

# Improving Striping Operations through System Optimization – Phase 2



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# **IMPROVING STRIPING OPERATIONS THROUGH SYSTEM OPTIMIZATION – PHASE 2**

**Final Report  
July 2016**

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# 1. INTRODUCTION

## 1.1 MoDOT Operations

The Missouri Department of Transportation (MoDOT) is responsible for maintaining nearly 34,000 miles of highways and over 10,000 bridges; as a result, Missouri maintains “the nation’s seventh largest state highway system” with more miles than the combined systems of Iowa, Nebraska, and Kansas (MoDOT 2015). The annual cost to keep Missouri’s transportation system in its current condition (including road maintenance, striping, snow removal, mowing, etc.) is estimated to be \$485 million (MoDOT 2015). One of the annual maintenance activities conducted by MoDOT is road striping, which involves the application of markings (primarily paint) to define lanes and other pieces of traffic-related information. According to Montebello and Schroeder (2000), most variations of paint used during striping operations have an estimated life between 9 and 36 months with variation largely dependent on traffic volume. Each year, MoDOT stripes more than 60,000 lane-miles of road on a scheduled basis. Additionally, citizens may place a request for a certain road to receive striping earlier than originally planned; such requests are generally given a high priority, with MoDOT attempting to complete the striping within a few days’ time.

Striping operations provide important information while allowing minimal diversion of attention from the roadway. Striping operations include the following:

- Obliteration of pavement markings (removing existing or temporary pavement marking, which is conflicting or might mislead traffic)
- Application of permanent pavement markings after construction or maintenance of roads
- Removal of permanent marking
- Line-striping for all major and minor roads that require it
- Symbol markings, turn markings, etc.
- Management of striped lines (keeping track of lines conditions, identifying which road segments will be striped each year, etc.)

For MoDOT, coordinating a plan to accommodate the striping of both major and minor highways on an annual basis represents a significant logistical challenge. Increasing efficiency in striping operations represents a substantial opportunity to decrease annual expenses by MoDOT. Inefficient scheduling can create an excess of “deadhead miles” in which striping crews must travel while not actively striping roads. Minimizing deadhead miles is an important aspect of reducing the waste of extraneous travel, time, and vehicle wear.

In general, the task of crafting a schedule for striping operations mirrors elements of the Rural Postman Problem, since the objective involves finding the route of minimum cost that traverses a subset of the arcs in a network (Eiselt et al. 1995 and Monroy-Licht et al. 2013). For MoDOT, cost is a function of the distance traveled; therefore, the route of minimum cost is equal to the route of shortest total length, which involves minimizing deadhead miles.

This report addresses the scheduling of striping operations for a subset of MoDOT roads; namely, those located in the Central District of Missouri. This report extends the work detailed in the 2015 report *Improving Striping Operations through System Optimization* (McGarvey et al. 2015). Three major changes have been made to the optimization model and decision support tool developed in the 2015 report:

- The model has been modified to limit the locations where striping crews can turn around to be at either intersections with other MoDOT roads or at dead ends to MoDOT roads. This prevents the model from identifying a solution that requires a striping crew to turn around in the middle of a road (which was possible with the initial optimization model).
- The model has been modified to add an additional what-if capability, allowing MoDOT to identify the impact of changing policies and removing the white edge line requirement for two-lane minor roads.
- The model outputs have been modified, replacing the text-only outputs that were generated by the previous model with output visualization, including maps and turn-by-turn directions for striping crews.

This report focuses on changes made to the optimization model and decision support tool since the publication of the 2015 report. It does not repeat all of the material that appears in the earlier report. Thus, readers desiring an overview of striping operations, along with a literature review of operations research models applied to similar problems, are referred to McGarvey et al. (2015) for these details.

## 2. MODEL MODIFICATIONS

To the best of our knowledge, the model presented in McGarvey et al. (2015) is the only optimization model that has been developed for scheduling road striping operations. A significant amount of work is necessary to prepare the necessary input files for the model. This 2015 report contains a detailed discussion of how ArcGIS data can be prepared and integrated with MoDOT spreadsheet files, which identify the set of roads in each county that require striping in any year, to generate two spreadsheets that are needed to utilize the decision support tool.

Due to concerns regarding lane width or road quality, MoDOT restricts travel by striping crews to roads on which the safe travel of striping vehicles can be ensured. With one rare exception (discussed below), our model considers only those segments for which general maintenance is the responsibility of MoDOT. The first spreadsheet (MODOTRoads.xlsx) contains details on the road network to be analyzed; an extract from this spreadsheet is presented in Figure 2.1.

The color shading in this spreadsheet can be interpreted as follows:

- Blue/dark blue identifies “difficult” segments that require a different number of passes in each direction.
- Orange identifies two-lane undivided roads with centerline only (receive only one pass).
- Pink identifies a segment that was disconnected from the road network.
- Green shows roads that were added (roads from other MoDOT districts or non-MoDOT roads) to maintain network connectivity. (This is the only exception in which non-MoDOT roads might be potentially added to the network.)

1	Name	Direction	COUNTY_NAME	NUMBER_OF_LANES	#of lanes in Opos.Dir	uid	BEG_CONTINUOUS_LOX	END_CONTINUOUS_LX	FNode	TNode	Combine	SegmentID	Distance(n
2746		8 E	WASHINGTON	1	1	1668	0	0.13001	8615	8151	8151_8615	E_WASHINGTON_MO_8_0_0.13001	203.2372
2747	U	N	WASHINGTON	1	1	1689	14.763	14.93001	16220	8154	8154_16220	N_WASHINGTON_RT_U_14.763_14.93001	269.078
2748		8 E	WASHINGTON	1	1	1691	55.277	56.518	8190	8151	8151_8190	E_WASHINGTON_MO_8_55.277_56.518	1937.090
2749		8 E	WASHINGTON	2	1	1691	55.274	55.277	8154	8190	8154_8190	E_WASHINGTON_MO_8_55.274_55.277	4.81158
2750		8 E	WASHINGTON	1	1	1715	54.642	55.196	8146	8153	8146_8153	E_WASHINGTON_MO_8_54.642_55.196	892.0844
2751		8 E	WASHINGTON	2	1	1715	55.196	55.274	8153	8154	8153_8154	E_WASHINGTON_MO_8_55.196_55.274	125.6049
2752		21 N	WASHINGTON	1	1	1717	126.069	135.914	842	832	832_842	N_WASHINGTON_MO_21_126.069_135.914	15838.27
2753		8 E	WASHINGTON	1	1	1719	54.608	54.642	832	8146	832_8146	E_WASHINGTON_MO_8_54.608_54.642	54.47714
2754	P	N	WASHINGTON	1	1	1738	13.756	14.03901	15304	8143	8143_15304	N_WASHINGTON_RT_P_13.756_14.03901	456.2925
2755		8 E	WASHINGTON	3	1	1742	54.409	54.503	8143	8144	8143_8144	E_WASHINGTON_MO_8_54.409_54.503	150.9402
2756		8 E	WASHINGTON	2	1	1742	54.503	54.608	8144	832	832_8144	E_WASHINGTON_MO_8_54.503_54.608	169.1440
2757		8 E	WASHINGTON	3	1	1939	54.36	54.409	9248	8143	8143_9248	E_WASHINGTON_MO_8_54.36_54.409	78.20956
2758		8 E	WASHINGTON	1	1	1939	53.608	54.36	8158	9248	8158_9248	E_WASHINGTON_MO_8_53.608_54.36	1207.629
2759		8 E	WASHINGTON	1	1	1943	53.547	53.608	8157	8158	8157_8158	E_WASHINGTON_MO_8_53.547_53.608	97.74326
2760		8 E	WASHINGTON	1	1	2033	53.13	53.547	1197	8157	1197_8157	E_WASHINGTON_MO_8_53.13_53.547	670.4666
2761	O	E	WASHINGTON	1	1	2037	0	2.216	8154	15058	8154_15058	E_WASHINGTON_RT_O_0_2.216	3568.438
2762		8 E	WASHINGTON	1	1	2064	53.007	53.13	9251	1197	1197_9251	E_WASHINGTON_MO_8_53.007_53.13	197.3077
2763	E	N	WASHINGTON	1	1	2109	0	0.784	8158	11976	8158_11976	N_WASHINGTON_RT_E_0_0.784	1261.617
2764		8 E	WASHINGTON	1	1	2117	43.875	53.007	9240	9251	9240_9251	E_WASHINGTON_MO_8_43.875_53.007	14695.77
2765	O	E	WASHINGTON	1	1	2123	2.217	2.58001	15058	15060	15058_15060	E_WASHINGTON_RT_O_2.217_2.58001	583.5407
2766		21 N	WASHINGTON	1	2,1	2181	135.914	137.25	832	845	832_845	N_WASHINGTON_MO_21_135.914_137.25	2148.737
2767		21 N	WASHINGTON	3	1	2181	137.25	137.287	845	846	845_846	N_WASHINGTON_MO_21_137.25_137.287	59.55811
2768	E	N	WASHINGTON	1	1	2183	0.784	1.517	11976	846	846_11976	N_WASHINGTON_RT_E_0.784_1.517	1179.458
2769	F	N	WASHINGTON	1	1	2220	0.728	0.948	12283	12284	12283_12284	N_WASHINGTON_RT_F_0.728_0.948	356.2257
2770	F	N	WASHINGTON	1	1		0.728	0	12283	8157		N_WASHINGTON_RT_F_0.728_0	
2771		185 N	WASHINGTON	1	1	2272	0	1.443	1198	1198_1198		N_WASHINGTON_MO_185_0_1.443	2323.979
2772	AA	E	WASHINGTON	1	1	2465	0	11.48601	9240	1198	1198_9240	E_WASHINGTON_RT_AA_0_11.48601	18483.80
2773	E	N	WASHINGTON	1	1,2	2652	1.517	6.613	846	3479	846_3479	N_WASHINGTON_RT_E_1.517_6.613	8204.234
2774		47 N	WASHINGTON	1	1	2654	7.037	12.297	3485	3479	3479_3485	N_WASHINGTON_MO_47_7.037_12.297	8465.34
2775		21 S	WASHINGTON	1	1	2724	52.267	56.865	1424	1444	1424_1444	S_WASHINGTON_MO_21_52.267_56.865	7400.266
2776		21 S	WASHINGTON	3	1	2724	56.865	57.066	1444	846	846_1444	S_WASHINGTON_MO_21_56.865_57.066	323.225
2777		47 N	WASHINGTON	1	1	2726	12.297	15.55	3479	1424	1424_3479	N_WASHINGTON_MO_47_12.297_15.55	5234.372
2778	F	N	WASHINGTON	1	1	2872	1.23	9.02901	12281	12282	12281_12282	N_WASHINGTON_RT_F_1.23_9.02901	12549.45
2779	F	N	WASHINGTON	1	1	2872	0.949	1.23	12284	12281	12281_12284	N_WASHINGTON_RT_F_0.949_1.23	450.835
2780		185 N	WASHINGTON	1	1	2876	1.443	10.747	1198	1200	1198_1200	N_WASHINGTON_MO_185_1.443_10.747	14972.5
2781	F	N	WASHINGTON	1	1	2926	6.613	12.76001	3479	11301	3479_11301	N_WASHINGTON_RT_F_6.613_12.76001	9889.605

Figure 2.1 – Extract from MODOTRoads.xlsx

At the end of each workday, striping vehicles must travel to a MoDOT maintenance building to remain overnight. At the beginning of the next workday, the striping vehicles return to service, although the striping crews do not necessarily need to begin from the point at which work ceased at the end of the previous workday. Thus, our model formulation accounts for travel to and from each maintenance building or overnight location within the allowable workday (the model user inputs the number of hours allowed per workday) as an element of the striping schedule. The second main input spreadsheet (OvernightLocationDistances.xlsx) is a table containing the distance between each node in our road network and the nearest allowable striping vehicle overnighting location. An extract from this spreadsheet appears in Figure 2.2.

