Constraint-Based Routing Models for the Transport of Radioactive Materials

Steven Peterson
Cheng Liu
Oak Ridge National Laboratory:1 Bethel Valley Road, Oak Ridge, TN 37831-6017, petersonsk@ornl.gov

INTRODUCTION

The Department of Energy (DOE) has a historic programmatic interest in the safe and secure routing, tracking, and transportation risk analysis of radiological materials in the United States. In order to address these program goals, DOE has funded the development of several tools and related systems designed to provide insight to planners and other professionals handling radioactive materials shipments. These systems include the WebTRAGIS (Transportation Routing Analysis Geographic Information System) platform. WebTRAGIS is a secure browser-based routing application developed at Oak Ridge National Laboratory (ORNL) focused primarily on the safe transport of spent nuclear fuel from US nuclear reactors via railway, highway, or waterway. It is also used for the transport planning of low-level radiological waste to depositories such as the Waste Isolation Pilot Plant (WIPP) facility. One particular feature of WebTRAGIS is its coupling with high-resolution population data from ORNL's LandScan project. This allows users to obtain highly accurate population count and density information for use in route planning and risk analysis.

To perform the routing and risk analysis WebTRAGIS incorporates a basic routing model methodology, with the additional application of various constraints designed to mimic US Department of Transportation (DOT), DOE, and Nuclear Regulatory Commission (NRC) regulations. Aside from the routing models available in WebTRAGIS, the system relies on detailed or specialized modal networks for the route solutions. These include a highly detailed network model of the US railroad system, the inland and coastal waterways, and a specialized highway network that focuses on the US interstate system and the designated hazardous materials and Highway Route Controlled Quantity (HRCQ) -designated roadways. The route constraints in WebTRAGIS rely upon a series of attributes assigned to the various components of the different modal networks.

Routes are determined via a constrained shortest-path Dijkstra algorithm that uses a calculated link impedance factor when determining an optimal route solution. The route constraints modify the various impedance weights to bias or prefer particular network characteristics as desired by the user. Both the basic route model and the constrained impedance function calculations are determined by a series of network characteristics and shipment types.

This study examines solutions under various constraints modeled by WebTRAGIS including possible routes from select shut-down reactor sites in the US to specific locations in the US. For purposes of illustration, the designated destinations are Oak Ridge National Laboratory in Tennessee and the Savannah River Site in South Carolina. To the degree that routes express sameness or variety under constraints serves to illustrate either a) the determinism of particular transport modes by either configuration or regulatory compliance, and/or b) the variety of constrained routes that are regulation compliant but may not be operationally feasible.

THE REGULATORY ENVIRONMENT

There are several regulatory frameworks which are applicable to the routing of radioactive materials, particularly spent nuclear fuel (SNF). Within the federal codes of regulations there are several sections that provide a guide to the types of constraints or environments that would inform route selection or would be useful in assessing the merits of a potential route. In some cases, the regulations are fairly brief and lack specific details, and in others, specific details are given, but are open to interpretation or are not particularly restrictive when determining route selection.

Within the regulatory oversight of the Nuclear Regulatory Commission (NRC) there are several component parts of 10 CFR that have some applicability to routing. Applicable sections of the 10 CFR regulations are Parts 73 and 960. Part 71 is Packaging and Transportation of Radioactive Material which covers how SNF packages should be handled and shipped.[1]

A relevant section from 10 CFR Part 73 is section 73.37 – Requirements for physical protection of irradiated reactor fuel in transit. This section calls for preplanning and coordination of shipments including route selection. Within this requirement (73.37(b)(1)(iv)), shipments are required to

- Minimize intermediate stops and delays;
- Arrange for state law enforcement escorts;
- Arrange for positional information sharing when requested; and
- Develop route information, including the identification of safe havens.

