Logistical Analysis Using ArcGIS Pro

Erin Turnbull
Bachelor of Physical Geography and Earth Sciences
Carleton University
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Introduction

My project looks at how to calculate the total cost along vector polylines based on a raster cost surface, and how to determine the lowest cost routes between points connected by these polylines. It is inspired by logistical planning; as a case study, I consider a logistics company interested in minimizing their greenhouse gas emissions by choosing suppliers to minimize production- and transportation-related greenhouse gas emissions.

To accomplish this, I leveraged Statistics Canada's road and census division data to construct a transportation model for Ontario. By modelling the emissions of tankers from two sources of gasoline in Ontario with different production costs, a cost raster that represents the emissions per unit distance travelled was developed. Applying this cost raster to the road network via graph theory provides a table of minimum cost routes between cities. From this, suppliers can be matched to consumers. To simplify some of these tasks, I developed and published a Python toolkit that applies several of the methods described.

Methodology

Transportation Network Model

Road network and city information was taken from Statistics Canada 2016 Census data[1]. These were projected into NAD 1983 Ontario MNR Lambert, as it is suitable for working with just Ontario data. A province map provided by the ESRI Catalog was used to clip the data.

The city data was provided as polygons. In order to identify them as points on the road network, the larger divisions marked as cities were extracted and converted using Feature to Point. A few cities were removed where they were tightly packed.

The road network was developed manually from the polyline data. Major highway segments (rank 1-4) were selected for inclusion in the network based on how they connected the major cities. A model was developed that copied the selected features, dissolved them, and saved them into a routes table with appropriate start and end points. In this way, a feature set containing seperate polyline routes connecting pairs of major cities was developed.

[1] https://www12.statcan.gc.ca/census-recensement/2016/geo/index-eng.cfm see Spatial Information Products

