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Strategic Freight Transportation Analysis

A Framework for Modeling Rail Transport Vulnerability

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Abstract

Railroads represent one of the most efficient methods of long-haul transport for bulk commodities, from coal to agricultural products. Over the past fifty years, the rail network has contracted while tonnage has increased. Service, geographically, has been abandoned along short haul routes and increased along major long haul routes, resulting in a network that is more streamlined. The current rail network may be very vulnerable to disruptions, like the failure of a trestle. This paper proposes a framework to model rail network vulnerability and gives an application of this modeling framework in analyzing rail network vulnerability for the State of Washington. It concludes with a number of policy related issues that need to be addressed in order to identify, plan, and mitigate the risks associated with the sudden loss of a bridge or trestle.

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Introduction

The railroad system in the United States represents the combination of hundreds of individual companies and their tracks and rolling stock. Altogether, the rail system hauls about 30% of the nation's freight (as measured in ton-miles). The bulk of the rail-bound freight is hauled by a few large railroad companies. The trackage in the US falls primarily within companied owned rights-of-way. Some of the rights-of-way were granted as an inducement in the late 1800's for companies to build and expand railroad operations. Beyond the original land grants, railroads have provided service without major subsidies, however, recent legislation may allow railroads a tax credit for infrastructure investment as an inducement to expand capacity. Hauling freight by rail is approximately three times more efficient than hauling by truck in terms of energy used. Rail also generates three times less pollutants per ton mile than truck. Thus, rail maintains significant advantages over truck when hauling over long distance (Morlok 1995).

In March 15, 2007 the Union Pacific (UP) railroad experienced a trestle fire in Sacramento, California. This trestle was built in order to raise the tracks above several street crossings. The cause of the fire has been classified as arson. The structure was built of creosote treated timbers and the fire was nearly impossible to put out. The trestle was considered a total loss. Although this structure was only 300 feet long, it required a major effort to rebuild the structure in a timely fashion. While the structure was inoperable, most trains were rerouted; the detour resulted in adding a distance of 125 miles to impacted routes. Even passenger trains operated by Amtrak were rerouted. Local rail traffic was rerouted along a link that had a number of at-grade crossings, resulting in additional congestion in downtown Sacramento. This relatively minor act of arson demonstrated that a strike against a rail asset can have significant impacts on the company and the public. It should be stated that the company bore all costs of rebuilding this trestle as well as faced added operation costs associated with the lengthy detours.

The service provided by rail is of significant value to the public in general (Wallace 1963). The US Department of Transportation has estimated that congestion in major cities would increase significantly, if just the intermodal traffic at ports that is normally handled by rail was offloaded to trucks (intermodal traffic entails container cargo that arrives at marine terminals and is placed directly on rail or transported a short distance to a rail terminal, and systems where containers or truck trailers are loaded onto rail for the long haul portion of a transport). Without rail transport, costs of shipping major commodities like coal, grain, chemicals, and automobiles would increase substantially (Wallace 1958). Thus, the direct loss of a rail asset could have far reaching impacts on the public as well as the operating railroad. This paper deals with developing a modeling framework for estimating the impacts of the loss of a rail asset to the operating railroad. Although the direct or indirect impacts to the public associated with the loss of a rail asset due to an intentional strike may be significant in itself, this problem is left for future research.

Railroad operations are regulated by the federal government. Many attempts by states to regulate railroad specific activities, *e.g.* limit air pollution, have been successfully thwarted in the courts by railroads, due to long standing federal legislation on interstate commerce. Regulation, in general, involves issues relating to the safety of the operation, in terms of the tracks, signals, switches, maintenance of the rolling stock (especially braking systems), as well as specific issues of calculating tariffs, like the manner in which fuel surcharges are calculated and passed on to customers. Although substantial regulation and policy does exist associated with railroads, this paper deals with a topic that falls outside most existing legislation: the impact of intentional harm directed to the assets of a railroad company. In the next section we provide a short discussion in terms of the operations of a railroad. Given this, we then develop a framework for modeling the impacts to a railroad in terms of the possible loss of an asset, like a bridge or tunnel. We then apply our framework to a scenario involving the impact on freight flows in the State of Washington, associated with a loss of a bridge in Sandpoint, ID. Finally, we focus our attention on policy related issues as well as problems for future research.

Background

Railroads compete for freight transport among themselves as well across other modes like truck and barge. For example the two largest railroads in the western states are the Union Pacific (UP) railroad, and the Burlington Northern and Santa Fe (BNSF). These two rail lines are the principal competitors for rail service originating in the State of Washington (the area chosen for the application of our modeling framework). Each operates a system of tracks that lie west of Chicago, St. Louis, and New Orleans. The UP maintains approximately 27,000 route miles of main line track and another 19,000 miles of yards sidings and track rights on other lines. BNSF operates 23,000 miles of main line track and uses about 9,000 miles of track through agreements with other lines. BNSF and UP own or lease more than 6,300 and 8,500 locomotives respectively. UP controls through ownership and lease agreements some 105,000 railcars of various types and BNSF owns or leases more than 85,000 cars. Such assets are necessary to carry a considerable fraction of the rail freight originating from the western states. Although these two companies compete against each other for business across much of the western United States they do share with each other certain track rights. For example, BNSF can route their trains on UP tracks leading from Sacramento, California to Denver, Colorado. Outside of specific track rights agreements, rail lines are confined to their own track. Track rights allow a company to operate a train on another company’s track using their own equipment and crew.