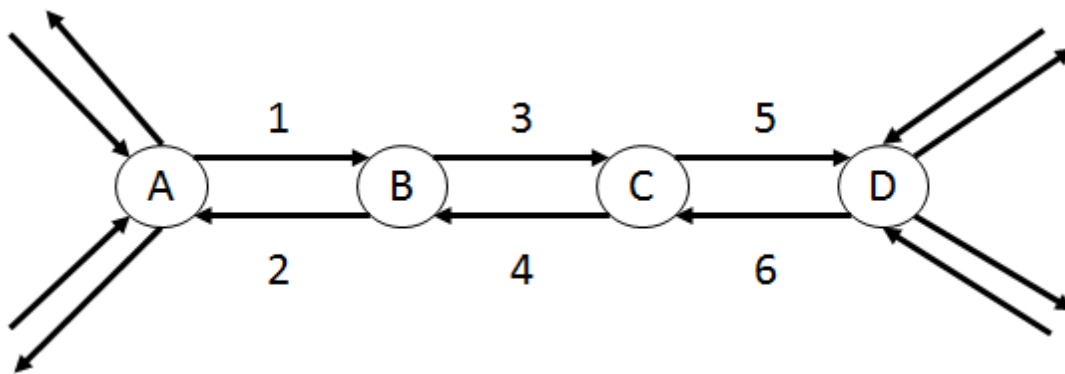
	A	B	C	D	E	F	G	H
1	ObjectID	NodeID	Closest overnight location Name	Overnight location County	FacilityID	Distance to closest facility (m)	Distance to closest facility (mi)	Closest node to facility
2	1	1	ELDON	MILLER	21	18523.2967	11.50982087	4719
3	2	2	ELDON	MILLER	21	18550.29316	11.52659566	4719
4	3	3	IBERIA	MILLER	23	22401.66402	13.91972197	692
5	4	4	IBERIA	MILLER	23	22614.64187	14.05206002	692
6	5	5	ELDON	MILLER	21	22274.21677	13.84053007	4719
7	6	6	ELDON	MILLER	21	23614.39367	14.6732758	4719
8	7	7	ST ROBERT	PULASKI	20	28259.61785	17.55967875	3045
9	8	8	ST ROBERT	PULASKI	20	28206.01844	17.52637368	3045
10	9	11	IBERIA	MILLER	23	10275.27894	6.384750077	692
11	10	12	IBERIA	MILLER	23	8190.884201	5.089569716	692
12	11	13	NEBO	LACLEDE	14	12415.57094	7.714663313	2035
13	12	14	NEBO	LACLEDE	14	11286.34904	7.012998704	2035
14	13	15	ST ROBERT	PULASKI	20	27432.45825	17.04570658	3045
15	14	16	ST ROBERT	PULASKI	20	27402.33821	17.02699089	3045
16	15	17	ST ROBERT	PULASKI	20	11651.80116	7.240079689	3045
17	16	18	ST ROBERT	PULASKI	20	11630.67462	7.22695229	3045
18	17	23	ST ROBERT	PULASKI	20	7329.450814	4.554300852	3045
19	18	24	ST ROBERT	PULASKI	20	7374.544646	4.582320807	3045
20	19	25	VIENNA	MARIES	6	29971.64803	18.62348294	7382
21	20	26	VIENNA	MARIES	6	29860.41564	18.55436647	7382
22	21	27	ST ROBERT	PULASKI	20	12249.15762	7.61125907	3045
23	22	28	ST ROBERT	PULASKI	20	11733.58908	7.290900246	3045
24	23	32	ST ROBERT	PULASKI	20	7478.562391	4.646954313	3045
25	24	34	ST ROBERT	PULASKI	20	12250.76827	7.612259878	3045

Figure 2.2 – Extract from OvernightLocationDistances.xlsx

## 2.1 Limiting Vehicle Turnaround Locations

Our decision support tool uses a genetic algorithm (GA) to optimize the schedule of striping operations, thus determining the sequence of road segments to be striped (including the direction of travel) in order to minimize total deadhead miles traveled. These deadhead miles include travel between segments to be striped (when necessary), along with travel to and from an allowed vehicle overnighting location at the beginning and end of each work day. The computation logic underlying this GA optimization model was presented in an earlier report (McGarvey et al. 2015).

The primary change that has been made to the model logic, as presented in this earlier report, was a modification to limit the locations where striping crews can turn around to be at either intersections with other MoDOT roads or at dead ends to MoDOT roads. This prevents the model from identifying a solution that requires a striping crew to turn around in the middle of a road (which was possible with the initial optimization model delivered in 2015). Consider the example presented below in Figure 2.3.



**Figure 2.3 – Example of turnaround logic**

Suppose that the striping crew is currently at node A. Road segments 1, 3, and 5 each need to be striped two times while road segments 2, 4, and 6 each need to be striped one time.

By observation, it is obvious that the minimum deadhead solution is to travel road segments 1-3-5-6-4-2-1-3-5, with no deadhead travel required. However, in the previous version of our optimization model, a feasible solution would be to travel road segments 1-2-1-3-4-3-5-6-5. Note that this solution also requires no deadheading and performs all required striping.

In discussions with MoDOT, we realized that such a solution is not actually feasible, since it would require the striping crew to turn around after every segment. Thus, we modified the model such that the striping crew can only turn around at an intersection with another MoDOT road or, in the case of MoDOT roads that dead end, at a dead-end road. In the example, this would prohibit a turnaround at either node B or node C, and the only solution with zero deadhead miles is to travel road segments 1-3-5-6-4-2-1-3-5.



### **3. GENETIC ALGORITHM MODEL**

While problems such as scheduling striping operations can be formulated without much difficulty, determining an optimal solution is difficult (do Rosário Moreira and Ferreira 2010). Thus, most practical solution techniques make use of heuristic procedures such as genetic algorithms.

#### **3.1 Installation Process of Required Programs and Libraries**

First, the user needs to extract the files in MoDOT.7z to the desktop (C:\Users\username\Desktop). Note that the screenshots included in this report are from a personal computer (PC) with a Windows 10 operating system. The new decision support tool assumes that the user has ArcGIS 10.2 already installed. Thus, much of the software that had to be installed for the previous model is no longer needed, since it is installed automatically along with ArcGIS 10.2. The user now needs to add Python 2.7 to the path variable as follows: Control Panel–System and Security–System–Advanced System Setting–Environment Variables–Path. Screenshots of this process are shown in Figure 3.1.

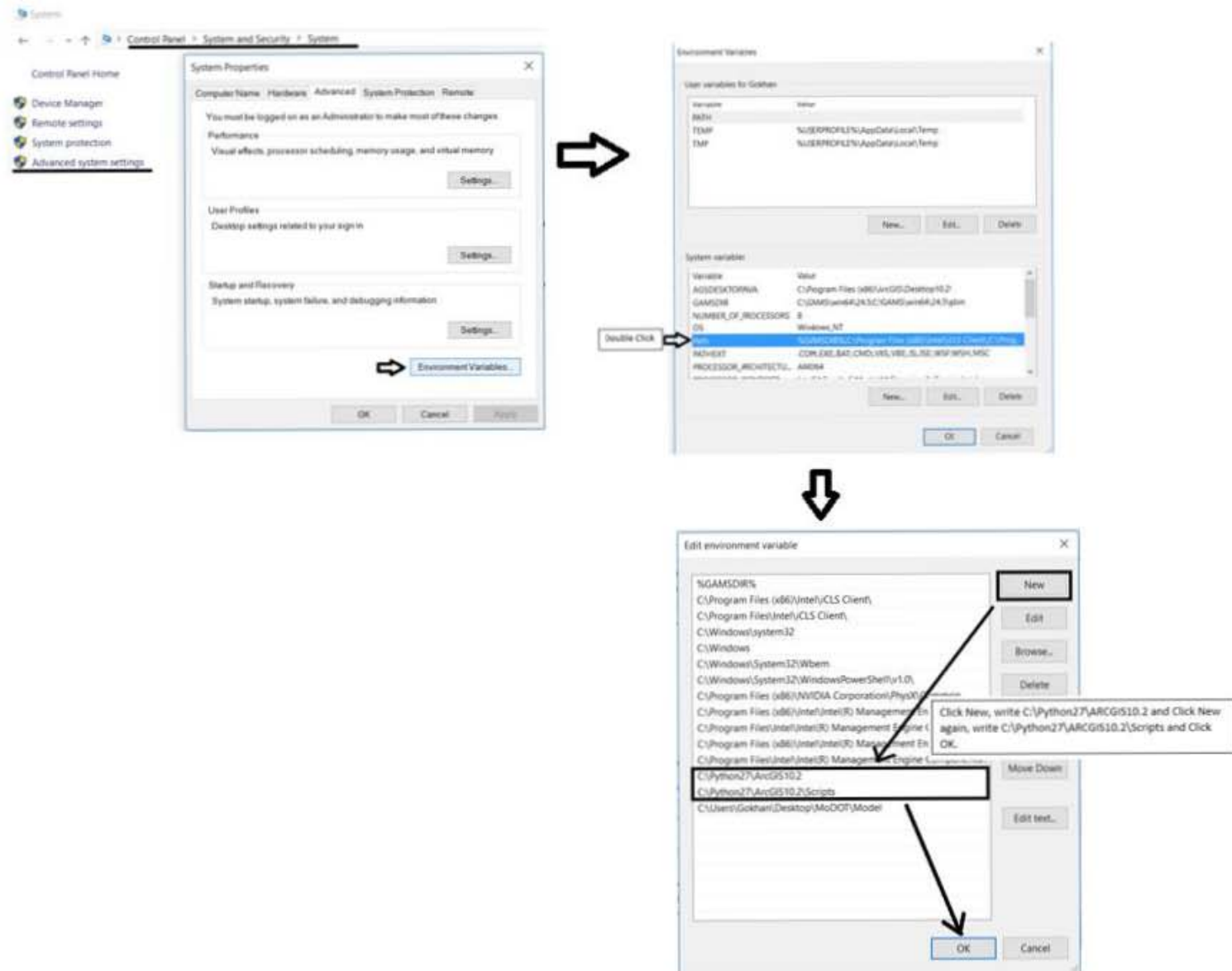
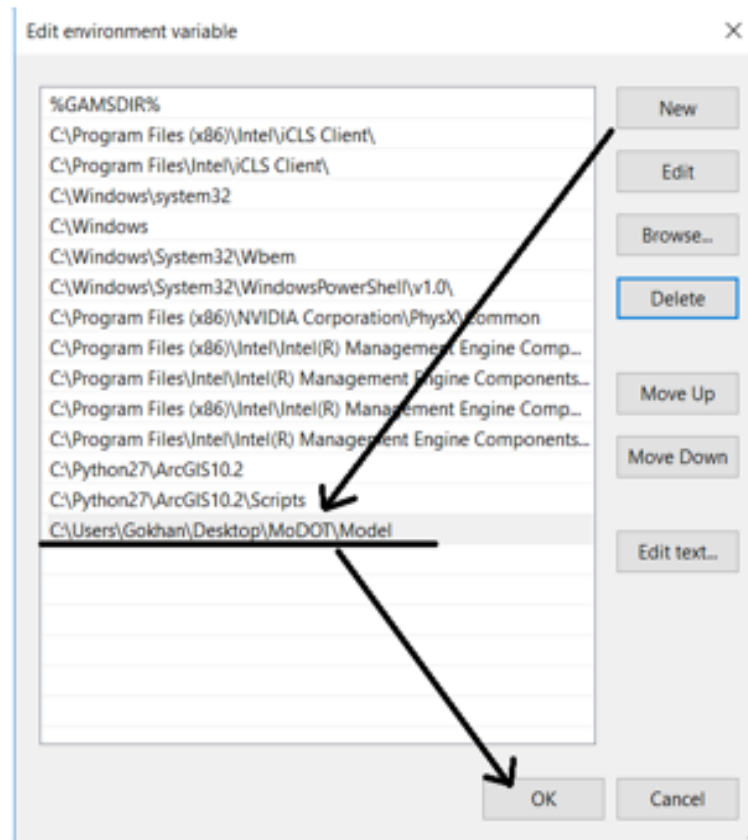


Figure 3.1 – Adding Python 2.7 to the path variable

Now, do the same process for pypy. Namely, add pypy to the path variable as follows: Control Panel–System and Security–System–Advanced System Setting–Environment Variables–Path (similar to the process shown in Figure 3.1 above). Write where you save the MoDOT file as a Variable value. As we saved it to the desktop, we need to write C:\Users\username\Desktop\MoDOT\Model as seen in Figure 3.2. Adding it to the path is shown below.