Section 73.37(b)(1)(v), calls for law enforcement coordination along the route, including ports where vessels carrying spent nuclear fuel are docked. [1]

10 CFR Part 960 is a relevant section from DOE regulations covering siting criteria for a SNF repository in accord with the Nuclear Waste Policy Act Section 112(a)[2,3]. Section 960.5-2-7 covers Transportation. This section requires that population density and distribution information for the site and for possible routes to the site to be determined and taken into consideration when planning routes. Further, the section also specifies that each transportation mode near a potential storage site needs to be identified including possible routes to and from the facility. For these possible routes and modes the identification of the following elements and considerations is to be done[2]:

- Availability of access routes from local existing highways and railroads to the site which have any of the following characteristics:
  - (i) Such routes are relatively short and economical to construct as compared to access routes for other comparable siting options.
  - (ii) Federal condemnation is not required to acquire rights-of-way for the access routes.
  - (iii) Cuts, fills, tunnels, or bridges are not required.
  - (iv) Such routes are free of sharp curves or steep grades and are not likely to be affected by landslides or rock slides.
  - (v) Such routes bypass local cities and towns.

The regulations note that these are not exclusionary criteria, but that such criteria should be taken into consideration when selecting both routes and sites.

Department of Transportation regulations are covered in 49 CFR and cover transportation by highway, rail, and, to some extent, by waterway. For highway shipments of SNF the following criteria are established for highway routing in Part 397.101 [4]:

- Minimizing radiological risk
- Accident rates
- Transit time
- Population density and activities
- Time of day

The regulations then recommend the use of interstate highways to minimize accidents and improve transit times. Time-of-day factors are to be used to evaluate population densities that might change during the course of a day in order to minimize population along a route. Activities of concern would be public parks, concerts, sports stadiums or other public venues. Further, in Part 397.103, the states are required to identify hazardous materials routes that would minimize radiological risk.[4]

Additional highway routing regulations are provided in 49 CFR 173.22 and 177.825[5, 6]. These regulations identify other factors to be taken into consideration when determining highway routes. These factors include emergency response capabilities, evacuation capabilities, and "special facilities" such as schools, hospitals, and stadiums.

For rail, the applicable sections of 49 CFR are 172.820, 172.822 and Appendix D of Part 172 [7,8]. These regulations specify that routes should be chosen based on the safest or most secure for both a preferred/primary and an alternate route. In general, the routes should minimize storage and delays in transit and should allow for adequate security of materials both in transit and when in a rail yard. Appendix D provides for 27 different criteria that are to be considered when determining primary and alternate routes. Those criteria are:

- Volume of hazardous material transported
- Rail traffic density;
- Trip length for route;
- Presence and characteristics of railroad facilities;
- Track type, class, and maintenance schedule;
- Track grade and curvature;
- Presence or absence of signals and train control systems along the route;
- Presence or absence of wayside hazard detectors;
- Number and type of grade crossings;
- Single versus double track territory;
- Frequency and location of track turnouts (sidings);
- Proximity to iconic targets;
- Environmentally sensitive or significant areas;
- Population density along the route;
- Venues along the route (stations, events, places of congregation);
- Emergency response capability along the route;
- Areas of high consequence along the route, including high consequence targets as defined in 172.820(c).
- Presence of passenger traffic along route (shared track);
- Speed of train operations;
- Proximity to en-route storage and repair facilities;
- Known threats, including any non-public threat scenarios provided by the Department of Homeland Security or the Department of Transportation for carrier use in the development of the route assessment;
- Measures in place to address apparent safety and security risks;
- Availability of practical alternate routes;
- Past incidents;
- Overall times in transit;
- Training and skill level of crews; and
- Impact on rail network and congestion.

As a result of these regulations, a system for route planning and identification needs to be both flexible and comprehensive in order to address the inherent tradeoffs existing between the identified criteria. The delineation of these various criteria then suggests a routing methodology that can incorporate multiple constraints when solving routes.

NETWORK ROUTING METHODOLOGY

Basic network routing methodology is a form of applied graph theory in which the graphs are representative of some topological network of directed or undirected vertices and edges. In transportation modeling, the vertices and edges are usually termed nodes and links. Depending upon the type of modal system, the links connecting the nodes may be directed or undirected. In general, transportation networks are also classified as finite graphs. [9]

Most routing problems seek to find the shortest path along the connected links of a network graph between two nodes. In order to determine these routes a variety of algorithms have been developed. Further, these algorithms may or may not have the capacity to incorporate constraints when considering solutions. Types of different graph algorithms are depth-first, breadth-first, minimum spanning trees, and lightest (shortest) path methods.