Like all railroads, UP and BNSF keep a shipment on their tracks as long as possible before handing it off to another shipper. They eventually will have to hand off a shipment if is destined to a point outside their service area. For example, a shipment from Seattle to Miami starting out on UP will probably be handed off to the CSX railroad in Memphis, Tennessee, which is at the eastern edge of the UP service territory. The objective for a railroad is to make as much of the transport of a given shipment on their own trackage, before handing it off to another company.

Considerable research and development has been invested in increasing operating efficiencies of rail, based on models of train building, routing, and scheduling (see for example: Hesse and Rodrigue 2004; Ballis and Golias 2002; Barnhart et al. 2000; Aril, et al. 2007; Assad 1980a). It is important to note, that some routes exist where operations are at capacity or close to capacity, and increasing traffic on certain routes will not be possible without reducing average velocities, or adding capacity (e.g. developing sections of dual track for trains to pass heading in the opposite direction). One of the objectives of such systems models has been to increase the effective capacity of tracks by improved operations (like train building), scheduling and network improvements. For example, as UP increases its dual track elements along the Los Angeles to El Paso route, it plans to increase capacity from 50 trains a day to more than 80 trains a day. This means that if a disruption occurs on a route for a given railroad, that that railroad may not have the capacity to handle the freight along an alternate route. This also means that if the alternate route is subject to track usage agreements, then other railroads may also be impacted. This issue will be discussed more in the modeling section of this paper.

Given that rail companies handle 30% of the freight in the US, it is important to understand the impacts of a major disruption, be it natural or man-made to an element of the system. Since the rail network is extensive and handles such large volumes, there may well exist critical components, which if lost due to some disaster or intentional strike, might curtail rail some services and routes. Do bridges or tunnels exist that justify added protection by the railroad or by public agencies? Such questions should be addressed in order to plan and ensure that such services are not compromised to the extent that significant harm to the economy and the public results from a potential disaster that could be averted. In the next section we propose a framework for modeling the impact of the loss of a bridge or a trestle on the rail network. Given this framework, we will then apply it for a scenario involving freight service to the State of Washington.

A modeling framework for analyzing impacts of interdiction to a rail network

The possible impacts of a lost bridge are numerous. Table 1 lists only a few of these issues, beginning with the cost of replacement. For many of these issues, public action may be warranted. For example, if a commuter rail route is impacted, it may be necessary to increase bus transit services to handle affected commuters. For most circumstances, the primary impact of a lost bridge will fall on freight movements. Freight needs to be rerouted if possible. In some cases, a detour might not exist. For example, if a trestle failure occurred along a branch line to a coal field, then all coal transported from that area would be interrupted. In the case of a coal-source branch line, there probably would not exist alternate transport modes of sufficient capacity to handle such sizable demand. Identifying critical components of networks has been the subject of a significant amount of recent research (see for example, Murray and Grubesic 2007), however little attention has been directed towards identifying critical elements of a rail network. The objective of this paper is to present a framework for strategically analyzing specific losses to the rail system, as it operates in the US.

To estimate the possible impacts of a scenario involving the loss of one or more bridges would require the capability to identify alternate routes, identify problems of capacity in handling increased flows on alternate routes, and model impacts, direct and indirect. To do this on a national scale, cutting across railroad jurisdictions requires a number of simplifying assumptions. It should be recognized that to model the impacts to all railroads in terms of the loss of a trestle, one must model the system as a whole and not by individual railroads. One can think of this as a strategic-level problem, in which the major objective is to estimate the impacts of a sudden loss of a bridge or tunnel across the railroad network, without addressing specific operational issues, *e.g.,* scheduling. It is also important to recognize that it is impossible to model all of the intricacies of the process used to build trains and schedule them across a network and remain practicable for high level strategic planning. The idea is to represent the problem in an aggregate form so that it captures the sense of operation patterns without the immense amount of detail used in day to day operations. Thus, one can think of the railroad problem as a network flow problem involving a network of nodes and arcs (G(N,A)), where G is the network, N is the set of nodes and A is the set of arcs or track segments. Most nodes on the network are locations of switches, where one track segment becomes split into two tracks, or where two track segments are joined into one track segment. Switches allow a train to change tracks and possible direction. Sidings represent places where a switch from the main track allows cars to be delivered to a destination for unloading. Nodes can also be placed along sidings to represent locations for unloading cars, lifting containers, etc. We will designate O as the subset of nodes, which represent points where freight originates. Similarly, we will designate D as the subset of nodes which represent delivery locations, or destinations.

The problem of freight routing can be viewed in two principal ways. First, we can view each freight movement as a single shipment starting at location *s* and ending destination *t*, where *s* and *t* are nodes of the network. Although looking at a shipment (say a carload) by itself is somewhat unrealistic, we can still capture enough detail so that the information obtained from a single shipment routing model is useful. We will discuss this idea at greater length after we present this model.

Consider the following notation:

$i, j =$ indices used to refer to nodes of G

$A = \{(i, j) \mid \text{ a track exists between nodes } i \text{ and } j \}$

$$x_{i,j} = \begin{cases} 1, \text{ if the freight is transported along arc } (i, j) \in A \\ 0, \text{ if otherwise} \end{cases}$$

$d_{i,j} =$ the distance along rail link $(i, j) \in A$

$c_{i,j} =$ special cost factors for rail link $(i, j) \in A$, e.g. added fuel factors for grades, useage rights, etc.

$r =$ the index of the railroad company that handles the initial transport leg.

$A_r =$ the arcs in the rail system used by company r, through ownership or track rights

$A_m =$ the arcs in the rail system that are classified as mainline

$A_t^r =$ the arcs that connect tracks used or owned by company r to another company

$I_t =$ impedance factor for transfering freight to another rail comapny

$I_m =$ the impedance factor for routing along arcs in the rail system that are not mainline

$I_d =$ the impedance factor for routing along arcs after transfer to another company

$I_c =$ the impedance factor for special costs, like added fuel needs for grades, etc.