**Figure 3.2 – Adding MoDOT model to the path variable**

We have installed the required programs. Now, we need to install the Python libraries. First, we will download setuptools from the following website:

<https://pypi.python.org/pypi/setuptools/0.6c11>.

The installation instructions can be found on the website, but we will also explain them here. Scroll down to the end of the page and download the setuptools exe file as shown in Figure 3.3.

File	Type	Py Version	Uploaded on	Size
setuptools-0.6c11-1.src.rpm (md5) built for redhat 4.3	RPM	any	2009-10-20	263KB
setuptools-0.6c11-py2.3.egg (md5)	Python Egg	2.3	2009-10-20	1MB
setuptools-0.6c11-py2.4.egg (md5)	Python Egg	2.4	2009-10-20	329KB
setuptools-0.6c11-py2.5.egg (md5)	Python Egg	2.5	2009-10-20	325KB
setuptools-0.6c11-py2.6.egg (md5)	Python Egg	2.6	2009-10-20	325KB
setuptools-0.6c11-py2.7.egg (md5)	Python Egg	2.7	2010-07-08	324KB
setuptools-0.6c11.tar.gz (md5)	Source		2009-10-20	250KB
setuptools-0.6c11.win32-py2.3.exe (md5)	MS Windows installer	2.3	2009-10-20	218KB
setuptools-0.6c11.win32-py2.4.exe (md5)	MS Windows installer	2.4	2009-10-20	222KB
setuptools-0.6c11.win32-py2.5.exe (md5)	MS Windows installer	2.5	2009-10-20	222KB
setuptools-0.6c11.win32-py2.6.exe (md5)	MS Windows installer	2.6	2009-10-20	222KB
setuptools-0.6c11.win32-py2.7.exe (md5)	MS Windows installer	2.7	2010-07-08	222KB

**Figure 3.3 – Installing setuptools library**

Now, download PIL from <http://www.pythonware.com/products/pil/> using setup's default setting. The version is Python Imaging Library 1.1.7 for Python 2.7 (Windows only) as shown in Figure 3.4.

**PIL 1.1.7**

- [Python Imaging Library 1.1.7 Source Kit](#) (all platforms) (November 15, 2009)
- [Python Imaging Library 1.1.7 for Python 2.4](#) (Windows only)
- [Python Imaging Library 1.1.7 for Python 2.5](#) (Windows only)
- [Python Imaging Library 1.1.7 for Python 2.6](#) (Windows only)
- [Python Imaging Library 1.1.7 for Python 2.7 \(Windows only\)](#)

**Figure 3.4 – Downloading PIL library**

Now, we can easily install other Python libraries by using the `easy_install` tool in the setuptools that we installed previously. This tool automatically downloads the appropriate version of the selected libraries for Python from the internet. Open a command line window and install the following libraries: `networkx` (Figure 3.5) and `openpyxl` (Figure 3.6).

```

Microsoft Windows [Version 6.3.9600]
(c) 2013 Microsoft Corporation. All rights reserved.

C:\Users\Elif>easy_install networkx

```

**Figure 3.5 – Installing networkx**

```

Microsoft Windows [Version 6.3.9600]
(c) 2013 Microsoft Corporation. All rights reserved.

C:\Users\Elif>easy_install openpyxl

```

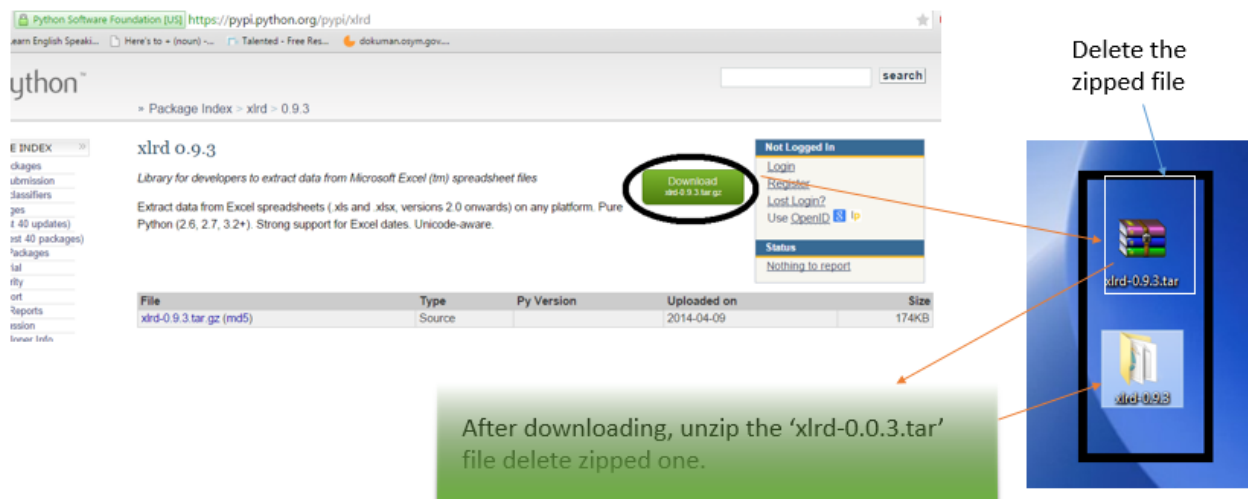
**Figure 3.6 – Installing openpyxl**

For pypy, we need to install xlrd and networkx, but the installation process of this library to pypy is different from the installation to Python.

First, download xlrd from the following website: <https://pypi.python.org/pypi/xlrd/0.9.3>.

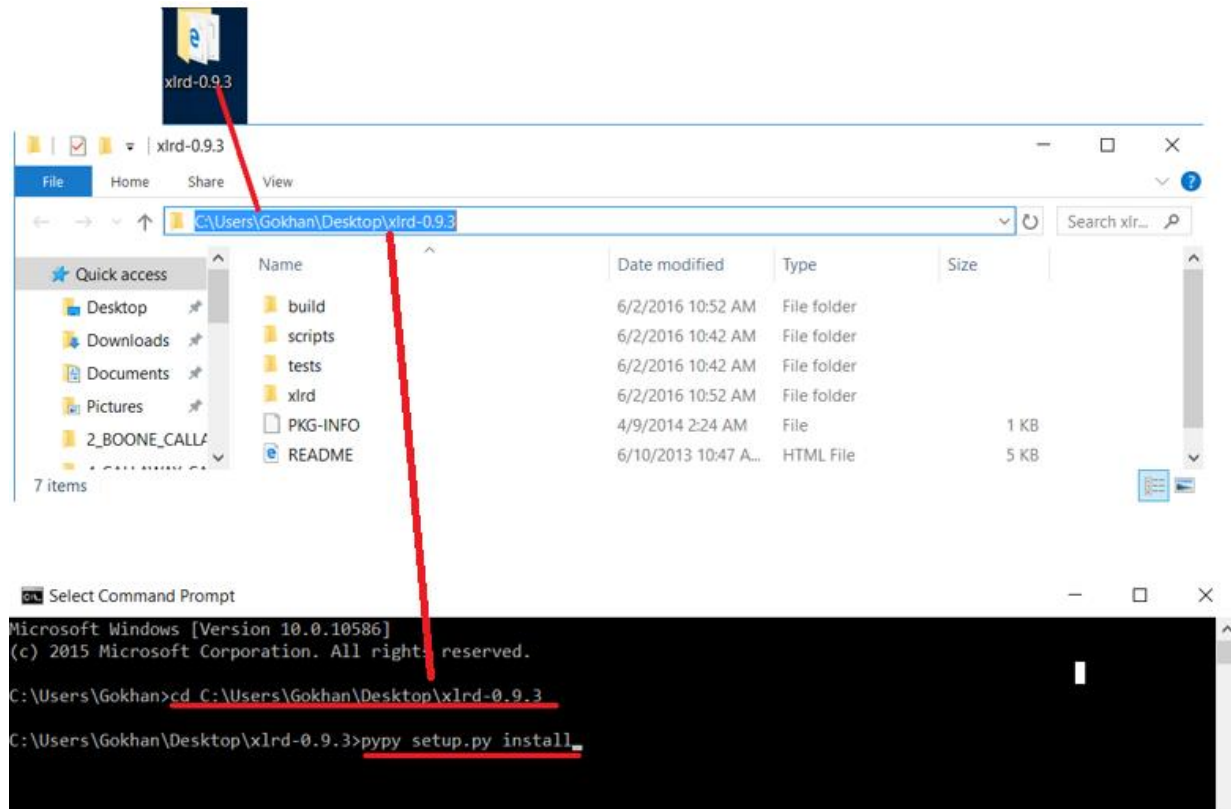
If you do not have WinRAR on your computer, you will also need to install the application WinRAR x86 (32 bit) 5.4 beta 2 in order to extract the files; this application can be downloaded from the following website: <http://www.rarlab.com/download.htm>.

Details for downloading xlrd for pypy are included in Figure 3.7.



**Figure 3.7– Downloading xlrd for pypy**

Second, open a command line window and change the directory to reflect where you unzipped file xlrd. Now, write *pypy setup.py install* and click enter (see Figure 3.8).