A commonly used routing algorithm is the Dijkstra algorithm. This model is an iterative process for determining the shortest path between two nodes on a graph. In so doing, the algorithm actually solves the route over the entire network graph by measuring every possible path from source node *a* to sink node *b* provided that the graph is non-negatively weighted and that the graph is connected. [10] Constraints may then be applied to the algorithm through changes in underlying network feature properties or by biasing and penalizing nodes or links during the link selection process.

THE WEBTRAGIS SOLUTION

In order to address spent nuclear fuel routing problems, ORNL developed the TRAGIS routing application for DOE. Currently, the version is known as WebTRAGIS and is used for routing, alternate route analysis, and critical infrastructure analyses. In doing so, WebTRAGIS employs a constrained Dijkstra routing algorithm across three transport modes: rail, highway and waterway.

The Transportation Routing Analysis Geographic Information System (TRAGIS) is a user-friendly, geographic information system (GIS)-based transportation routing and analysis computer model. Funding for the development of TRAGIS has been provided by DOE's Office of Environmental Management (EM) through the Office of Packaging and Transportation. TRAGIS works with highway, rail, and waterway routing networks.

Routes are modeled using both inherent network features for the underlying modal networks, and by user defined constraint parameters. These parameters are expressly designed to incorporate some of the route selection criteria established by federal regulations. Other constraints can be applied post-solution by users when weighing the costs and benefits of alternative routes against the criteria.

One particular advantage of the WebTRAGIS system is its incorporation of a highly detailed population database, LandScan USA.[11] LandScan has a highly detailed population distribution model that allows WebTRAGIS users to get highly detailed population count measures within 800m for any route solution within the contiguous United States at a resolution of 3 arc seconds (~90m).

ROUTING UNDER CONSTRAINTS IN WEBTRAGIS

As noted, TRAGIS incorporates a constrained Dijkstra algorithm when determining paths on the networks. The algorithm specifically calculates routes by minimizing impedance over the route, where impedance is a function of time and distance for each link. The basic routing formula is defined as

$$L = Min \sum_{i} (\alpha D_i + \beta T_i) \qquad (1)$$

where

L = total impedance of a route;
α = distance bias;
D_i = distance of segment *i*;
β = time bias;
T_i = time required to travel segment *i*.

Within this basic format additional route parameters and biases can be selected by the user to further constrain the route calculations. These may include constraints on time or constraints based upon the underlying features of the selected modal network. For example, for the highway mode WebTRAGIS defaults to using a network that conforms to the Highway Route Controlled Quantity (HRCQ) regulations. As a result, the network of possible links itself is constrained. Similar constraints can be employed for standard hazardous materials routes or radioactive restricted routing options that limit or constrain the underlying network of links.

Railroad Routing

Routing on the railroad network is of particular interest in the case of SNF. DOE has stated in the regulations that rail is its preferred mode, a position that was supported by the conclusions of the Committee on Transportation of Radioactive Waste of the National Academies of Science in 2006. [12] As a result, the railroad network within WebTRAGIS has received the most attention and is the most detailed operational model of all three transport modes.

Due to the operational structure of the US (and North American) rail network, the routing options available to WebTRAGIS users differ substantially from those available for highway routing. Railroads operating in the US are essentially privately owned and operated, yet because of their quasi-utility status as territorial monopolies, the railroads face a regulatory environment that requires them to accept hazardous materials shipments for originating and terminating locations on their networks. DOE has expressed the desire that SNF shipments be operated by DOE crews and trains that will run in a manner that might best be described as "network neutral" in which the ownership characteristics constraining routes on the overall network are attenuated.

The WebTRAGIS model determines rail routes by simulating the actual routing practices of US railroads as closely as possible. The basic algorithm solves the shortest least-impedance path biased by rail network features such as ownership, traffic density, track class, and signal system. In general, the network properties bias routes to stay on rail main lines with the best signal systems and the highest grade of track. Under previous versions of TRAGIS, the biases focused primarily on traffic densities expressed in gross ton-miles to determine a hierarchy of links within the network. Recently, ORNL has modified the algorithm to use track class (track class determines allowable track speed and is an indicator of the quality of the track) as the primary biasing element of the network when determining routes. Railroad ownership, and penalized transfers between railroads, biases the algorithm to keep routes on the originating railroad as long as possible before transferring to another railroad to complete the route. These features mirror the actual process of rail routing in which the originating carrier keeps the shipment in possession as long as possible in order to maximize revenue ton-miles.[13]

