.

[18] Less frequent mowing may not affect carbon sequestration rates of grasses but can reduce maintenance costs and carbon emissions.

here. The tool is available upon request from carson.poe@dot.gov.

Conclusions

In the current debate regarding national climate change legislation, the U.S. Congress is placing great emphasis on minimizing the cost of any cap-and-trade system on the economy and consumers. Allowing the sale of carbon offsets opens up a potential revenue stream for those who wish to adopt carbon sequestration as a land management strategy.

In the highway context, there are considerable ecological, economic, and political uncertainties related to whether highway land management practices for carbon sequestration can offer a practical source of revenue. This research only examined a few of these uncertainties, particularly those relating to the amount of NHS land that might be available for carbon sequestration and, in turn, the magnitude of revenue possible should a cap-and-trade system be established. Even under the best scenarios, revenue generated from biological carbon sequestration will vary greatly from state to state based on carbon prices, management techniques, and ecological variability. However, development of a carbon market is one step toward a more complete valuation of ecosystem services. Furthermore, considering the use of vegetation for living snow fences, landslide minimization, and other such human infrastructure protection may, in some cases, eventually be found to be more cost-effective than traditional engineering solutions, especially when all costs are included.

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APPENDIX A. Estimated NHS ROW Acres, by state

	Estimated Total NHS Acres	Estimated Total Acres Range		Estimated Unpaved NHS Acres	Estimated Unpaved Acres Range	
		LOWER	UPPER		LOWER	UPPER
Rhode Island	8,591	2,373	14,809	5,850	691	11,005
Delaw are	10,764	2,974	18,554	7,329	866	13,788
Vermont	22,545	6,228	38,862	15,352	1,814	28,879
New Hampshire	25,233	6,971	43,495	17,182	2,030	32,322
Connecticut	29,875	8,253	51,496	20,343	2,404	38,268
Maine	40,026	11,058	68,995	27,255	3,221	51,272
Maryland	45,107	12,462	77,753	30,715	3,630	57,781
West Virginia	57,549	15,899	99,199	39,187	4,631	73,717
Massachusetts	60,519	16,719	104,319	41,209	4,870	77,522
New Jersey	63,331	17,496	109,167	43,125	5,096	81,125
Nevada	68,063	18,803	117,323	46,346	5,477	87,186
Utah	68,616	18,956	118,276	46,723	5,521	87,894
Idaho	74,523	20,588	128,457	50,745	5,997	95,460
South Carolina	83,400	23,041	143,760	56,790	6,711	106,832
North Dakota	83,599	23,095	144,102	56,925	6,727	107,086
Louisiana	84,635	23,382	145,889	57,631	6,810	108,414
Arizona	86,709	23,955	149,464	59,043	6,977	111,071
Mississippi	87,685	24,224	151,146	59,708	7,056	112,321
South Dakota	90,739	25,068	156,410	61,787	7,301	116,233
Indiana	91,383	25,246	157,520	62,226	7,353	117,057
New Mexico	92,970	25,684	160,255	63,306	7,481	119,090
Arkansas	93,026	25,700	160,352	63,344	7,485	119,162
Nebraska	93,525	25,838	161,213	63,684	7,526	119,802
Kentucky	93,721	25,892	161,550	63,818	7,541	120,052
Wyoming	94,284	26,047	162,520	64,201	7,587	120,773
Iow a	101,036	27,913	174,159	68,799	8,130	129,422
Washington	101,634	28,078	175,190	69,206	8,178	130,189
Oklahoma	104,425	28,849	180,002	71,107	8,403	133,764
Tennessee	105,059	29,024	181,094	71,538	8,454	134,576
Virginia	107,766	29,772	185,760	73,382	8,671	138,043
Colorado	110,156	30,432	189,880	75,009	8,864	141,105
Kansas	116,997	32,322	201,673	79,667	9,414	149,869
Oregon	117,120	32,356	201,883	79,751	9,424	150,025
Montana	120,614	33,321	207,907	82,130	9,705	154,501
Alabama	122,342	33,799	210,885	83,307	9,844	156,715
Minnesota	122,772	33,918	211,627	83,600	9,879	157,266
Wisconsin	131,644	36,369	226,919	89,641	10,593	168,630
North Carolina	134,155	37,062	231,247	91,350	10,795	171,846
Florida	134,897	37,267	232,526	91,856	10,855	172,797
Ohio	139,507	38,541	240,473	94,995	11,225	178,702
Georgia	140,383	38,783	241,983	95,592	11,296	179,825
Missouri	143,209	39,563	246,854	97,516	11,523	183,444
Michigan	149,500	41,302	257,698	101,800	12,030	191,503
New York	159,804	44,148	275,459	108,816	12,859	204,701
Pennsylvania	170,479	47,097	293,861	116,085	13,718	218,376
Illinois	179,166	49,497	308,835	122,000	14,417	229,504
California	233,899	64,618	403,180	159,270	18,821	299,614
Texas	432,339	119,440	745,238	294,394	34,788	553,807