**Figure 3.8 – Installing xlrd for pypy**

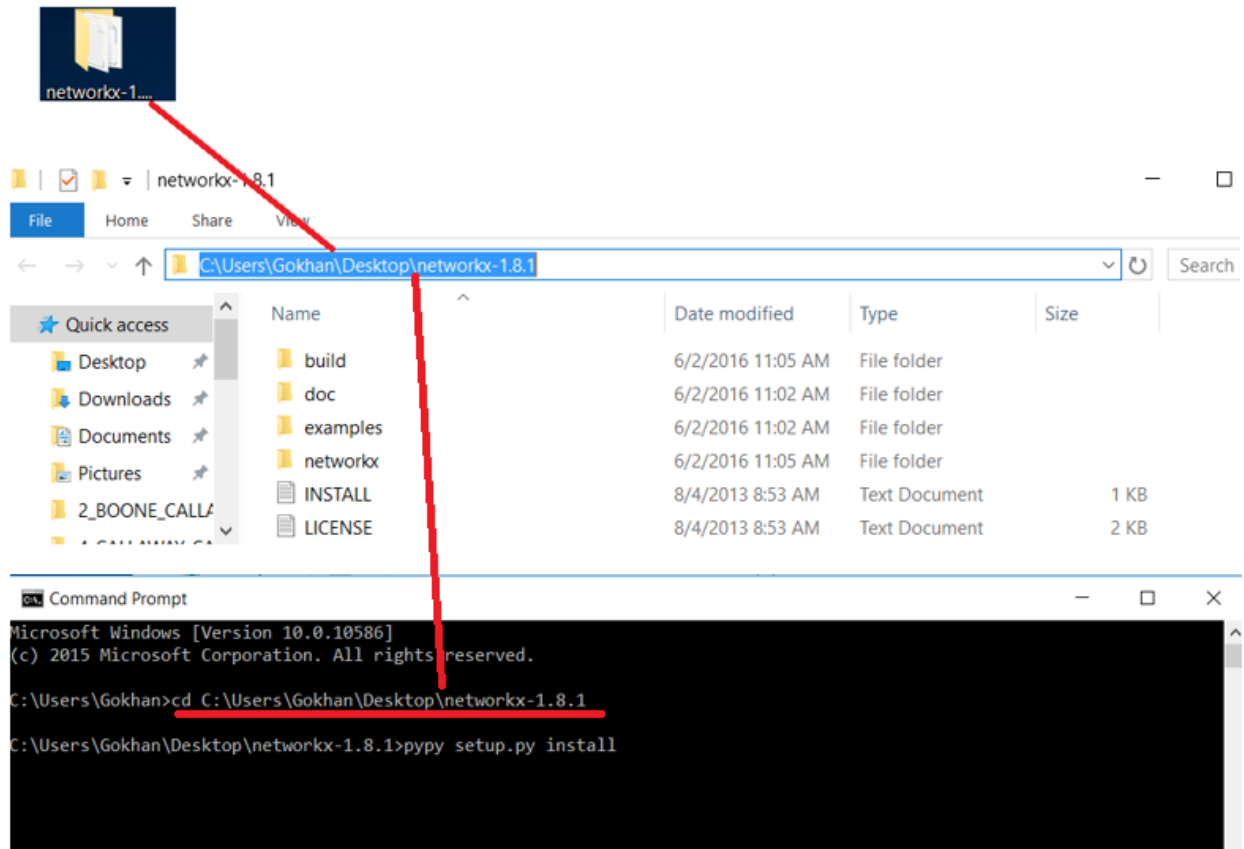
After installation is completed, both the zipped and unzipped xlrd files can be deleted from the desktop.

Now, download networkx to the pypy (see Figure 3.9) from the following website:  
<http://pkgs.fedoraproject.org/repo/pkgs/python-networkx/networkx-1.8.1.tar.gz/b4a9e68ecd1b0164446ee432d2e20bd0/>.

Index of /repo/pkgs/python-networkx/networkx-1.8.1.tar.gz/b4a9e68ecd1b0164446ee432d2e20bd0			
Name	Last modified	Size	Description
Parent Directory	-	-	-
<a href="#">networkx-1.8.1.tar.gz</a>	2013-08-09 22:45	788K	

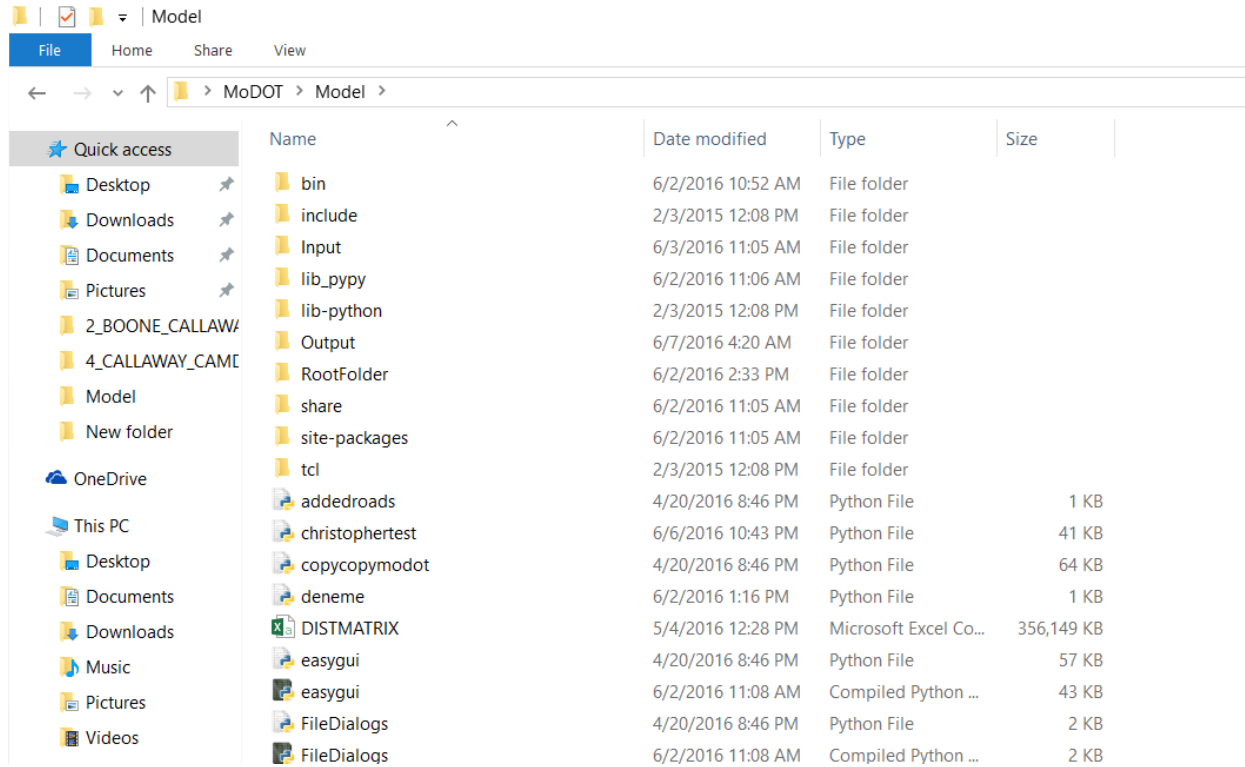
**Figure 3.9 – Downloading networkx for pypy**

As we did for xlrd, open a command line window again and change the directory to reflect where you unzipped file networkx. Now, write `python setup.py install` and click enter. Details for installing networkx for pypy are included in Figure 3.10.



**Figure 3.10 – Installing networkx for pypy**

Finally, all requirement programs are now installed. All files are listed in the MoDOT\Model folder, as seen in Figure 3.11.



**Figure 3.11 – Model folder**



### 3.2 Using the Decision Support Tool Interface

Double-click UserMODOT.py to open the user interface, as shown in Figure 3.12.

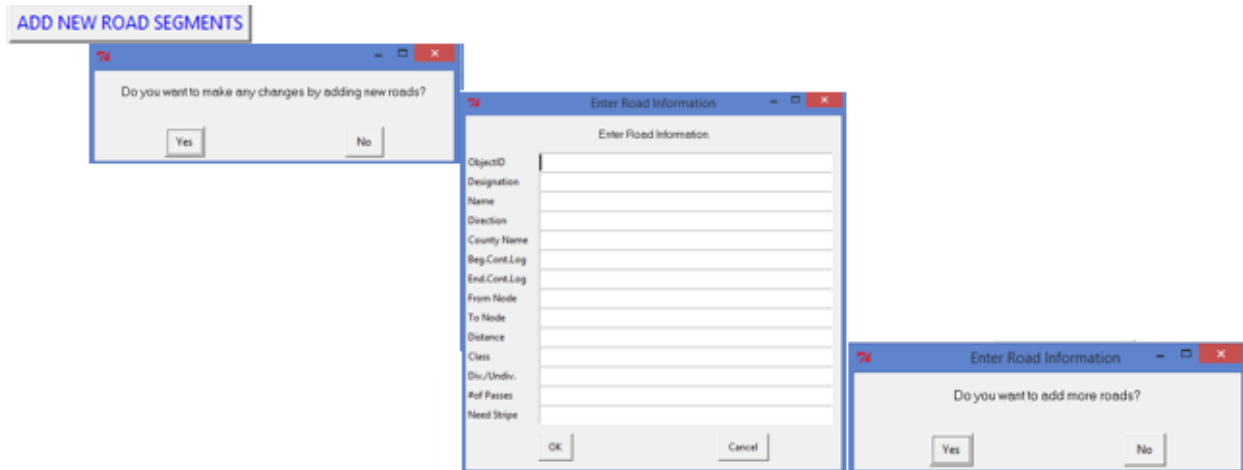


**Figure 3.12 – User interface**

#### 3.2.1 Adding Arcs to the Network

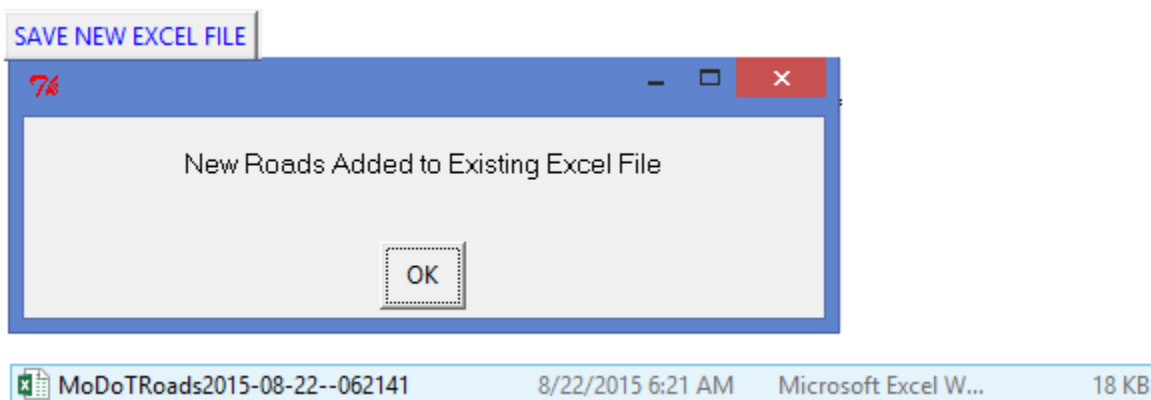
This section may be skipped unless the user wishes to modify the underlying network by adding new road segments. By adding new road segments, we are referring to adding a new arc over which travel may occur and *not* simply changing the set of arcs that require (or don't require) striping.

If the user wishes to add arcs, as shown in Figure 3.13, the decision support tool contains the button ADD NEW ROAD SEGMENTS, which will allow the user to add new road segments.