While the basic routing algorithm incorporates several network-determined constraints, WebTRAGIS also allows for several user-determined constraints to be applied. The user-determined options for rail allow for either, a) the standard rail routing algorithm which is the default routing option, or b) a dedicated train option that attenuates ownership biases and seeks to be network neutral and conform to DOE routing preferences. Option b) reduces railroad ownership biases and transfer penalties. With these constraints either in place, or relaxed, the WebTRAGIS algorithm then determines the lowest impedance path from origin to destination. A final user-determined constraint is the ability for users to block or restrict particular elements from the possible route set. Originally this was done by direct entry of links or nodes to remove from the solution set. ORNL has modified this methodology and users may now block both nodes and links by selecting a bounding box in the WebTRAGIS user interface. This allows users who may not be familiar with the specific node names or link id's to apply blocking to the network. In doing so, they can replicate some regulatory routing criteria and generate alternate routes.

Constraints and Regulatory Criteria

A major issue when determining the preference of routes is the incorporation of regulatory criteria in the routing algorithm or a post-generation assessment. Criteria can be applied either before a route is calculated in the form of biases or constraints, or after routes have been generated as means of assessing the appropriateness of routing solutions. WebTRAGIS has opted to minimize the applicable constraints in order to improve route solution performance of the algorithm. In this manner, routes and alternates can be generated quickly for subsequent analysis[1].

SOLUTIONS AND ROUTE RESULTS

In the wake of the recent Blue Ribbon Commission on America's Nuclear Future, attention has been focused on the SNF in storage at the various decommission reactors or "orphan" sites around the US[14]. This study examines route solutions under some of the user and network constraints modeled by WebTRAGIS. For purposes of illustration, the designated destinations are Oak Ridge National Laboratory in Tennessee and the Savannah River Site in South Carolina[2]. The designated origin points are Crystal River nuclear plant in Florida and San Onofre nuclear plant in California. The routes as presented will provide an illustration of how application of different constraints alters route solutions. One result is that routes may have radically different path solutions depending on the regulatory constraints and biases applied. In some cases these routes may be regulation compliant, but operationally suboptimal.

Highway Routing and Results

As a first example of highway routing, a route is generated from Crystal River nuclear plant to ORNL (Fig. 1). Subsequently a route with the HRCQ restrictions is generated (Fig. 2) and the route results are then compared in TABLE I. The results presented are summaries of distance (in miles), impedance, travel time, and a count of population within 800 meters of the route based upon LandScan population calculations. WebTRAGIS provides detailed output of route links, population counts by link, associated population densities by link, and critical infrastructure such as schools, nursing homes, day care centers, hospitals, police, and fire stations to users.