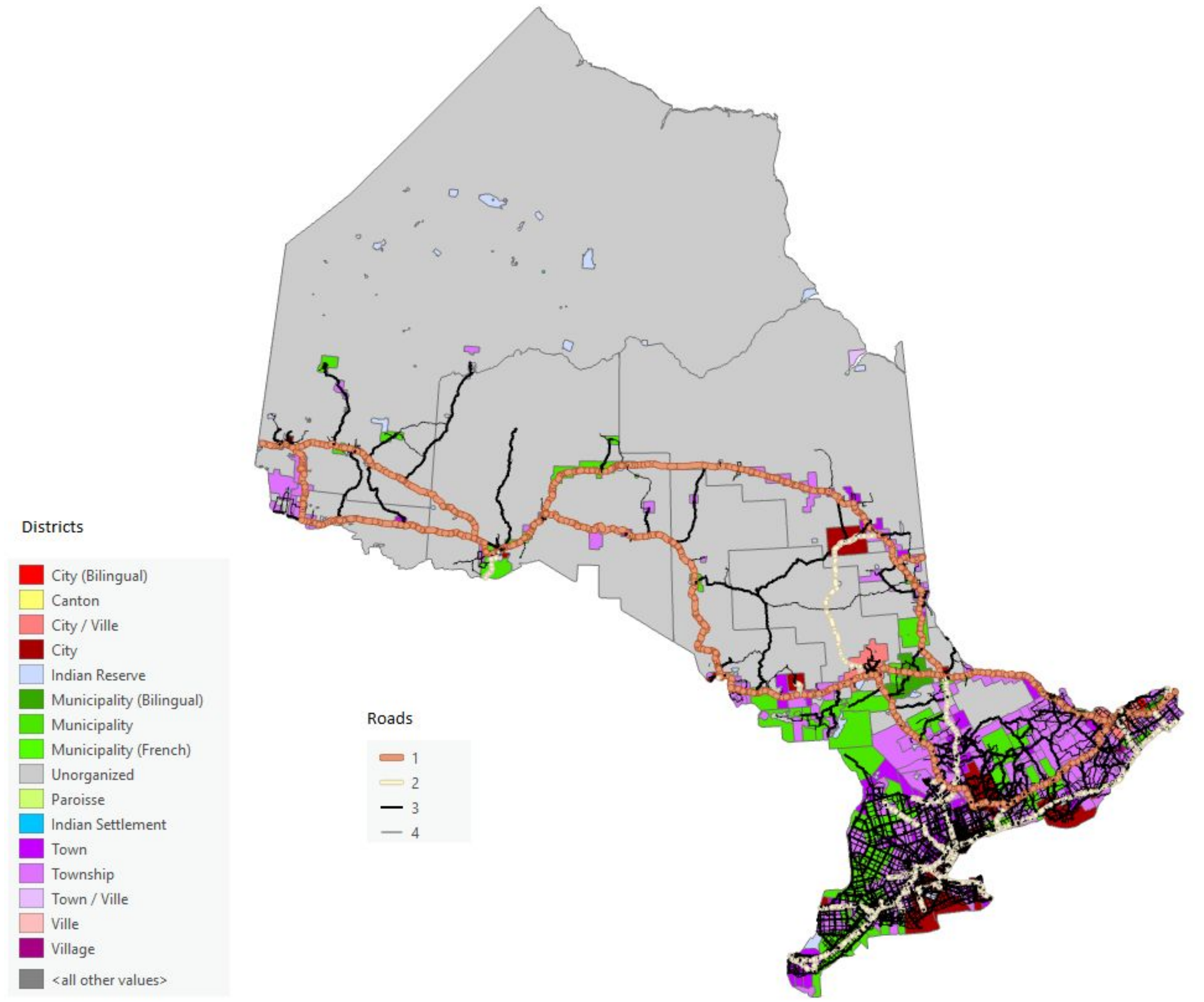

Figure 1: The original road and district data from Statistics Canada, clipped to Ontario. Roads are shown using their RANK, with RANK=5 excluded.

Figure 2: A portion of the driving network in Ontario (featuring Northern and Eastern Ontario). Road segments are in orange, cities are represented with red dots.

Table 1: An excerpt from the driving network table. It shows the Start and End point, along with a length. A cost field was also added for later use.

Start	End	Shape_Length (m)	Cost (kg CO_2)
Thunder Bay	Dryden	394303	<NULL>
Thunder Bay	Timmins	809065	<NULL>
Thunder Bay	Sault Ste. Marie	690343	<NULL>
Timmins	Greater Sudbury / Grand Sudbury	296815	<NULL>

Cost Model

In order to decide the cost of taking each route, a cost raster was developed. This represents the cost per unit distance travelled through the cell. In order to determine the total cost of taking a route, the length of the road through each cell multiplied by the cell's value will represent the total cost of taking the road.

This raster was developed based on the source emissions to produce the fuel (S), the emissions at the tailpipe (T), and the transportation cost. The transportation cost is the accumulated sum of the product of the fuel efficiency of the tanker (ε_s), distance through the cell (x), and a speed efficiency factor (f) that I assigned based on the rank of the road, with off-road areas having the highest factor. This needs to be divided by the capacity of the fuel tanker (c) and multiplied by the fuel efficiency of the transport vehicle (ε_t) to obtain a cost in terms of $kg\ CO_2\ m^{-1}$. This is represented in equation 1.

$$C = \left(\left[\sum_{i}^{D} \frac{1}{c} f_i \varepsilon_s T x \right] + S + T \right) \varepsilon_t \qquad \text{(eq. 1)}$$

To implement this in ArcGIS, the road network was reclassified to obtain the speed efficiency factor and the raster calculator used to determine the cost to move fuel through each cell. The cost distance tool was then applied to this metric with an appropriate source cost. As a demonstration of this approach, I assumed two sources for gasoline in Ontario: foreign-produced through Hamilton and oil sands-produced through Kenora[2]. See Table 2 and Figure 3 for the underlying assumptions. Please note that these are approximations.