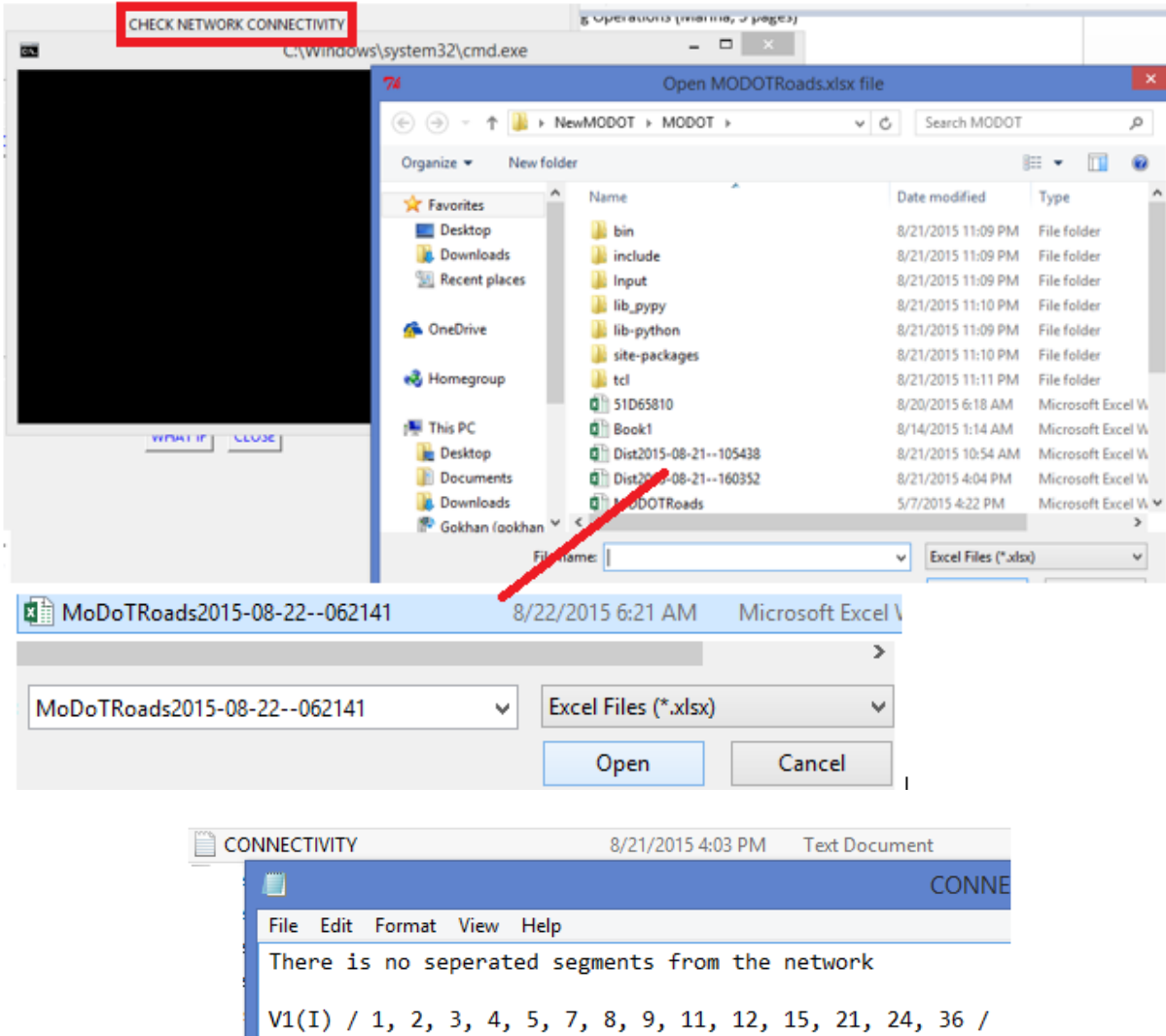
**Figure 3.13 – Adding new road segments**

Start by adding the necessary input information for the new road segment. After adding new roads, we need to make sure that the file is saved by using the button SAVE NEW EXCEL FILE. It adds the date to the name of the MODOTRoads file. For example, if the initial file name is MODOTRoads.xlsx, if you add new roads to the network the new Excel file will have a timestamp appended to the end of the file name, as shown in Figure 3.14.



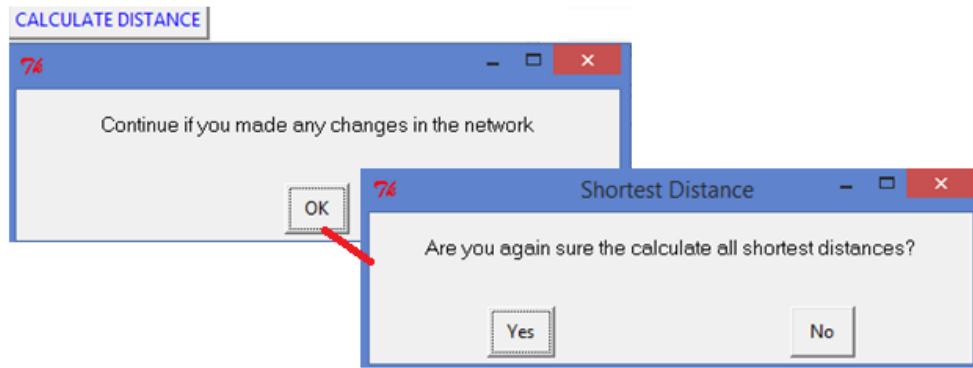
**Figure 3.14 – Saving new road segments**

After this process, we have to make sure that we have a fully connected network again. In other words, we do not want to have a cut in the network. Therefore, the button CHECK CONNECTIVITY allows us to see if the network is fully connected or not by generating a connectivity text file, which specifically shows the node numbers for every separated graph if there is a network disconnectivity. Hence, the user is able to identify which segments need to be reconnected (see Figure 3.15).

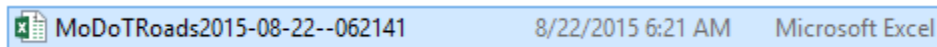


**Figure 3.15 – Confirming network connectivity after adding new road segments**

Finally, if MODOT makes any change from the data that were previously generated, the next step is to calculate new shortest distances (see Figure 3.16). Generating distances takes approximately two days using a laptop with an Intel 4 CPU, 4 GB RAM, and 64-bit OS. However, this process is done only once. Once this file is obtained, it can be used in all future analysis (until additional arcs are added to the network).



Select Excel file



It creates new distance file:



**Figure 3.16 – Calculating shortest distances table**

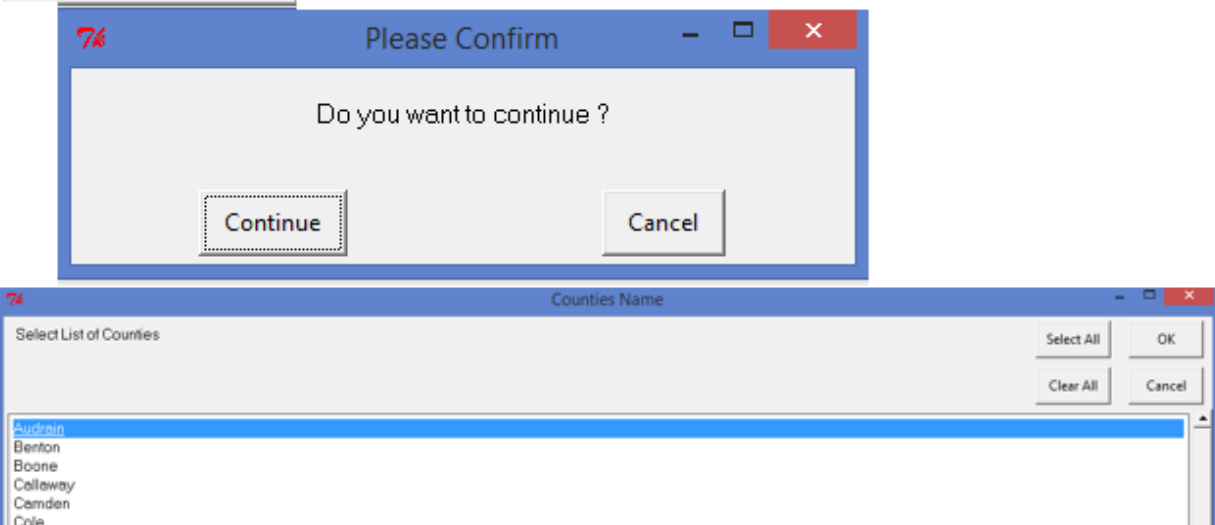
### 3.2.2 Preparing the Model to Run

Next, consider the Input Data section shown in Figure 3.17.

**Figure 3.17 – Input Data section**

This section is fairly straightforward for the user. First, select the list of counties over which the user wants to determine a striping schedule (see Figure 3.18). Note that in the MODOTRoads Excel file, the last column (showing the striping decision for each segment for the planning period) needs to be updated manually.

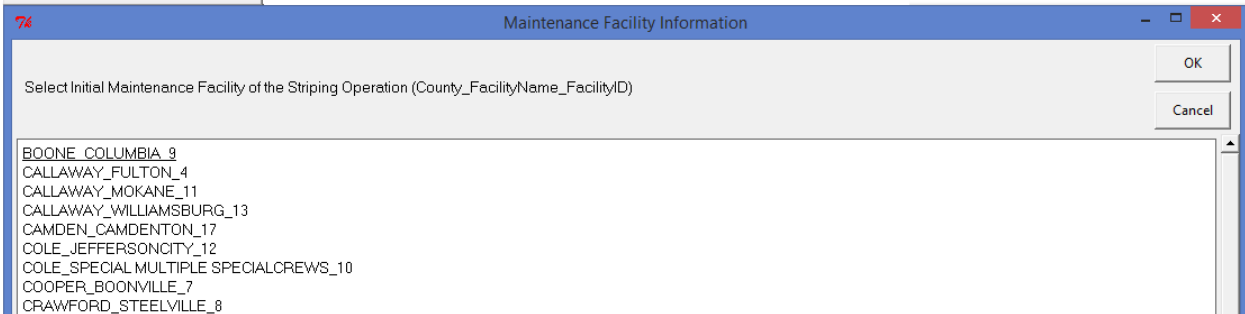
SELECT LIST OF COUNTIES



**Figure 3.18 – Selecting counties for striping scheduling**

Second, select the starting maintenance building where the striping vehicle is parked for the beginning of the striping operations to be scheduled (see Figure 3.19).

SELECT START MAINTENANCE FACILITY



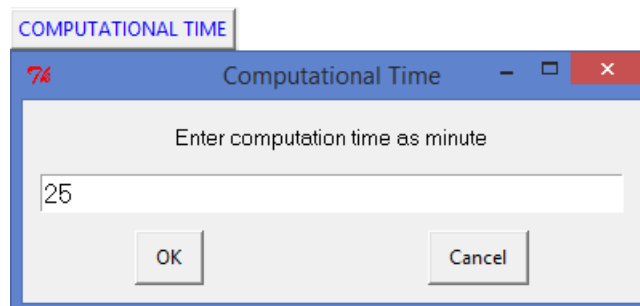
**Figure 3.19 – Selecting initial location of striping crew**

Third, select the road type to be striped (recall that directed and undirected roads cannot be striped at the same time) (see Figure 3.20).



**Figure 3.20 – Selecting road types for striping scheduling**

Finally, enter the maximum-allowable computational time (in minutes) (see Figure 3.21).

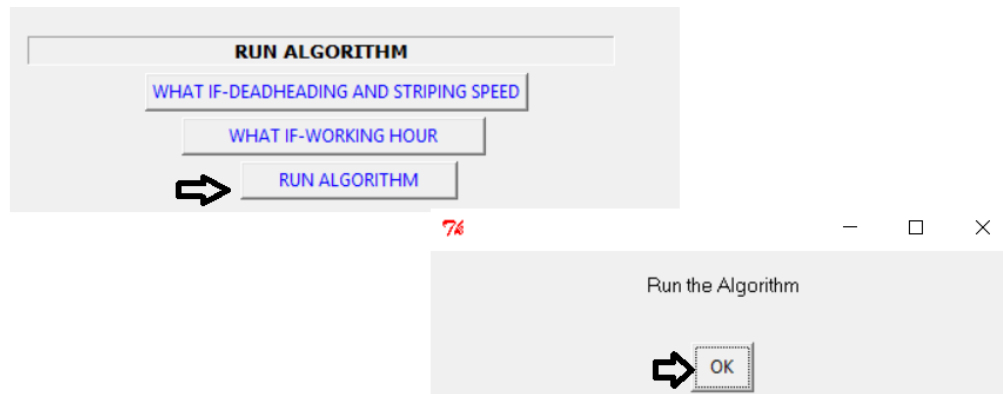


**Figure 3.21 – Selecting maximum-allowable computational time**

Note that computational time does not include the model’s data preparation and initialization time, nor the time required to generate output maps. It counts only the time spent by the optimization routine. When running the model, the start of the optimization routine is indicated by the appearance of the “Initial population is XXX” text in the output window.