We can then structure a simple routing model (SRM) in the following manner:

1) $$Min\ \ Z = \sum_{(i,j)\in A} d_{i,j}x_{i,j} + \sum_{(i,j)\in A_t^r} I_t x_{i,j} + \sum_{(i,j)\in A-A_r} I_d d_{i,j}x_{i,j} + \sum_{(i,j)\in A-A_m} I_m x_{i,j} + \sum_{(i,j)} I_c c_{i,j} x_{i,j}$$

2) $$\sum_{(s,j)\in A} x_{s,j} = 1 \quad \text{for origin } s$$

3) $$\sum_{(i,j)\in A} x_{i,j} \ - \sum_{(j,k)\in A} x_{j,k} \ = \ 0 \quad \text{for each node } j \in N, \ \text{where } j \neq s,t$$

4) $$\sum_{(i,t)\in A} x_{i,t} = 1 \quad \text{for destination } t$$

5) $$x_{i,j} \in \{0,1\} \quad \text{for each arc } (i,j) \in A$$

The SRM model is a form of the classical shortest path problem (Dijkstra 1959; Belman 1959; Dreyfus 1969). The objective is to find the path that minimizes the sum of impedance and distance values for originating railroad *r*. The constraint set ensures that the arcs chosen for the route form a path that is continuous, starts at node *s*, and ends at node *t*. Constraint (2) ensures that the path starts at node *s*. Constraint (4) specifies that the path ends at node *t*. Constraints (3) specify that for any intermediate node (a node other than the origin or destination) that: if the path enters an intermediate node, it must also leave that intermediate node. If all of the impedance factors are set to zero in value (i.e. $I_t = 0, I_d = 0, I_m = 0,$ and $I_c = 0$), the above model would identify the shortest path connecting node *s* to node *t*. This technically could be the most efficient route with respect to the customer or the public. But such a route might not be very feasible as freight is handled when possible on mainline links. To encourage a route to use mainline arcs as much as possible, the impedance factor, I_m , can be made positive. Although, such a strategy would lead to a feasible route, it does not mimic how a railroad company routes a shipment. The idea is that a company will try to keep the freight in their hands for as much of the route as possible, before handing it off to another company. Thus, a company will try to route along their tracks or tracks with rights of use as long as possible. This property can be encouraged by having a positive impedance value, I_d , which places an extra cost to routing along tracks outside railroad company *r*. Since routing on track outside of company *r's* purview is all weighted the same, the route chosen will be relatively efficient (not necessarily the shortest), but maintain the greatest portion of the route along the tracks of company *r*. Additionally, impedance weight, I_t , can be used to minimize transfers. In this case, if a route can be accomplished entirely on company r's tracks, even though longer than perhaps necessary, this impedance will encourage the selection of this route. Thus, with the right selection of impedance values, the above model can be used to select routes that mimic choices made by company *r*.

Once the SRM model has been solved for the originating railroad, *r* , either the shipment has been accomplished entirely on company *r's* tracks or it has not. If the freight is handed off to another railroad, then technically the SRM should be solved again for the next company starting at the point of the handoff from company *r*. Thus, the SRM model should be solved successively, in the order of each rail company handling the freight until it has arrived at the destination node, *t*. Since the SRM is a special form of the shortest path problem, it is easy to program a shortest path algorithm with the nuances associated with SRM. Large networks will pose no problem in solving SRM, as state-of-the-art shortest path algorithms are easily capable of handling hundreds of thousands of nodes and arcs. The basic idea underlying SRM is well established in the literature (Lansdowne 1981; Bronzini 1983; Southworth 2003). The above formulation represents a form of a model that has been developed by Oak Ridge National Laboratory (Johnson 2006) called the Railroad Routing and Visualization Analysis (RRVA) module. This module is an extension of the Transportation Routing Analysis Geographic Information System (TRAGIS) of ORNL.

The SRM model then can be solved for a given freight shipment going from *s* to *t* using RRVA. SRM does not address, however, possible capacity issues or congestion. So, the answer for this model would be an optimistic estimate of the route in terms of distance and impedance factors, as congestion factors may make shipments longer and slower in transit time, as the best alternate route may be unavailable. Given this caveat, SRM is useful as it represents a lower bound on the length and impedance factors of a selected route (as the actual route given capacity issues will be the same or even longer). We can then use the SRM model to estimate a lower bound on the impact of a lost bridge or tunnel along arc *(f,g)* by the following procedure:

Step 1: identify all OD pairs for freight shipment. Initialize set $IR = \text{empty}$. Set IR represents the shipments which will be impacted by the loss of arc *(f,g)*.
Step 2: for each OD pair, solve the SRM model to identify the most likely route. If this route uses link *(f,g)* add the OD pair to the set, IR.
Step 3: for each OD pair in the set, IR, solve the SRM model where cost of using link *(f,g)* is set at a prohibitively high value. Track the cost and route associated with this "detour" route.
Step 4: for each OD pair in set, IR, compare the consequences of not being able to use link *(f,g)* with the existing routes.
Step 5: summarize the impacts associated with all detours due to the loss of link *(f,g)*

This five step process involves using the SRM before and after a bridge or tunnel failure, calculating the impacts for all freight OD pairs that would have normally used the bridge or tunnel. By summarizing impacts on all of the affected routes, we would then be able to estimate a lower bound on the impact of the loss of an asset. Figure 1 depicts this process. Given appropriate data from the network and freight statistics (1), we can use a simple routing model (2) to identify affected shipping routes, before and after interdicting an element of the network. These routes and impacts can then be visualized in module (3).