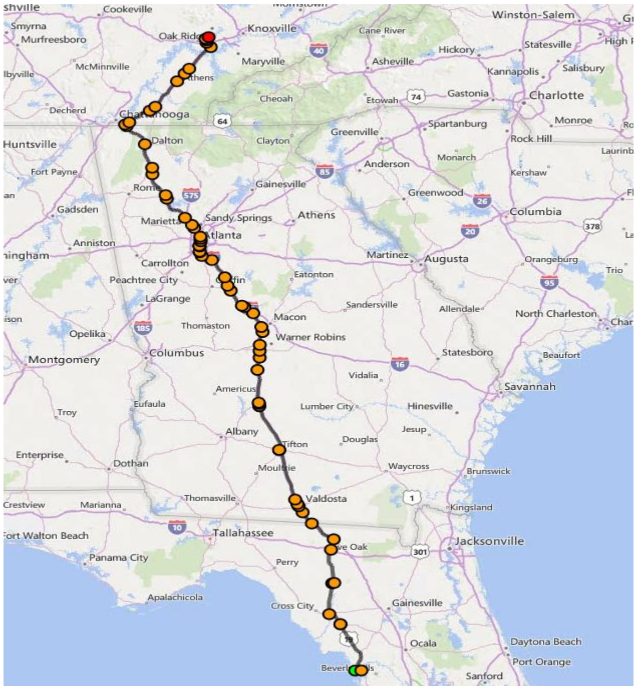

Fig. 1. Commercial highway route, Crystal River to ORNL

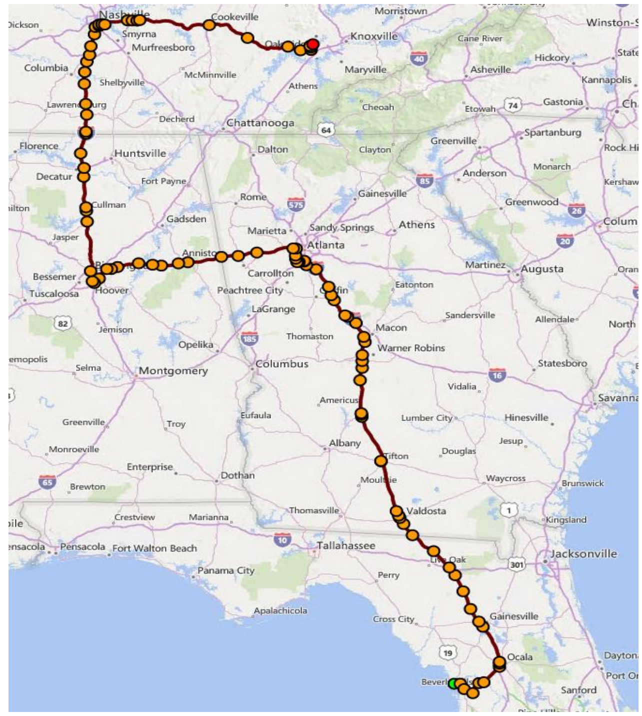

Fig. 2. HRCQ highway route, Crystal River to ORNL

TABLE I. Comparison of Route Result Summaries.

Route Type	Dist.	Imped.	Time	Population
Commercial	572.7	555.8	9:38	513,063
HRCQ	896.7	2349.2	23:20	495,317

As can be seen in both the figures and the table, the HRCQ routing constraint alters the route solution considerably as the constraint forces routes to use HRCQ designated links. Route length increases by over 56%, and the travel time more than doubles. However, total potential population diminishes slightly by ~3.5%.

Rail Routing and Results

Rail routing is subject to fewer constraints than highway, primarily due to the relative fixity of rail capital infrastructure and the absence of much operational redundancy in the network structure. While this improves rail operational efficiency, it limits the numbers of possible east-west or north-south movements. The most common feature in WebTRAGIS that defines the route under normal operations is the originating railroad bias. This constraint biases the routing to stay on the originating railroad as long as possible before transferring to another railroad by preferencing the originating railroad network through a reduction in the impedance and penalizing transfers through increases in impedance.

For example, Figure 3 provides a view of a rail route from San Onofre nuclear plant in California to ORNL. The originating rail carrier is BNSF. BNSF maintains control of the shipment on their network until it reaches Memphis, Tennessee. At this point, the BNSF network has reached one of its eastern termini and must transfer the shipment into the custody of another railroad, Norfolk Southern (NS) who will carry the shipment across Tennessee and then transfer custody to the railroad that will make the final delivery of the car to ORNL, CSXT.

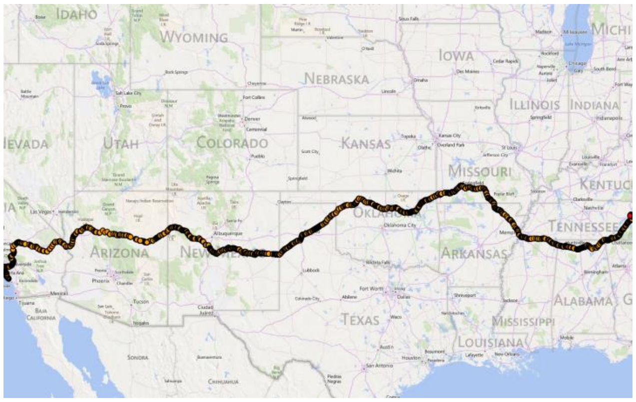

Fig. 3. Standard rail route from San Onofre to ORNL

However, if route planners want to generate a route solution that aligns more closely with the stated DOE preference of DOE trains operating over the most efficient or shortest path on the entire network, then the dedicated train option would be selected. This option removes the originating railroad bias and reduces transfer penalties between railroads. As a result, this relaxation of the constraints most closely resembles a pure Dijkstra algorithm solution on the network graph.