[2]This information was drawn from the following sources:

https://cdn.ihs.com/ihs/cera/Oil-Sands-Greenhouses-Gases-and-US-Oil-Supply.pdf (figure 4)
https://www.eia.gov/tools/faqs/faq.php?id=307&t=9
https://westmor-ind.com/wp-content/uploads/2017/10/Proline-Transport-WMLT2065ENWB01.pdf
https://www.nrcan.gc.ca/energy/efficiency/transportation/commercial-vehicles/reports/7607

Table 2: A summary of the numbers used for the variables in this case study.

Variable	Units	Hamilton	Kenora
Supply Cost (S)	$kg\ CO_2\ L^{-1}$	0.6289	0.9434
Emissions (η)	$kg\ CO_2\ L^{-1}$	2.7	2.7
Capacity (c)	L	41500	41500
Efficiency (ε_S)	$L\ m^{-1}$	0.0004	0.0004
Cell Size (x)	$m\ cell^{-1}$	10000	10000
Source	$kg\ CO_2\ L^{-1}$	3.3289	3.6434
Cell	$kg\ CO_2\ m^{-1}\ L^{-1}$	$0.00026024 f_i$	$0.00026024 f_i$

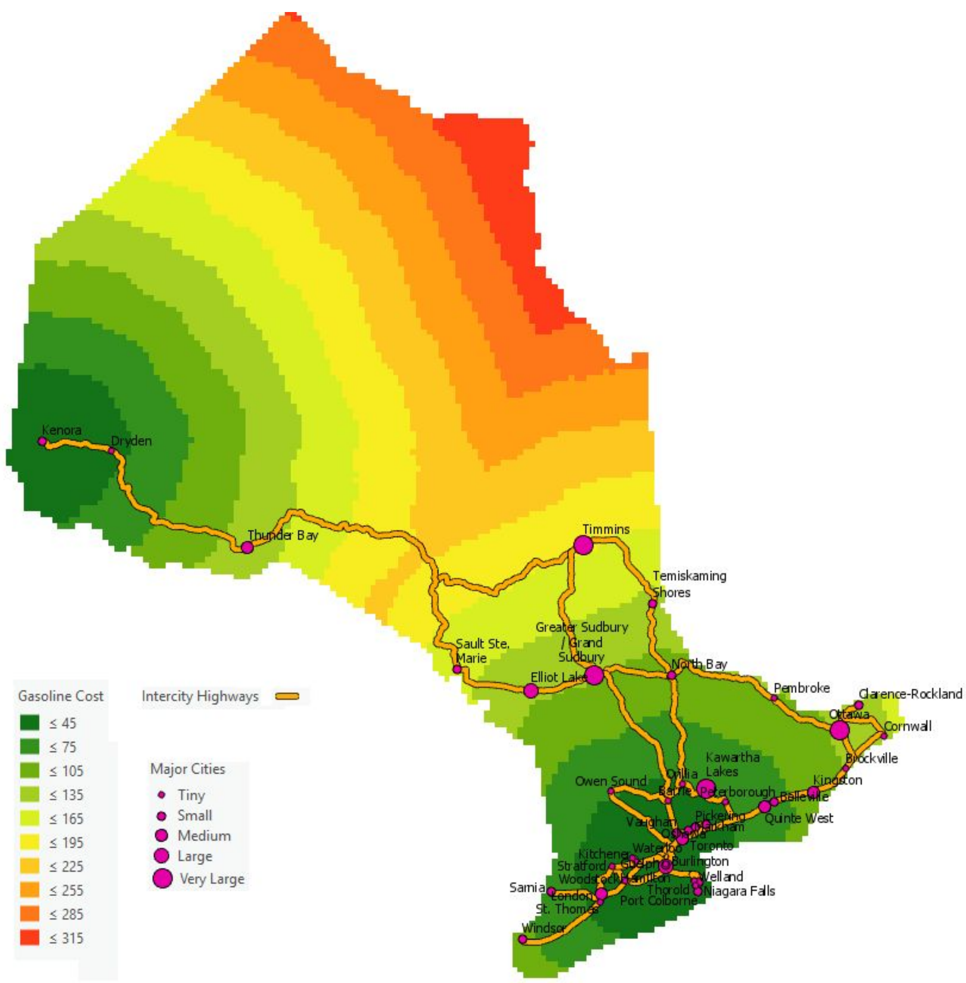

Figure 3: The Ontario driving network from Figure 2, with the cost surface overlain. The cost is in kg CO_2 L^{-1}. Cities have been styled to show their size, for reference. The cost is relatively cheap near sources and along transportation corridors, and significantly more expensive elsewhere.

Python Development

I developed three Python tools to help identify the fastest routes. Past projects have handled the task of applying a distance-weighted raster to polylines by vectorizing the raster and clipping. The first tool I developed leverages the arcpy library to clip the polyline to the cell using the cell size and determine the distance of the clipped line. This tool is published on GitHub[3], in case others would like to use it.

After applying the first tool to determine the total cost to take each route in terms of kg CO_2, I applied graph theory to find the shortest routes between cities. By considering the cities as vertices and the roads as edges between them weighted by the cost, a shortest path algorithm can be used to identify the fastest route between cities. I developed a Python script that applies the Floyd-Warshall algorithm to a pair of feature classes representing verticies and edges, which outputs a table with all the pairs of verticies, the accumulated cost between them, and the next node on the trip. An excerpt from this table can be found in Table 3.