APPENDIX B. Polygon Area Analysis Land Cover Percentages, by state

	Devel. Open Space	Devel. Low Intensity	Devel. Med. Intensity	Devel. High Intensity	Deciduous Forest	Mixed Forest	Evergreen Forest	Cultivated Crops	Emergent Herbaceous Wetlands	Hay/ Pasture	Herbaceuous	Open Water	Shrub/ Scrub	Woody Wetlands	Barren Land
ND	62.6%	28.7%	0.3%		1.5%			2.3%			1.3%	3.3%			
NE	58.8%	20.5%	5.6%	1.8%				10.8%			2.5%				
NV	51.3%	13.1%	7.7%				1.5%				2.3%		22.8%		1.3%
CO	51.0%	17.5%	17.0%	5.6%		0.7%		0.8%	0.9%	0.5%	4.9%		1.0%		
SC	50.2%	18.3%	9.5%	6.8%		0.7%	7.0%			6.3%			1.1%		
ME	49.2%	28.0%	14.4%			8.4%									
CT	48.2%	41.4%	10.4%												
OR	47.3%	24.0%	9.1%	5.1%		0.7%	4.8%	1.8%	3.6%			1.1%	2.2%	0.3%	
SD	45.8%	26.1%	2.5%	0.2%			1.5%	9.6%	0.6%	6.6%	7.2%				
AR	45.1%	26.5%	10.5%	2.2%	4.1%	1.6%	3.2%	5.9%		0.7%					
NM	44.9%	21.0%	17.0%	2.6%							2.2%		12.3%		
WY	42.1%	29.5%	1.7%				1.1%	3.6%			3.8%		18.1%		
OK	41.6%	17.5%	21.1%	3.0%				1.4%	0.2%	8.0%	7.2%				
GA	41.5%	30.6%	9.9%	2.5%	4.5%	1.7%	6.7%	0.4%		1.5%	0.7%				
MT	40.7%	18.9%	7.0%					13.4%		1.1%	9.2%		7.4%	1.8%	
MS	40.4%	29.7%	6.8%	1.1%	4.1%	1.7%	4.1%			4.6%		0.6%	2.3%	1.5%	3.1%
KS	39.8%	30.3%	7.2%	3.5%	1.7%	0.6%		3.0%		4.5%	9.4%				
TN	39.7%	33.0%	10.5%	0.6%	8.8%	1.8%		1.8%		2.7%				1.1%	
IA	38.9%	18.2%	21.6%	3.1%	2.6%			8.3%		4.5%	2.8%				
NH	36.8%	28.4%	24.1%	0.7%	6.2%		2.3%			1.5%					
AL	36.4%	33.0%	6.9%	0.9%	6.5%	0.5%	0.2%	1.7%		6.9%	1.1%	0.6%	2.0%	2.9%	0.5%
PA	36.3%	30.5%	10.0%	0.5%	10.7%	0.4%	0.8%	2.9%	0.5%	5.8%				1.7%	
NY	34.4%	28.1%	11.5%	7.1%	5.3%		1.8%	3.3%		6.2%			0.2%	2.0%	
NC	34.3%	22.7%	5.0%	0.7%	7.4%	2.0%	5.0%	3.4%	0.9%	7.1%	2.7%			8.8%	
TX	33.9%	23.4%	12.5%	6.7%	0.6%		1.5%	3.4%		3.4%	5.9%		8.5%		0.1%
MA	33.2%	22.1%	20.8%	7.0%	9.2%		1.8%			0.6%				4.2%	1.2%
MN	32.0%	19.6%	15.7%	10.3%	6.0%		2.3%	6.2%	0.3%	4.9%	0.9%			1.8%	
ID	31.7%	27.4%	4.9%	0.5%	0.5%		20.6%	1.4%		1.1%	4.1%		6.6%	1.2%	
RI	28.1%	28.8%	22.2%		20.9%										
MO	28.0%	31.2%	16.7%	3.7%	5.9%			3.0%		10.9%	0.5%				
IN	27.7%	33.9%	19.7%	1.6%	4.7%			10.6%	0.9%		0.7%				
AZ	27.2%	24.8%	9.5%	0.5%				5.7%			3.1%		29.2%		
FL	26.1%	29.1%	15.8%	9.6%		0.9%	2.4%	1.6%	4.3%	0.6%	4.2%		1.0%	4.3%	
WA	25.5%	31.7%	21.3%	2.3%		0.6%	2.7%	3.7%		2.2%	0.7%		5.0%	0.5%	3.8%
OH	24.7%	31.5%	23.4%	3.6%	0.7%			15.6%		0.5%					
WV	22.1%	11.2%	24.7%	2.3%	34.0%					5.6%					
WI	21.9%	29.2%	16.1%	3.9%	3.5%		2.3%	16.3%	1.0%	4.6%			0.2%	1.0%	
CA	21.8%	18.1%	18.7%	4.7%			6.9%	7.7%		1.1%	7.9%		11.5%		1.6%
VA	20.9%	33.2%	19.8%	5.5%	10.1%		0.5%	2.5%		7.2%	0.3%				
KY	19.2%	19.2%	16.3%	4.5%	22.0%		3.0%	8.5%		1.2%	1.9%	3.9%		0.3%	
IL	16.6%	29.5%	21.5%	12.2%	1.8%			13.9%	0.3%	4.1%				0.1%	
VT	15.6%	23.9%	4.5%		13.1%	7.6%	4.2%	17.0%		4.5%	8.1%		1.5%		
UT	14.8%	11.8%	22.9%	19.2%			0.8%						29.9%	0.7%	
NJ	14.6%	14.6%	33.1%	11.5%	10.6%	0.8%		5.2%	5.8%	0.5%				1.8%	1.5%
MD	13.5%	28.0%	32.4%	4.6%	4.6%			8.0%		8.9%					
MI	13.2%	30.1%	30.5%	7.6%	4.7%	1.0%	0.7%	5.3%	0.1%	2.6%	0.5%			3.8%	
LA	11.8%	51.3%	3.9%	6.3%			5.8%	8.1%	1.8%	4.9%			3.3%	2.9%	
DE	4.9%	26.2%	16.8%	4.9%				47.2%							