We know that using the SRM model iteratively, once for each OD pair, is a bit simplistic, but it is useful in that it can capture many of the impacts associated with a lost bridge or tunnel. The simple fact is that congestion can happen in a rail network, and detours may need to circumnavigate links already at capacity or nearing capacity. We can design a model which can estimate the impacts of congestion in the following manner. First, we need to be able to route shipments for each OD pair as a separate commodity, thus creating what would be termed a multi-commodity flow problem. Consider the following added notation:

$x_{i,j}^{s,t} =$ the number of rail cars trnsported between s and t along arc (i, j)
$a_{s,t} =$ the number of railcars being shipped between s and t during the time period

$Cap_{i,j}$ = capacity in railcars being shipped along arc (i, j) during time period

$a_{s,t}$ = the number of railcars being shipped between s and t during the time period

The decision variables are now extended to represent shipments between each OD pair, designated as *s* and *t*. Rather than identifying a path, we need to route freight as the number of carloads needing to be shipped between a specified OD pair. Thus, the routing of freight volumes across the network can be described as the following minimum cost multi-commodity transshipment flow model (CMRM):

$$6)\quad Min\ \ Z = \sum_{\substack{(i,j)\in A \\ (s,t)\in OD}} d_{i,j}x_{i,j}^{s,t} + \sum_{\substack{(i,j)\in A_t^r \\ (s,t)\in OD}} I_t x_{i,j}^{s,t} + \sum_{\substack{(i,j)\in A-A_r \\ (s,t\in OD}} I_d d_{i,j} x_{i,j}^{s,y} + \sum_{\substack{(i,j)\in A-A_m \\ (s,t)\in OD}} I_m x_{i,j}^{s,t} + \sum_{\substack{(i,j)\in A \\ (s,t)\in OD}} I_c c_{i,j} x_{i,j}^{s,t}$$

$$7)\quad \sum_{(s,j)\in A} x_{s,j}^{s,t} = a_{s,t} \quad \text{for origin } s \text{ and each } (s,t)\in OD$$

$$8)\quad \sum_{(i,j)\in A} x_{i,j}^{s,t} - \sum_{(j,k)\in A} x_{j,k}^{s,t} = 0 \quad \text{for each node } j \in N, \text{ and } (s,t)\in OD \text{ where } j \neq s,t$$

$$9)\quad \sum_{(i,t)\in A} x_{i,t}^{s,t} = a_{s,t} \quad \text{for destination } t, \text{ where } (s,t)\in OD$$

$$10)\quad \sum_{(s,t)\in OD} x_{i,j}^{s,t} + x_{j,i}^{s,t} \leq Cap_{i,j} \quad \text{for each arc } (i,j)\in OD$$

$$11)\quad x_{i,j}^{s,t} \in \{0,1\} \quad \text{for each arc } (i,j)\in A \text{ and } (s,t)\in OD$$

This Capacitated Multiple Route Model (CMRM) maintains a number of features found in the SRM, except all OD route assignments are calculated simultaneously in contrast to handling route assignments one at a time using the SRM. It uses the similar impedance functions to mimic route choice as before. The main added feature is that an upper capacity for freight handled along each arc is maintained across all shipments. Such capacities can be estimated along specific routes in terms of the number of trains that can be handled per unit time period, e.g. 50 trains per day from LA to El Paso, times the average size of a train in rail cars times a balance factor representing capacity that is used to reposition empty rail cars. It should also be pointed out that in the short run, capacity along a route is also constrained by the number of available crews that are qualified to operate a train along the route. Additional demand along a detour may be difficult to handle unless enough qualified crews are available. Constraints for building trains in hump and switching yards can be maintained in terms of an upper limit on cars entering or leaving a yard area. It may be necessary to add such conditions as “side constraints.”

Modeling transport as a multi-commodity network flow problem has been proposed by a number of researchers (see for example, Crainic and Rosseau 1986), although its use in rail transportation is rare or non-existent, as the emphasis for rail modeling has been placed on operations level problems, like train blocking, hump yard operations, and train scheduling (Abril, et al. 2007; Assad 1980a, 1980b). Detailed reviews of the literature in railroad modeling can be found for earlier work in Assad (1980a) and recent work in Abril et al. (2007). Most rail operations models are designed for day-to-day operations, and not modeling an entire sector at a strategic level.

The main problem with the CMRM is that it “pits” one railroad against another, in terms of achieving overall network efficiency. To give complete autonomy to each railroad would mean that the flows for each company should be solved separately by using the above model applied to the network, optimizing estimated flows handed off to them from other railroads as well as optimizing flows for those shipments originating on their network, where arcs outside of their ownership or track rights would be un-capacitated. Thus, the model could be solved from the perspective of each railroad. Solving such a series of models before and after a bridge is removed from the network would generate an estimate of the impact on the loss that bridge in terms of additional impedance and distance, within capacity limits.

Although the application of CMRM would generate a more realistic bound on the impact of a lost asset, there are several difficulties to overcome. First, the size of the rail network is very large and the number of OD pairs is large as well, creating a very large optimization model that is outside the limits of commercial optimization software. To solve this problem will require the development of a heuristic solution strategy. Second, publically available data sets do not contain capacity values. To make use of a model like the CMRM, it is necessary to add or generate capacity values for primary elements of the system, including hump yards, track routes, etc.