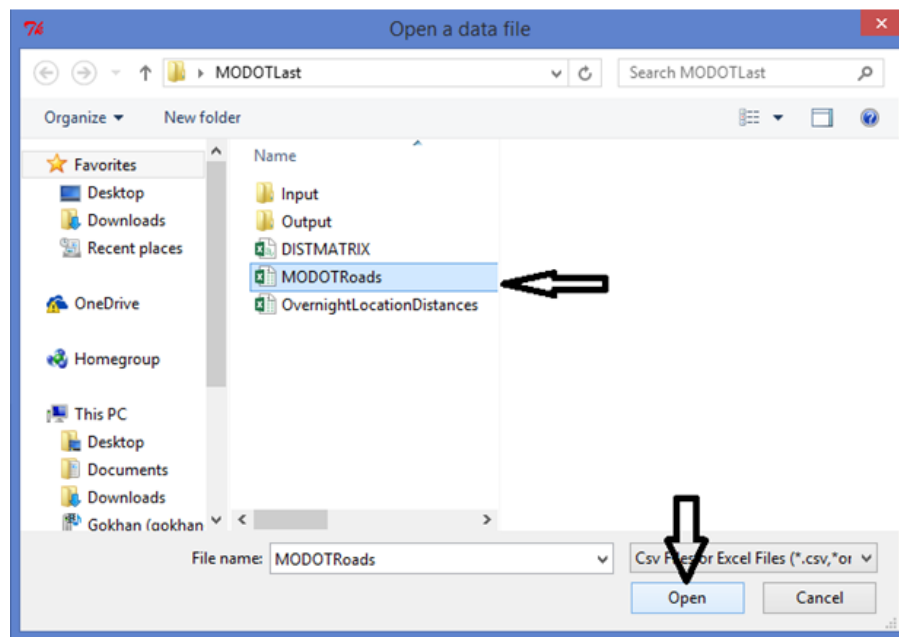
### 3.2.3 Running the Model

Now, we can run the model by clicking on the RUN ALGORITHM button (see Figure 3.22).



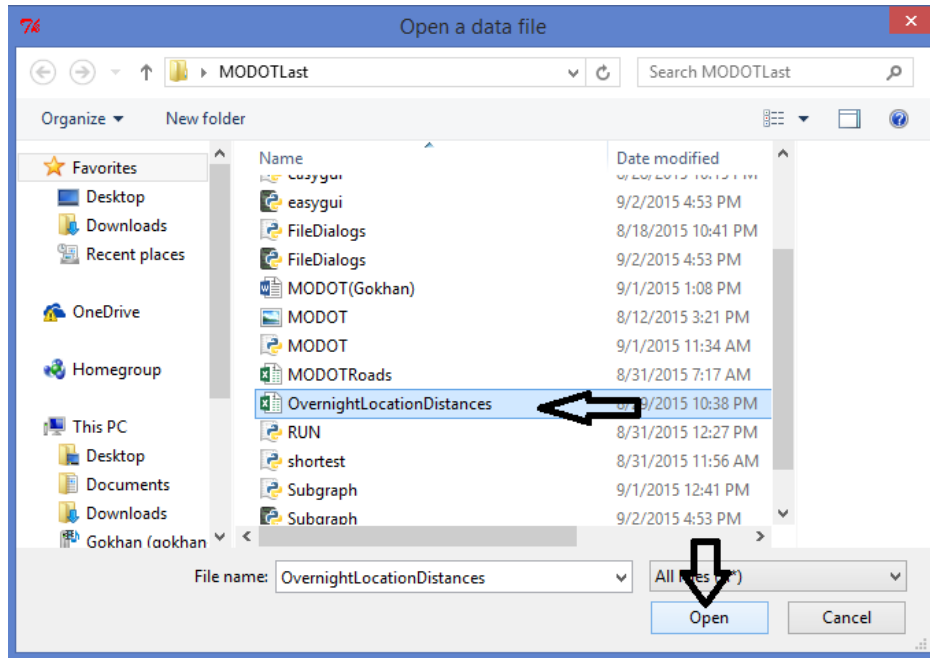
**Figure 3.22 – Running the model**

We first need to select which road network we want to analyze (typically MODOTRoads.xlsx) (see Figure 3.23).



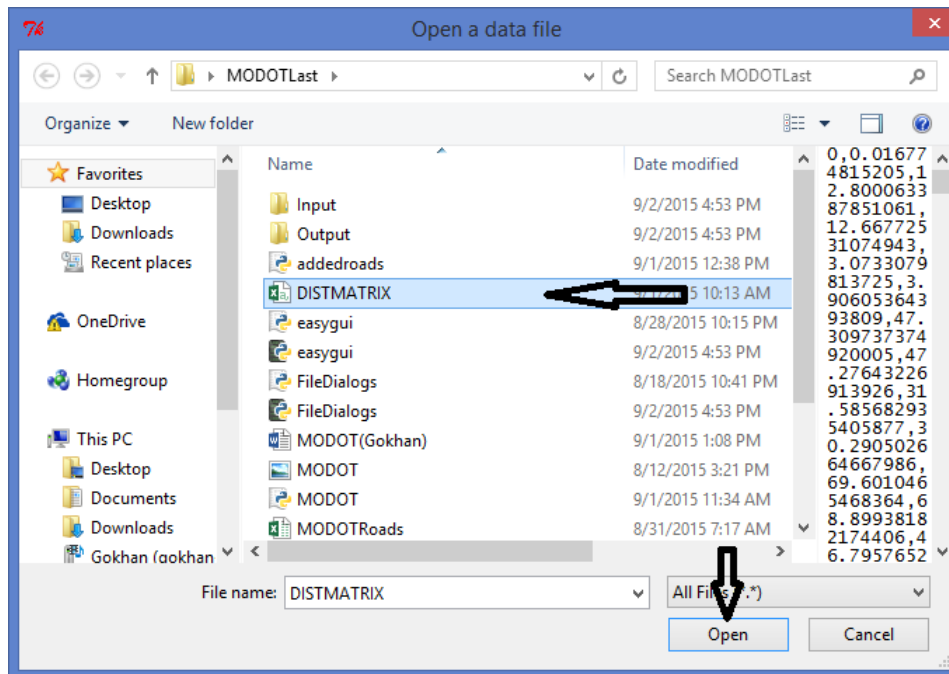
**Figure 3.23 – Selecting the road network**

We next need to select the distance table between the nodes of our road network and the set of allowable striping vehicle overnighting locations (typically OvernightLocationDistances.xlsx) (see Figure 3.24).



**Figure 3.24 – Selecting distance table for overnighting locations**

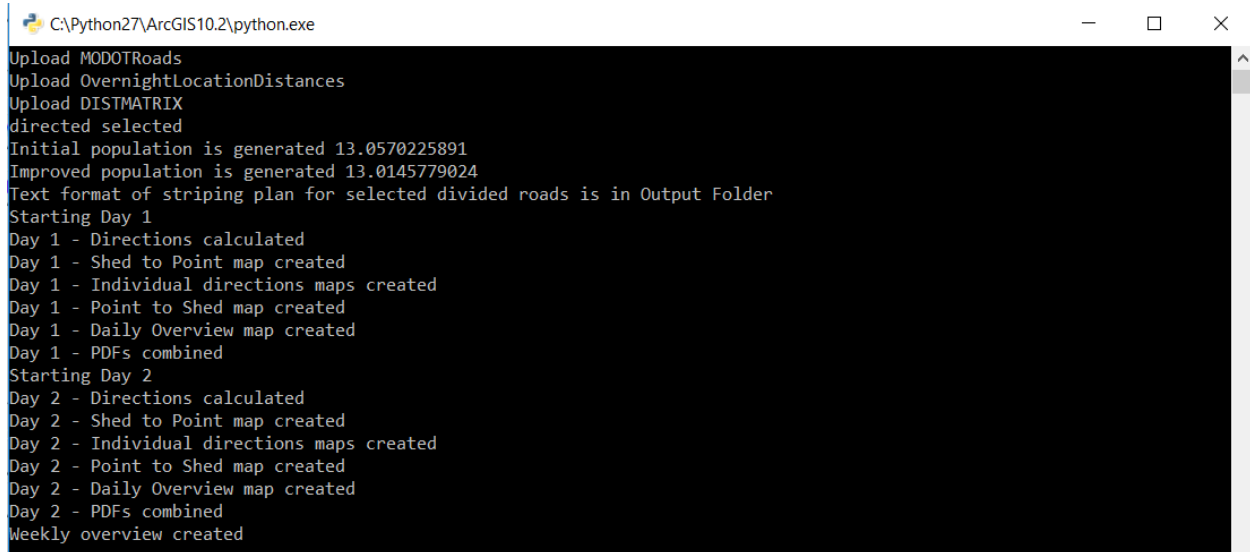
Finally, we need to select the distance table corresponding to our road network (typically DISTMATRIX.csv) (see Figure 3.25).



**Figure 3.25 – Selecting the distance table**



The model now runs, determining an ordered schedule (i.e., a sequence) of road segments to be striped that minimizes the total deadhead miles traveled. When the model has finished running, the PYTHON.EXE window will display the following: Weekly overview created (see Figure 3.26).



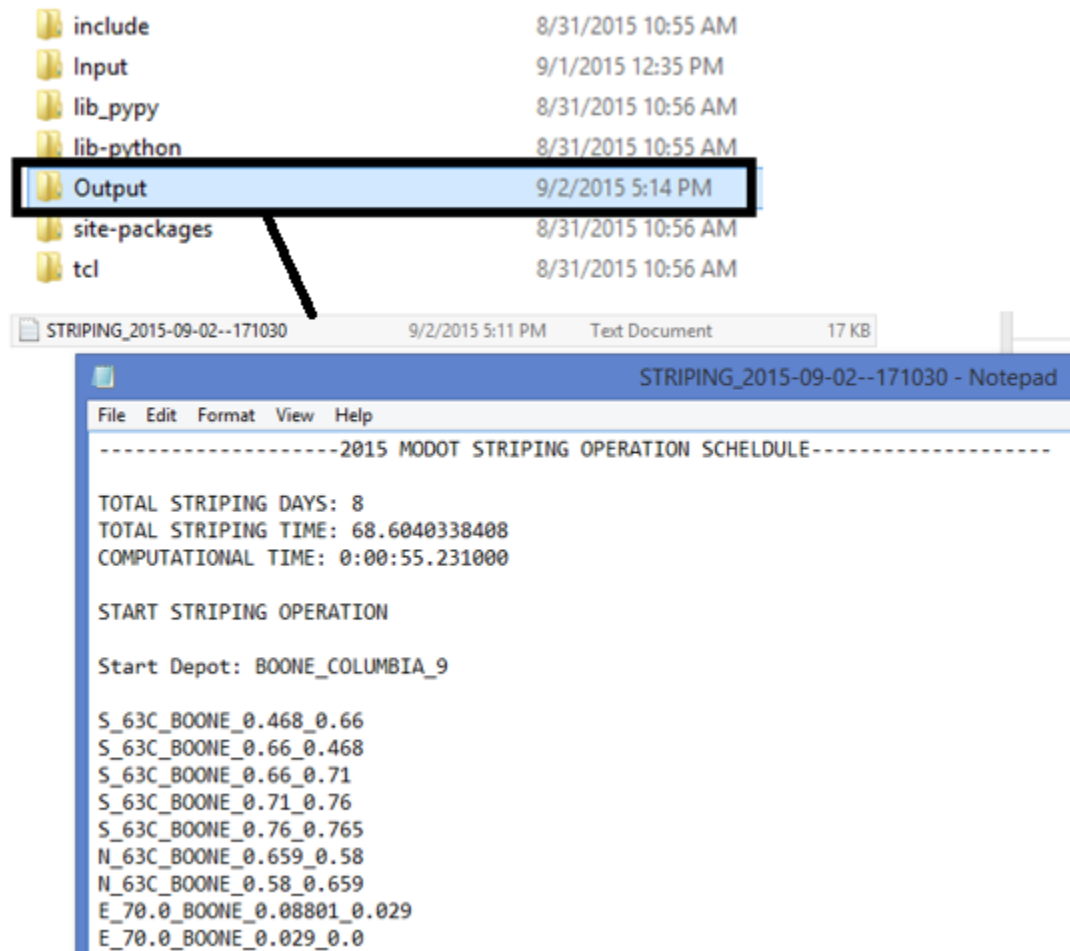
```
C:\Python27\ArcGIS10.2\python.exe
Upload MODOTRoads
Upload OvernightLocationDistances
Upload DISTMATRIX
directed selected
Initial population is generated 13.0570225891
Improved population is generated 13.0145779024
Text format of striping plan for selected divided roads is in Output Folder
Starting Day 1
Day 1 - Directions calculated
Day 1 - Shed to Point map created
Day 1 - Individual directions maps created
Day 1 - Point to Shed map created
Day 1 - Daily Overview map created
Day 1 - PDFs combined
Starting Day 2
Day 2 - Directions calculated
Day 2 - Shed to Point map created
Day 2 - Individual directions maps created
Day 2 - Point to Shed map created
Day 2 - Daily Overview map created
Day 2 - PDFs combined
Weekly overview created
```