APPENDIX C. Carbon Sequestered on NHS, by state*

	Unpaved Acres	Carbon Sequestered (metric tons/acre/yr)	Carbon Equilibrium (Metric Tons of Carbon) Low Estimate	High Estimate
RI	5848	9392	500,086	1,157,842
DE	7327	11767	626,545	1,450,630
VT	15347	24647	1,312,315	3,038,384
NH	17176	27585	1,468,768	3,400,616
CT	20336	32660	1,738,962	4,026,193
ME	27246	43758	2,329,865	5,394,303
MD	30705	49312	2,625,615	6,079,048
WV	39174	62913	3,349,799	7,755,741
MA	41196	66161	3,522,690	8,156,033
NJ	43110	69235	3,686,406	8,535,083
NV	46331	74408	3,961,825	9,172,756
UT	46708	75013	3,994,020	9,247,297
ID	50728	81470	4,337,823	10,043,298
SC	56771	91175	4,854,573	11,239,723
ND	56906	91392	4,866,117	11,266,450
LA	57612	92525	4,926,458	11,406,157
AZ	59024	94793	5,047,189	11,685,683
MS	59688	95859	5,103,986	11,817,184
SD	61767	99198	5,281,750	12,228,759
IN	62205	99902	5,319,225	12,315,524
NM	63285	101637	5,411,592	12,529,381
AR	63324	101698	5,414,858	12,536,942
NE	63664	102244	5,443,924	12,604,238
KY	63797	102457	5,455,302	12,630,582
WY	64180	103073	5,488,073	12,706,457
IO	68776	110455	5,881,104	13,616,435
WA	69183	111108	5,915,921	13,697,046
OK	71083	114160	6,078,402	14,073,235
TN	71515	114853	6,115,275	14,158,608
VA	73357	117812	6,272,854	14,523,449
CO	74984	120425	6,411,963	14,845,526
KS	79641	127904	6,810,197	15,767,551
OR	79725	128038	6,817,315	15,784,031
MT	82103	131858	7,020,720	16,254,973
AL	83280	133747	7,121,301	16,487,845
MN	83573	134217	7,146,353	16,545,847
WI	89611	143916	7,662,743	17,741,438
NC	91321	146661	7,808,893	18,079,817
FL	91826	147472	7,852,090	18,179,831
OH	94964	152512	8,120,418	18,801,087
GA	95560	153470	8,171,432	18,919,199
MO	97484	156559	8,335,905	19,300,000
MI	101766	163437	8,702,108	20,147,865
NY	108780	174701	9,301,867	21,536,478
PA	116047	186371	9,923,264	22,975,190
IL	121960	195869	10,428,937	24,145,967
CA	159218	255703	13,614,818	31,522,191
TX	294298	472642	25,165,626	58,265,610

*These values represent calculations from aggregated data. Observed pooled average pavement and vegetation widths for all states' transect sites were multiplied by each individual state's NHS mileage to provide ROW estimates. The project team then used average sequestration rates for grasses and coniferous and deciduous tree species to calculate the carbon sequestration estimates below. Specific numbers will vary widely from state to state, and states are strongly encouraged to use FHWA's Highway Carbon Sequestration Estimator (or other appropriate tool) to assess the return on investment for various carbon sequestration scenarios based on more state-specific considerations than possible here. The tool is available for download at www.climate.dot.gov.