It needs to be emphasized that the CMRM is a simple abstraction of the rail system, just as the SRM. Both models do not handle the specifics of building or scheduling trains, but are useful abstractions in terms of estimating basic routes and detours should parts of the rail network be destroyed. Figure 1 gives a flowchart for a framework for modeling the impacts of the sudden loss of network components of a rail network, based upon the SRM and CMRM models. To support these models detailed rail network and demand data is necessary. From network and demand data, it is possible to then use the SRM model as described above in the five step process to measure the impacts of changes in the rail network. The output of the model should then be presented as a set of maps and tables (module 3 of framework). More detailed capacity analyses can be done by generating estimates of network capacity in module 4 and then using a model like CMRM to solve for routes that are sensitive to capacity restrictions (module 5). Results from modules 2 and 5 can then be used to model impacts outside of the rail system, *e.g.* additional demand for trucks, impacts on fuel demand, etc. Altogether, such a framework can help assess many of the important issues and factors itemized in Table 1. In the next section, we present an application of this framework using the SRM model in analyzing the impacts due to a loss of a bridge in Sandpoint, ID on the freight traffic starting or ending in the State of Washington.

Application of modeling framework for freight routing to and from the State of Washington

The data for this study comes from the 2000 Carload Waybill survey provided by the Surface Transportation Board (STB) of USDOT. We used waybill information associated with freight shipments originating, passing through or terminating in the state of Washington (RailInc Business Services Division 2003; Wolfe and Linde 1997). While waybill data is available for 2001 and 2002, the year 2000 represents a recent maximum in observation counts (45,483). In order to make the analysis more tractable, the observations were further restricted to originating shipments only. This reduced the number of observations to 19,425.

The carload waybill survey is designed to capture approximately one percent of the total freight traffic moving in the United States in one year. The waybill data provides several items of information valuable for route creation and simulation. The survey provides the origin and destination locations denoted by the Standard Point Location Code (SPLC) maintained by the National Motor Freight Traffic Association. This code specifies the state, county and locality, including rail stations or nodes that originate and/or terminate freight shipments. The waybill survey also includes information on the railroads involved in the shipment from origin to destination, the states that were traversed in the move, and the tonnage involved. The tonnage value is derived from the billed tonnage from the actual waybill that has been expanded using a factor to account for the total number of railcars per year.

Routes were generated using the SRM approach. To solve the SRM model we used software developed at the Oak Ridge National Laboratory (ORNL). This computer model is called the Railroad Routing and Visualization Analysis (RRVA) module (Johnson, 2006), which is an extension of the Transportation Routing Analysis Geographic Information System (TRAGIS) program (Johnson and Michelhaugh 2003) RRVA is a rail-specific extension to TRAGIS and uses a 1:100,000 scale railroad network developed by the Federal Railroad Administration (FRA). This network consists of over 24,000 nodes and 28,000 link segments contained within 97 sub-networks. These networks identify the various railroads, railroad operators, owners and different trackage rights that comprise the available rail track mileage for each US railroad. RRVA's routing system is designed to emulate the SRM model. Routes are determined using a shortest-distance criterion, including impedances which encourage traffic to be routed along mainline segments. The system also minimizes the number of transfers between railroads (i.e. positive I_t value) and it lowers impedances for shipments that stay within the same railroad network.

In order to facilitate route creation in RRVA, the waybill survey data was matched to corresponding rail network nodes in the TRAGIS/RRVA system using the available SPLC. For those nodes that could not be matched initially, a second rail network maintained by the Center for Transportation Analysis (CTA) at ORNL was used (see Peterson, 2003 for a description of the CTA network). If SPLC points could be identified on the CTA network, then approximate locations were then identified on the RRVA network. By using both data sets, we were able to match locations for over 14,500 (75%) of the original waybill observations.

From this final observation set, there were 999 distinct origin-destination pairs among the 14,500+ shipments. These OD pairs were used as input data for the RRVA module, creating 999 routes originating in the State of Washington. Figure 2 illustrates two potential routes for shipments originating in the State of Washington. The first route originates in Seattle and terminates in Chicago, Illinois, while the second route begins in Spokane (Eastern Washington) and ends in Miami, Florida. These routes were created in RRVA by specifying the origin rail node or junction, the originating carrier, and the terminating node and carrier. For these routes, BNSF was the originating carrier. Both routes travel through Sandpoint, ID (location is predicted in Figure 2). Figure 3 illustrates originating shipments from the same location, Ayers Junction, by two different railroads that terminate at the same Chicago junction. Using BNSF, the route travels northeast through Spokane and then through Montana on its way to Chicago. If the shipper were to use UP, the route travels south through Oregon, along the Snake River in Idaho and then through the mid-West to Chicago.

The location chosen for illustrating the effects of an interdiction on Washington State rail transport is Sandpoint, Idaho. This small town on the shores of Lake Pend Oreille in the northern Idaho panhandle is a major channel for trains traveling to and from Washington State and locations east and south. Sandpoint serves as a major junction location for both BNSF, UP, and Rail Link (MRL) operations in eastern Washington. Union Pacific's network does not cross the lake at Sandpoint, but does pass through Sandpoint on a northerly route to Eastport (junction to Canadian Pacific Railway). As BNSF has a more extensive eastern Washington network than UP it provides a good illustration on the full statewide effects of an interdiction on the network. Sandpoint is also a major switching point for trains originating in Canada. While these trains transfer at Eastport, Idaho, much of the switching actually occurs in Sandpoint.

The major physical feature of interest here is the one-mile long BNSF bridge across Lake Pend Oreille. Almost all railcars traveling through Sandpoint will cross this bridge between Sandpoint to the north and Sagle, Idaho on the south shore. We use the possible loss of this bridge to demonstrate the type of results which can be generated using the modeling framework described in the previous section. That is, will the loss of this bridge dictate extensive rerouting distances and associated time delays for traffic originating in the State of Washington?