**Figure 3.26 – Display when model has finished running**

We can now find the output in the Output folder. The model generates three types of output files:

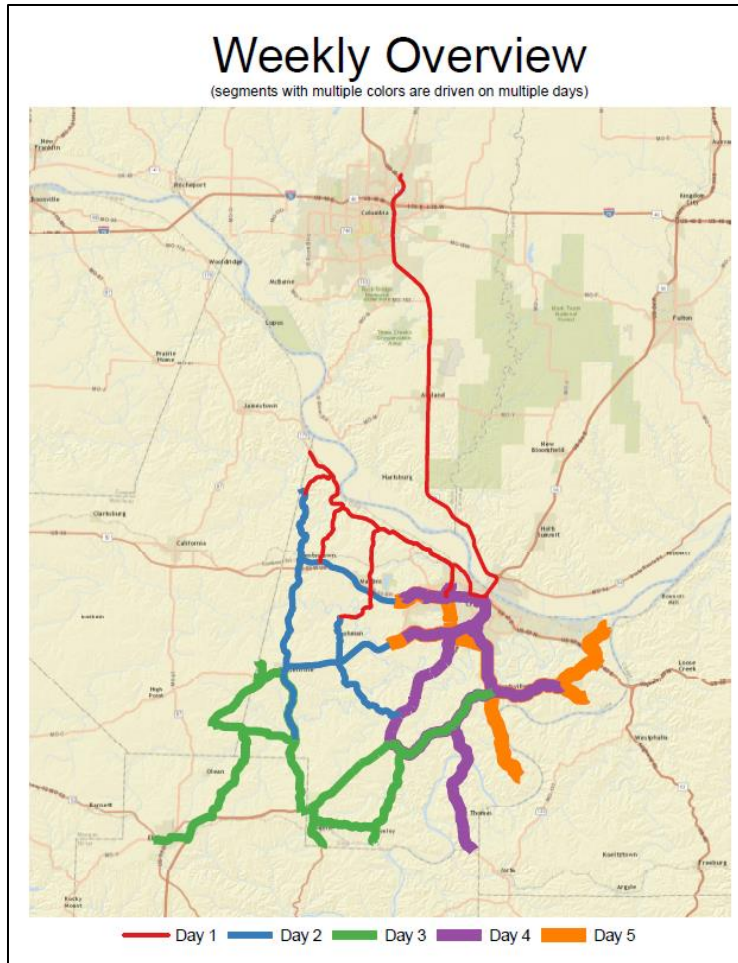
- A text file, containing the sequence of segments to be striped
- A weekly overview file that contains an ArcGIS map image of all travel to be performed by the striping crew during that week
- A series of daily overview files, each containing ArcGIS map images with details on the striping activity to be performed on each day

As shown in Figure 3.27, the text output file presents overall statistics on the total striping days, total striping time, and the model run's computational time. Then, for each day, the output lists the maintenance building where the day's operations began, and the order in which segments should be striped for that day. Segments are identified as Direction\_Highway ID\_County Name\_starting log mile\_stopping log mile; for example, S\_63C\_BOONE\_0.468\_0.66.



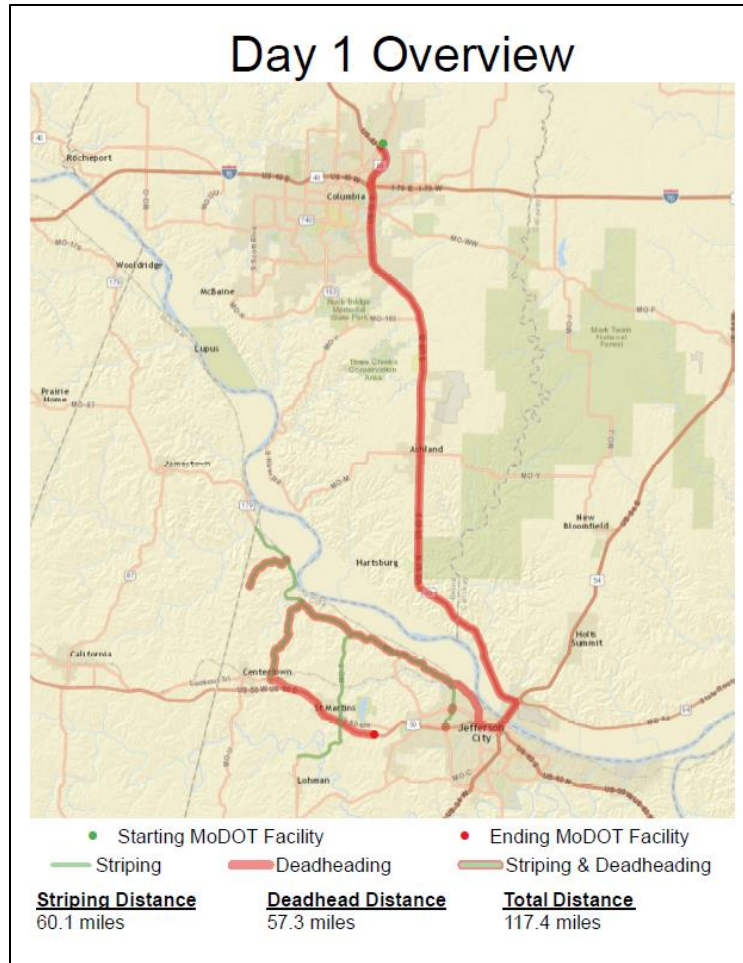
**Figure 3.27 – Opening the model output**

The weekly overview file presents a map of all striping crew travel (both striping and deadheading) for one week, as shown in Figure 3.28. Segments with multiple colors are driven in multiple days (e.g., the green and purple segments in Figure 3.28 are traveled on both Day 3 and Day 4).



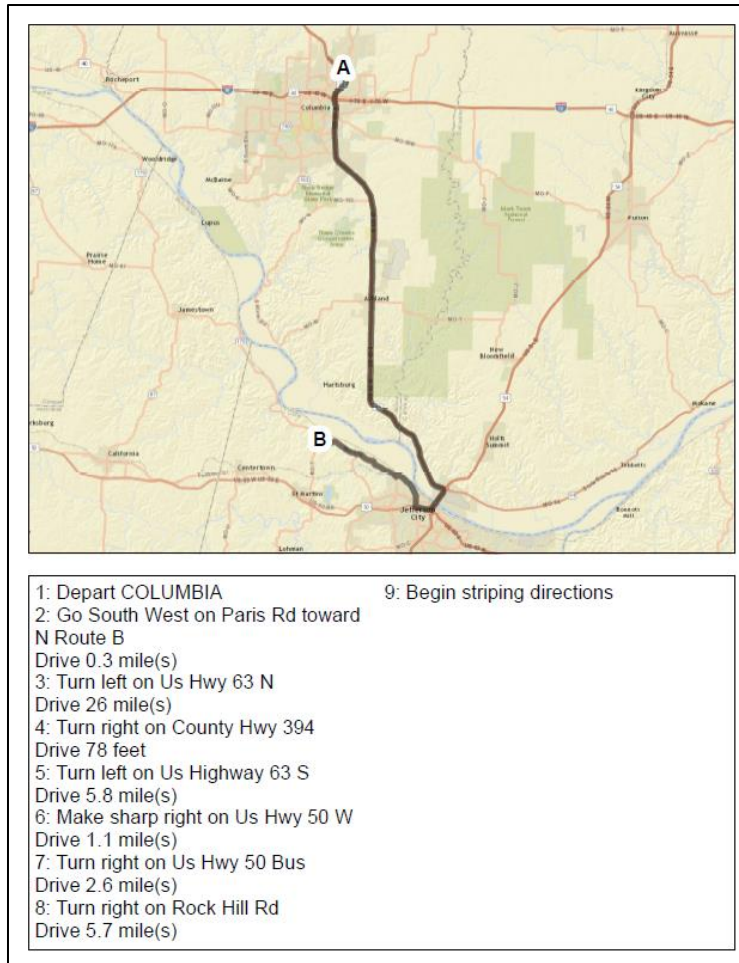
**Figure 3.28 – Weekly overview map**

The daily overview file contains three separate types of maps. First, as shown in Figure 3.29, a daily overview ArcGIS map showing all striping activity to be performed on that day, with green segments denoting segments to be striped, red segments denoting segments requiring deadheading, and green and red segments denoting segments that are both striped and deadheaded. This first map also presents the total striping distance and deadhead distance traveled on that day.



**Figure 3.29 – Daily overview map**

The second type of map contained in the daily overview file are maps showing the start-of-day and end-of-day deadheading. Figure 3.30 presents such a start-of-day map. Turn-by-turn directions are presented for all travel between the overnighting location and the segment at which striping operations begin.

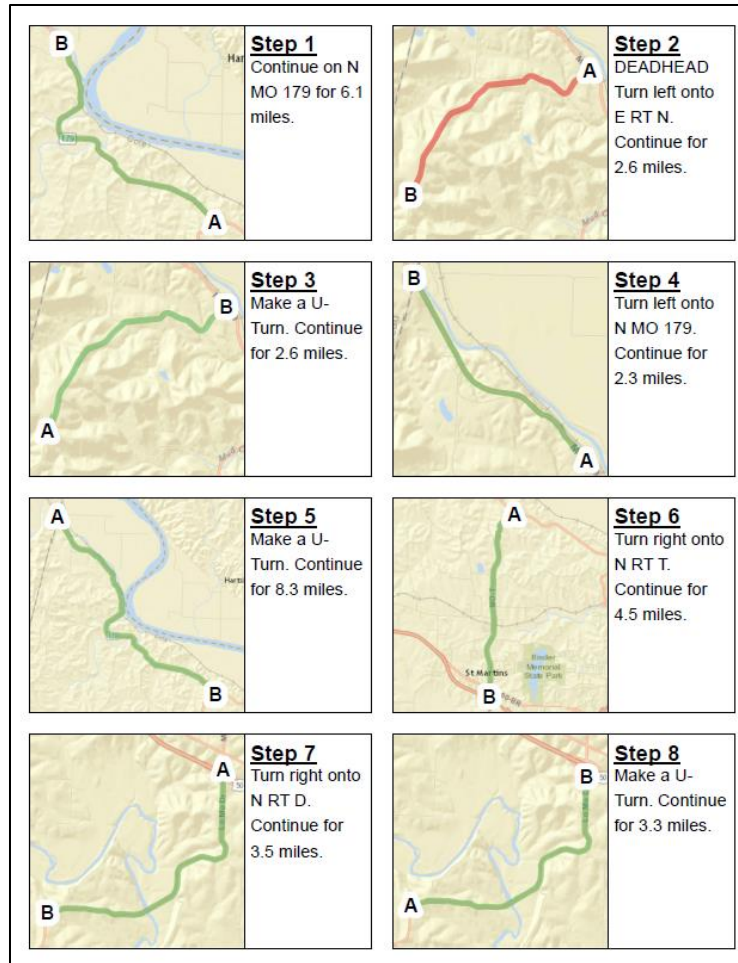


**Figure 3.30 – Start-of-day map**

Note that Figure 3.30 shows start-of-day deadheading for this example. The end-of-day map is not shown, but follows an identical format (showing travel between the last striped segment and the day's ending overnighting location).