Figure 4 provides an example of how this “network neutral” constraint relaxation potentially alters the route solution. Here, under the dedicated train parameters, the route originates on the BNSF network, but transfers to the UP system while still in the greater Los Angeles area and then travels to Memphis where it transfers to the NS network and then to Harriman, Tennessee to switch onto the CSXT network for final delivery to Oak Ridge.

Fig. 4. Dedicated rail route from San Onofre to ORNL

TABLE II provides a summary of the differences in the two route solutions. The standard route is slightly longer, but the estimated time of transit and population counts are lower. In this case, a shorter trip distance results in a higher population exposure. This simple example serves to illustrate that tradeoffs between regulatory criteria are highly likely when the dimension s of the physical network itself constrains the available routing options.

TABLE II. Comparison of Rail Route Result Summaries.

Route Type	Dist.	Imped.	Time	Population
Standard	2547.3	3232.5	52:53	2,515,428
Dedicated	2410.4	2928.4	60:15	2,865,983

Applying Regulatory Criteria

If a user desires to generate a route that seeks to avoid selected areas of concern such population, or iconic targets, or environmentally sensitive areas, particular links and nodes can be blocked. As a result, those links and nodes are removed from the potential route solution set. In WebTRAGIS, this feature has been provided as a bounding box drawn on the map layer screen. Any network features lying within the bounding box are removed from the possible solution set. A major factor in rail routing is that many of the track segments with the highest grade of track, the best signaling systems, and other desirable network properties are located in or near major US population centers. Several large metropolitan areas in the US also serve as major interchange locations between eastern and western railroads including Chicago, St. Louis, Kansas City, Memphis, and New Orleans. As a result, blocking particular areas because of the presence of iconic targets, public venues or high population counts, may lead to either inefficient rail routing outcomes, or even routes that cannot be completed because the constraints imposed sever the connectivity of the network.

To illustrate a simple case of how blocking based upon a set a or criteria works we provide the example of a route from Maine Yankee nuclear plant near Wiscasset, Maine to DOE’s Savannah River Site (SRS) in South Carolina. Both the standard route and the dedicated route are identical in this case. The route passes through many of the major metropolitan regions of the eastern US such as the greater New York City area, Philadelphia, Baltimore and Washington, DC. This route is illustrated in Figure 5.

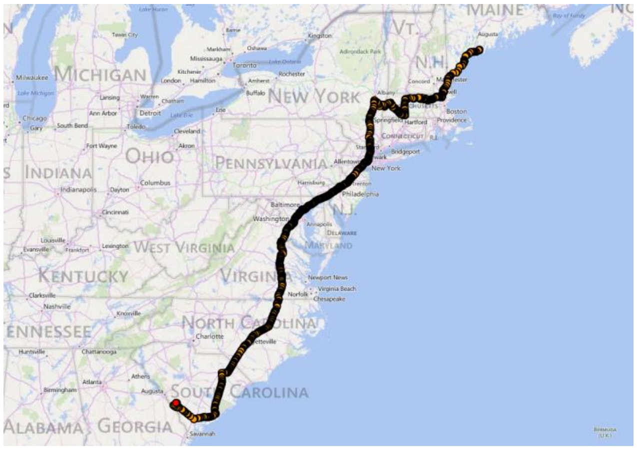

Fig. 5. Route from Maine Yankee to SRS – no blocking

In recent years, there have been concerns about hazardous materials traveling through the US capitol including attempted bans, and calls for hazardous materials to be routed around the DC metropolitan area. [15] In order to illustrate the impacts on route solutions by blocking a metropolitan area due to a combination of public venues, iconic targets, and population, we have chosen to examine the case of blocking the DC area from the possible solution set. A detail of the original route, along with a blocking box is given in Figure 6.

The resulting route is illustrated in Figure 7. The route is identical to the original route until it reaches Philadelphia. At this point it then heads west before again turning south to avoid DC. The route continues on a parallel path to the west of the original route until it approaches the vicinity of SRS. Differences between the two routes are summarized in TABLE III.