Of the 999 generated routes, 366 routes used the BNSF bridge traversing Lake Pend Oreille at Sandpoint, Idaho. These routes then constitute the set, IR, defined in the five step procedure. For each of these 366 routes, it is necessary to rerun the RRVA model, where the Pend-Oreille bridge has been effectively removed from possible use. Table 2 compares the distance and impedance on the network for the 366 OD pair dataset. These routes had 50 different origin locations in Washington State and results are presented by origin means and statewide totals. Due to the bridge interdiction at Sandpoint, the average distance traveled per railcar increased by almost 330 miles. Impedances also increased substantially, moving from 2,331 to 2,879 (an increase of over 23 percent). The largest impacts were for railcars originating in Ellensburg, Gibbon and Burlington, with distances increasing over 800 miles and impedances increasing by almost the same. Even in locations that had minimal or positive effects on distance, impedances increased, often due to increasing the number transfers necessary to complete the routes.

Figure 4 provides an illustration of a pre- and post-interdiction route taken from the route data. The route is for a freight shipment of 3,747 tons that originated in Seattle, Washington and terminated at Memphis, Tennessee. The pre-interdiction route (dashed line) covers 2,509.7 miles with an impedance of 2,389.9. The lower impedance results from a minimum number of transfers and the ability for the route to stay entirely on mainline track across the BNSF and MRL networks. After interdiction at Sandpoint, the new route must now head south to Portland, Oregon, through northeastern California and then across the Rockies and on to Memphis (the detour portion of the route is indicated as a doted line). This route stays almost entirely on the BNSF network until transferring to CSX, but the distance traveled has increased to 3,158 miles, over 25 percent. Impedance also has increased to 2,934.3, having been mitigated somewhat by remaining in the BNSF network.

We can estimate the impact of detour costs due to the loss of the bridge by using average operating costs. Wilson and Britzan (2003) estimated average operating costs per ton-mile of 1.557 cents for the year 1997. Operating costs include labor, equipment, fuels, materials and structures, and represent the additional costs to the system from re-routing shipments on the network. The total ton-miles associated with diverting shipments from the interdicted Sandpoint bridge is provided in Table 3. The addition of 87.6 million ton-miles due to rerouting leads to an increase in systemic operating costs of \$1.36 million in 1997 dollars. As the observations represent approximately 75 % of the total originating shipments, the total systemic operating costs would be increased by the remaining 25% and by shipments terminating in Washington State. With these factors included, the total operating cost increases to over \$3.6 million per year. This figure does not include operating cost increases due to shipments that do not cross into Washington State, but may remain or travel through the state of Idaho and use the BNSF bridge, as well as the impacts on the Canadian rail system. Finally, the increased system operating costs do not account for the impacts of delays within the system on the shippers and firms reliant upon timely delivery of their goods to market. Overall, the impact due to the loss of this one bridge can have a significant impact on operating costs.

Discussion and Conclusion

We have presented a strategic-level modeling framework for identifying the impact on rail operations in the event of the loss of one or more bridges or tunnels. We have applied this framework, using the simple SRM model. Our application involved determining the impact on freight routes originating in the State of Washington due to the loss of a bridge in Sandpoint, ID. Simple rerouting created an increased cost of operation by more than \$3.6 million per year (using 1997 operating costs). Rail cars which would normally cross the bridge were rerouted, resulting in increases in route distance that averaged 329 miles. Ton mileage increased by 87 million ton miles per year when the bridge was considered inoperable. It is important to also mention that impedance values also increased. Such values tend to indicate increased difficulty in shipping freight (e.g. routes included more transfers between railroads, routes used tracks that are not mainline, etc.). This analysis did not consider capacity issues, nor did it analyze the impacts on yards, building trains, etc. Never-the-less, the estimate can be considered a lower bound on likely impacts as including additional factors such as capacity will likely force detours to be even longer. It is easy to see that one bridge can be an important feature in operational efficiency. When the impact costs associated with losing a critical bridge or tunnel is high, it may well be justifiable to consider countermeasures to lesson the chance that an asset could be successfully struck.

We consider the model results presented here as the first step in a more comprehensive analysis of railroad vulnerability analysis. It is obvious that the level of impacts generated in the example presented in the last section are significant, without consideration of capacities. Future research should be devoted to expanding the modeling framework to developing a working version of the CMRM model as well as developing explicit impact models. Impact models should address the possible impact of rerouting dangerous cargo, the potential need for truck fleets to carry loads not handled on a timely basis by rail, and generating better estimates on the cost impacts to rail companies, to name a few. We have not attempted to identify the most critical link or the set of most critical links, but have proposed an approach for estimating the impact on a rail system when one or more elements are lost. We leave to future research the problem of identifying the elements which are most critical as well as identify countermeasures for protection.

The Pipeline and Hazardous Material Safety Administration (PHMSA) and the Federal Railroad Administration (FRA) of the US Department of Transportation (USDOT) have been given the responsibility to develop regulations pertaining to the transportation of hazardous materials and rail safety. Under the Homeland Security Act of 2002 (*P.L.* 107-296), the USDOT shares responsibility with the Transportation Security Administration (TSA) of the Department of Homeland Security (DHS) for rail security. PHMSA sets standards for how shipments of hazardous cargo must be identified, packaged, and handled in transit. PHMSA also funds hazardous material emergency preparedness grants to assist local agencies. FRA oversees the safety of track, signal and train controls, operating practices, highway-rail grade crossing safety, and hazardous materials. FRA conducts inspections annually to ensure compliance with regulations. The principal focus of most of the security issues are focused on the safety and security of hazardous materials transport, including radioactive materials like spent nuclear fuel. For example, the DHS has identified certain cities as high threat areas based upon the amount of hazardous material transported through urban core areas by rail. In response to this identified threat, the U.S. Congress is now considering legislation to require rail based hazmat to be rerouted to avoid downtown areas whenever possible.