The final type of output contained in the daily overview file are turn-by-turn directions, with local maps, for each segment that is traveled (both striping and deadheading) between the start of striping operations and end of striping operations for each day. An example of these turn-by-turn directions is presented in Figure 3.31.

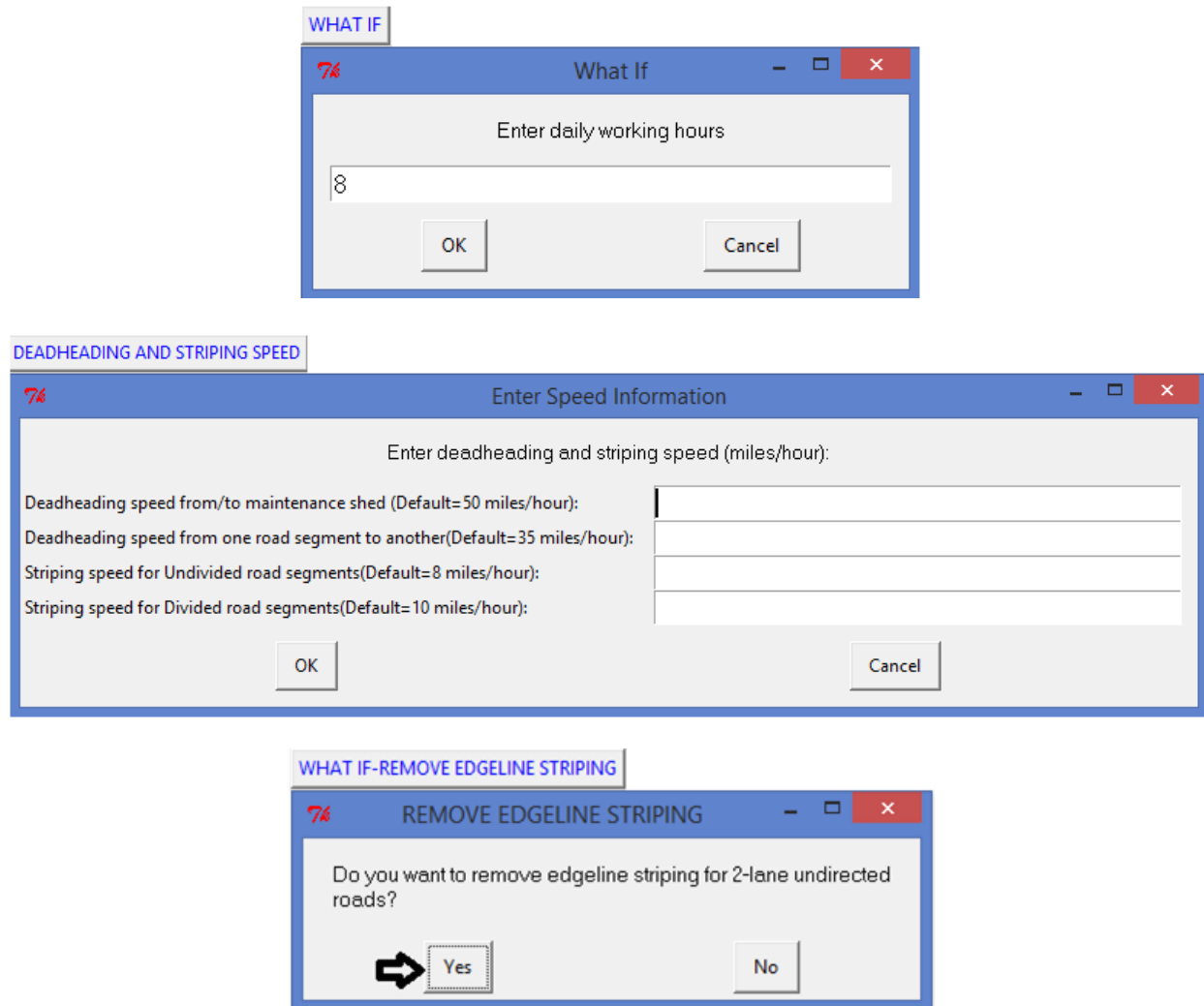




**Figure 3.31 – Turn-by-turn directions map**

### 3.2.4 Performing What-if Analysis

We have designed the tool to allow MoDOT users to perform three types of what-if analyses. The first two types of what-if analysis were included in the model that was delivered to MoDOT in 2015: (1) the user can change the allowable daily working hours, and (2) the user can change the speed at which striping vehicles travel while striping and deadheading. This report describes a new what-if functionality: (3) the user can elect to remove the requirement to stripe edge lines on two-lane undirected road segments. These what-if analyses can be used to determine the impact of such changes on system outputs such as the number of days required to complete striping operations, the total distance traveled, etc. See Figure 3.32 for a visual representation of these three types of what-if analyses.



**Figure 3.32 – Performing what-if analyses**

Based upon discussions with MoDOT staff, one new what-if analyses that was of interest included potentially removing the edge line striping requirement for two-lane undirected road segments. These segments would receive a centerline stripe only. Because the striper can paint two lines at one time, when edge lines are included on such road segments, two passes of the striping equipment are necessary (one in each direction) to stripe the road segment. By removing the edge line striping requirement, only one pass of the striping equipment is necessary, reducing the total miles that need to be traveled by the striping crew.

Note that MoDOT currently has some two-lane roads with no edge lines. Figure 3.33 presents an extract from the spreadsheet that MoDOT previously used to track the annual progress of striping operations. In this spreadsheet, roads that have no entry in the White E/L column are roads that do not have edge lines and thus require only the yellow centerline to be striped.

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U
1		Contract Striping					Striping Program 2014										8%				
2		Maybe Striped by other District					Not wide enough to stripe routes that may need restriped										Grand Total Completed to Date				
3		Omit Routes					Contract Seal Coat - Modot S 2014										CONTRACT OR MODOT WORK IN 2014				
4		Completed Routes					Modot Seal Coat, Patch - Modot Stripe														
5		DON'T TYPE R HERE					CLC / Contract Resurfacing 2014														
6		COUNTY	DESG.	TWAY	Total Length	Yellow w/ E/L	White E/L	C/L	Skip s	Yellow Ramp s	White Ramp s	Lane Line s	One lane Bridge	Gores	Total Line Miles	Mill Thick.	Total Progress	Striping Density	Done ?	Line Miles Completed	
28		WOW E/L	RT	CC	10.81		5.2	11.08							16.28		16.28		Done	0	
29			RT	D	1.59			2.12							2.12		0		No	0	
30		WOW E/L	RT	DD	2.86		5.72	4.39							10.11		10.11		Done	0	
31		Significant	RT	E	12.96		27	25.98	0.1						53.08		0		No	0	
32			RT	EE	1.98		3.96	3.01							6.97		6.97		Done	0	
33		wow/narrow	RT	F	12.91			23.14					0.6		23.74		23.74		Done	0	
34			RT	FF	1.58		4	1.98							5.98		0		No	0	
35			RT	H	4.09		8.2	5.06							13.26		13.8		Done	0	
36			RT	HH	5.75		11.5	9.34							20.84		20.84		Done	0	
37			RT	J	12.94		25.8	22.17							47.97		47.97		Done	0	
38		Significant	RT	K	7.35		14.4	12.73							27.13		0		No	0	
39		Significant	RT	KK	2.52		5.04	4.96							10		0		No	0	
40		w/OW E/L	RT	M	8.08		16.16	14.52							30.68		30.68		Done	0	
41		wow/narrow	RT	MM	4.48			8.53							8.53		8.53		Done	0	
42			RT	N	5.79		11.6	11.04							22.64		22.64		Done	0	
43			RT	NN	8.44			15.53							15.53		0		No	0	
44		wow/narrow	RT	O	6.48			12.37							12.37		12.37		Done	0	
45			RT	OO	4.62		8.8	8.36							17.16		0		No	0	
46		Significant	RT	PP	6.07		13.6	10.63	0.2						24.43		0		No	0	
47			RT	T	1.26			2.52							2.52		0		No	0	
48		Significant	RT	TT	1.33		0.78	2.36	0.21			0.45			3.8		0		No	0	
49			RT	U	3.44		2.1	5.43							7.53		7.53		Done	0	
50		w/OW E/L	RT	UU	4.14		5.6	6.97							12.57		12.57		Done	0	
51			RT	V	9.4		18.8	14.7							33.5		33.5		Done	0	
52			RT	VV	7.18		14.2	12.63							26.83		26.83		Done	0	
53		Significant	RT	W/W	7.82		17.4	13.08	0.1			0.1			30.68		0		No	0	
54		w/OW E/L	RT	Y	4.92		9.84	8.99							18.83		18.83		Done	0	
55			RT	YY	2.31			4.62							4.62		0		No	0	

**Figure 3.33 – Identification of segments that have centerline only**

When the user selects YES from the WHAT IF-REMOVE EDGE LINE STRIPING window, all two-lane undirected road segments have the edge line striping requirement removed. The user can then run the model and see how the total striping days and total distance traveled are changed in the new solution. Note that the user would need to have saved the outputs from an identical run in which the edge line striping requirement was not removed in order to determine the extent of the savings achieved.

Other what-if capabilities could be generated in the future, should MoDOT so request.



## 4. CONCLUSIONS

Road line striping operations generate a significant workload for MoDOT. The requirement for each road striping crew to replenish its stock of paint and other consumable items from a bulk storage facility, and the possible requirement of traveling unrequired roads to reach the roads that need striping, generate the potential for inefficiencies in the form of “deadhead miles” that road striping crew vehicles must travel while not actively applying pavement markings.

In an earlier report (McGarvey et al. 2015), we developed an optimization-based decision support tool, which implements genetic algorithm techniques to identify a minimum-distance striping schedule that satisfies the requirements of MoDOT striping operations. The research presented in this updated report describes our improvements to the model, limiting locations at which striping crews can turn around, adding new what-if capabilities to the model, and improving the model outputs, replacing the text-only outputs that were generated by the previous model with output visualization, including maps and turn-by-turn directions for striping crews.

Despite the fact that some factors remain unrepresented in the model (e.g., highway ramps requiring striping), the current results of our model can be used to help MoDOT more quickly calculate a striping schedule and dynamically respond to unexpected conditions such as schedule disruptions that occur due to weather or construction delays like chip seal operations not completed on the scheduled date. While MoDOT does not have records from which a comparison between the current and proposed system can be evaluated, the advantage of the genetic algorithm is apparent in the alleviation in time and effort dedicated to manually developing a striping schedule. Assuming MoDOT is able to manually calculate an optimal striping schedule to minimize the total distance traveled, the task still represents an exceedingly lengthy and laborious one. As such, this model provides an ability to significantly reduce the effort necessary to produce said striping schedule as well as test what-if scenarios examining the impact of changing resource levels, policies, etc.

The inefficiencies due to deadhead miles are manifested not only in additional, unnecessary miles traveled by road striping crews, but also in the required capacity for road striping crews and equipment. Were a more-efficient utilization of road striping equipment possible, MoDOT could potentially reduce costs by reducing its inventory of road striping assets, without reducing the frequency with which it reapplies pavement markings to Missouri highways. In this regard, the what-if capabilities of our model could be useful beyond solely the creation of striping operation schedules.

## REFERENCES

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