Table 3: An excerpt from the routing table. It shows the transportation cost (in kg CO_2 L^{-1}) to travel between two cities, as well as the first city that is passed through on the route. The second city can be found by taking the first city and looking up it's route to the end city.

OID	Start	End	Cost	Next
13	Cornwall	Barrie	41451275	Ottawa
223	Toronto	Barrie	2146109	Vaughan
559	Barrie	Barrie	0	
643	Belleville	Barrie	10351778	Quinte West
685	Quinte West	Barrie	9241918	Oshawa

A simple allocation model was considered as a part of this project. Tables of suppliers (Table 4) and consumers (Table 5) were created. The allocation tool accepts these tables as well as the shortest route table (Table 3) and allocates suppliers to consumers with respect for their demands and production capacities, as well as minimizing the transportation and production costs.

Table 4: The suppliers table.

OID	Location	Production Cost	Capacity
0	Timmins	100	20
2	London	120	20

[3] https://github.com/emturnbull/arcgis-logistics

Table 5: The consumers table.

OID	Location	Request	Priority
0	Ottawa	10	5
1	Sarnia	10	10
2	Thunder Bay	10	0
3	Kingston	10	20

Results

The results of running the allocation tool with and without consideration of production quantities is noted in Table 6. These results show that each consumer is assigned an appropriate amount of production that minimizes costs. Note that when production is limited to 20 units each, Ottawa is supplied by Timmins instead of London.

Table 6: Resulting allocation of suppliers to consumers given limited and unlimited production.

	Unlimited Production			Limited Production		
Consumer	**Supplier**	**Unit Cost**	**Quantity**	**Supplier**	**Unit Cost**	**Quantity**
Kingston	London	0.9744	10	London	0.9744	10
Sarnia	London	0.2056	10	London	0.2056	10
Ottawa	London	1.4948	10	Timmins	2.6456	10
Thunder Bay	Timmins	5.3492	10	Timmins	5.3492	10

While the models used here are simple, this project has shown that GIS can be a powerful tool for logistical planning and reducing greenhouse gas emissions due to transportation for major organizations. With additional data, constraints and the addition of overseas and air transportation methods, ArcGIS Pro could be used to fully examine a range of transportation options and identify the true cost and ideal shipping method for products.