The issue of rail infrastructure vulnerability, however, has been primarily left as an issue for the railroads companies themselves. A recent GAO (GAO, 2003) report on rail safety and security stated that railroad infrastructure security is an issue that is being addressed by the Association of American Railroads (AAR). AAR is an association that represents most if not all of the railroads in America. Thus, railroad infrastructure security and vulnerability is a primary issue of the rail companies and not the US government.

After 9/11, the AAR developed a security plan that addressed security and safety issues within five areas: hazardous materials, operations, infrastructure, information technology and communications, and military movements (AAR, 2007). The AAR states that, using national intelligence community “best practices,” the Railroad Security Task Force developed a comprehensive risk analysis and security plan. Their analysis examined and prioritized all railroad assets, vulnerabilities, and threats and then identified countermeasures (AAR, 2007). Such “best practices” have not been defined in a public arena. Since the focus of resources has been generally directed at dangerous cargo, *e.g.* chlorine, it is not clear how much attention specific assets, like bridges and tunnels, have received. It is obvious that a strike against a dangerous cargo like a chlorine tanker car in an urban area could kill not only thousands of people, but would present a crisis to the freight industry. But, the economic impacts due to a lost bridge or tunnel may be significant as well. While, public policy has been directed at “high profile” hazmat cargo, little attention appears to be directed at the system as a whole.

It is important to note that some states such as Pennsylvania have considered legislation which would mandate specific state agencies to “identify and evaluate critical railroad assets and infrastructure, including threats to those assets and infrastructure” (The General Assembly of Pennsylvania 2006). Pennsylvania’s proposed legislation would direct their state DOT to establish a contingency plan to reroute rail traffic due to a loss of railroad infrastructure, such as a bridge, tunnel, yard, or station. The results of this paper suggest that such legislation is needed and that public policy should take a more active role in rail infrastructure protection.

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Table 1: Possible impacts of a destroyed bridge or trestle

Issue	Type of Impact	Impact on:	Public/Policy issue
Bridge needs to be replaced	Cost	Railroad/insurance company must bear cost of replacement	incentives to speed replacement, subsidize cost
Detour route is longer	Increased ton miles	Increased cost to railroad company	
	Longer transit time	Lower level of service for customers	
	Increased flows on alternate routes	Possible impact for vehicular crossings	
Detour routes have limited slack capacity	Some freight can not be handled by rail	Railroad some looses business, increased Barge and truck traffic is likely. For trucks, more fuel consumed and pollution generated	Prioritize freight in terms of critical public needs, e.g. fuel, chlorine, etc.
No detour route exists with existing slack capacity	All freight must be handled by another mode, or not transported at all	Increased truck and barge traffic; increased pollution and fuel consumption for trucks, or possible no shipment	Prioritize freight in terms of critical public needs, e.g. fuel, chlorine, etc.
Passenger/commuting routes disrupted	Alternate route might be inferior or not exist	Increased use of commuting by car	Increase bus service to effected commuters