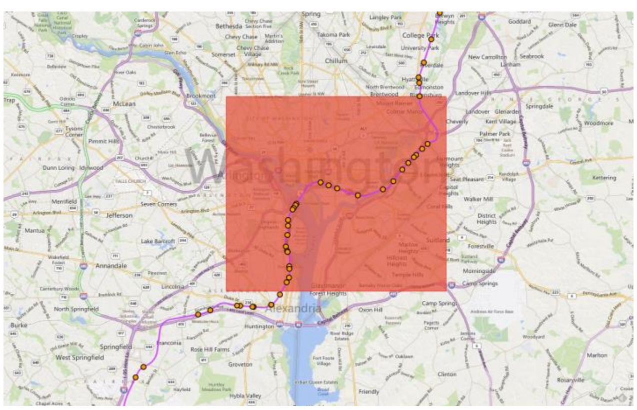

Fig. 6. Detail of DC Metro area with blocking box

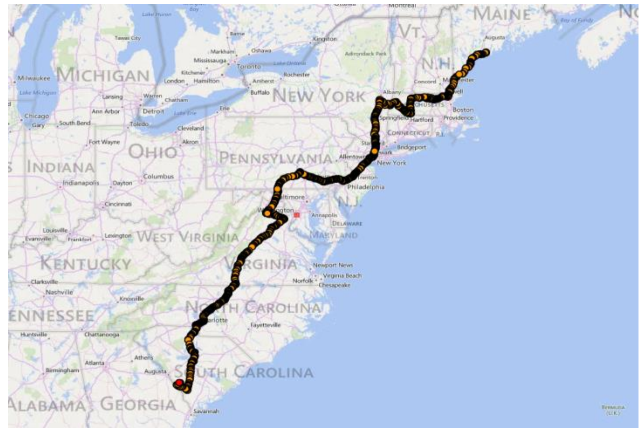

Fig. 7. Route from Maine Yankee to SRS – DC blocked

TABLE III. Comparison of Maine Yankee route results.

Route Type	Dist.	Imped.	Time	Population
Unblocked	1345.5	2184.9	41:55	4,461,602
Blocked	1447.9	2370.5	55:34	4,274,965

In this instance, blocking the Washington, DC area might be a viable consideration as total population along the route is minimized and the additional distance and time in transit might be viewed as acceptable trade-offs in relation to minimizing proximity to iconic targets in the capitol. However, if similar constraints are also applied to other metropolitan areas such as Philadelphia or Newark, then route solutions may become less efficient. For example, if Philadelphia and Newark (effectively the Northeast Corridor) are also blocked, the route from Maine Yankee to SRS shifts further west into central New York state and Pennsylvania before conforming to the first route blocking Washington. As can be seen in TABLE IV, this route further reduces population along the route as it now avoids many large population centers. Distance also decreases slightly, but time in transit increases implying that the railcars are going through more yards and facing more potential for delays. These delay and stoppage in transit indicators could then call into question the need for additional route security which may increase shipments costs.

TABLE IV. Comparison of Maine Yankee route results.

Route Type	Dist.	Imped.	Time	Population
DC Blocked	1447.9	2370.5	55:34	4,274,965
NEC Block	1415.0	2594.3	62:20	2,579,316

CONCLUSION

This study has briefly introduced the WebTRAGIS implementation of a constrained Dijkstra algorithm for use in routing SNF in compliance with many aspects of federal regulations governing such shipments. In doing so, the impacts of different constraints, or their relaxation, upon route solutions has been demonstrated. Further, the study points toward the complexities involved in weighing the various trade-offs inherent in complying with the applicable regulations. The WebTRAGIS system allows users to have an accurate platform employing specific constraints while allowing users to apply their own judgment or criteria in selecting appropriate routes.

ENDNOTES

1. A recent ORNL study [16] involved solving multiple possible route solutions from the orphaned sites to possible intermediate storage facility locations. As part of a multi-integer linear program (MILP) framework using multiple constraints and an explicit cost function, the WebTRAGIS algorithm was able to solve over 120,000 routes using GUROBI on a single-node computer in ~2 hours.
2. The ORNL study [16] found that ORNL was an optimal location if one intermediate site was to be built. SRS is also within the optimal solution set and has both the necessary infrastructure to handle shipments via multiple modes and experience in handling a variety of radioactive materials in transport.

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