Table 2. Distance and Impedance values associated with rerouted freight

Origin	statistic	Distance	impedance	new distance	new impedance	chg dist	chg imp
23RD AVENUE	Mean	2801.6	2767.1	3420.5	3443.3	618.9	676.3
ABERDEEN	Mean	2578.8	3153.4	2700.7	3414.9	121.9	261.5
AINSWORTH JCT.	Mean	2546.2	2541.9	3038.2	3069.2	491.9	527.3
AUBURN (NP)	Mean	2257.0	2123.2	2626.6	2587.2	369.6	464.0
BASSET JCT	Mean	2394.1	2897.1	2508.0	3473.8	113.9	576.7
BREMERTON	Mean	2855.7	3583.6	2801.0	3670.4	-54.7	86.8
BURLINGTON	Mean	2389.7	2263.4	3269.4	3073.1	879.7	809.7
CHEHALIS	Mean	2278.0	1849.2	2321.8	1951.0	43.9	101.7
CHERRY POINT	Mean	2486.9	2349.4	2945.4	2800.5	458.5	451.1
COLUMBIA JCT.	mean	2254.0	2776.5	2331.7	2989.3	77.7	212.8
CONNELL	mean	2456.4	2361.2	2885.9	3038.4	429.5	677.2
DAYTON	mean	1714.2	2556.5	2001.4	2579.2	287.2	22.7
DELTA JCT	mean	1921.1	1741.0	2388.8	2414.2	467.6	673.2
ELLENSBURG	mean	2226.9	1974.4	3071.7	2756.1	844.8	781.7
ELMA	mean	2506.3	3005.7	2399.6	3034.2	-106.7	28.5
GIBBON	mean	2889.6	3094.1	3734.4	3875.8	844.8	781.7
HOOUIAM	mean	2292.7	2688.8	2283.4	2998.9	-9.3	310.1
INTALCO	mean	2540.7	2317.4	3157.0	2934.1	616.3	616.7
IRVIN	mean	1955.4	2184.1	2250.8	3036.5	295.4	852.4
KENNEWICK	mean	2604.7	2626.5	3243.5	3223.7	638.8	597.1
KETTLE FALLS	mean	1945.8	1625.3	1952.8	2462.0	7.0	836.7
LAKEVIEW	mean	2854.1	2713.6	3405.9	3188.4	551.8	474.8
LONGVIEW	mean	2595.2	3174.4	2527.7	3406.5	-67.5	232.2
LONGVIEW JCT	mean	2132.2	1923.7	2423.0	2356.0	290.7	432.2
LYNDEN	mean	2103.7	2143.0	2110.7	2979.7	7.0	836.7
MCLOUGHLIN	mean	2213.7	1771.4	2809.8	2354.2	596.1	582.8
NEWPORT	mean	1005.8	1446.4	1073.6	1818.0	67.8	371.6
OROVILLE	mean	1936.7	2616.7	2019.0	3416.6	82.2	799.9
OTHELLO	mean	2521.5	3126.3	2769.6	3535.2	248.1	408.9
OTIS ORCHARDS	mean	1373.4	1738.0	1593.9	2086.5	220.5	348.5
PASCO	mean	2537.7	2481.8	3200.7	3247.2	663.0	765.4
PULLMAN	mean	2244.7	2789.8	2268.9	3114.3	24.2	324.5
PUYALLUP	mean	2133.8	1723.2	2854.9	2404.3	721.1	681.1
RICHLAND	mean	2337.9	2277.9	2721.8	3013.5	383.9	735.6
ROCK ISLAND	mean	2350.2	2230.8	2372.7	3049.4	22.6	818.6
SEATTLE	mean	2408.2	2252.8	2933.5	2884.7	525.3	631.9
SHELTON	mean	1964.3	2521.1	2100.8	2658.0	136.6	136.9
SNOHOMISH JCT	mean	2151.9	1776.1	2857.1	2380.3	705.2	604.2
SPOKANE	mean	2179.1	2181.9	2279.1	2829.6	100.0	647.7
SUMAS	mean	2335.7	2113.0	2823.3	2578.9	487.6	465.9
SUNNYSIDE	mean	2293.1	2127.6	3024.2	2754.5	731.2	626.9
TACOMA	mean	2338.1	2129.1	2779.4	2645.7	441.2	516.7
TOPPENISH	mean	2486.9	2358.8	3086.9	3026.0	599.9	667.2
UNDERWOOD	mean	1898.5	1651.4	2177.8	2049.9	279.3	398.5
VANCOUVER	mean	2049.8	1855.8	2383.3	2434.0	333.5	578.2
WALLA WALLA	mean	2724.0	3477.3	2787.0	3535.1	63.0	57.8
WALLULA JCT	mean	1823.4	1845.2	2222.0	2551.5	398.7	706.3
WENATCHEE	mean	2027.9	2021.1	2179.3	2693.6	151.4	672.5
WISHRAM	mean	2160.6	1867.1	2606.4	2351.1	445.8	484.1
YAKIMA	mean	2364.3	2239.6	2783.4	2821.6	419.1	582.0
Totals	mean	2314.6	2330.9	2643.5	2879.2	328.9	548.3
	std. dev.	585.1	706.0	765.3	705.2	345.5	271.5
	Sum	847141.2	853120.8	967519.2	1053782.0	120378.0	200661.2

Table 3. Ton Mile values associated with rerouted freight

Origin	statistic	tons	Ton-miles	rerouted ton-miles	chg_ton-miles
23RD AVENUE	mean	143.0	340113.9	406694.6	66580.7
ABERDEEN	mean	137.5	339911.8	348719.3	8807.5
AINSWORTH JCT.	mean	80.9	197932.0	234890.6	36958.6
AUBURN (NP)	mean	71.5	164152.5	195928.1	31775.7
BASSET JCT	mean	447.8	984812.3	1050386.0	65574.1
BREMERTON	mean	136.0	374600.8	361626.1	-12974.7
BURLINGTON	mean	97.0	231800.9	317131.8	85330.9
CHEHALIS	mean	296.0	674417.0	812562.7	138145.7
CHERRY POINT	mean	189.2	467617.5	560020.6	92403.1
COLUMBIA JCT.	mean	337.8	748973.8	766302.8	17329.0
CONNELL	mean	203.4	518436.2	614344.2	95908.0
DAYTON	mean	126.0	215989.2	252176.4	36187.2
DELTA JCT	mean	8259.8	4768720.0	4896695.0	127975.3
ELLENSBURG	mean	103.0	233163.2	320170.6	87007.4
ELMA	mean	141.0	352786.3	333105.4	-19680.9
GIBBON	mean	44.0	127142.4	164313.6	37171.2
HOQUIAM	mean	492.3	1152090.0	1157621.0	5530.8
INTALCO	mean	164.0	386952.6	484441.1	97488.5
IRVIN	mean	233.0	455608.2	524436.4	68828.2
KENNEWICK	mean	165.0	425577.5	526285.9	100708.4
KETTLE FALLS	mean	420.0	817236.0	820176.0	2940.0
LAKEVIEW	mean	124.0	353908.4	422331.6	68423.2
LONGVIEW	mean	228.9	576608.3	568044.9	-8563.3
LONGVIEW JCT	mean	105.2	236366.6	269041.2	32674.6
LYNDEN	mean	66.0	138844.2	139306.2	462.0
MCLOUGHLIN	mean	148.0	327627.6	415850.4	88222.8
NEWPORT	mean	650.0	653770.0	697840.0	44070.0
OROVILLE	mean	672.4	1717642.0	1736216.0	18573.9
OTHELLO	mean	132.2	308498.6	357197.1	48698.5
OTIS ORCHARDS	mean	95.7	144452.4	167533.4	23080.9
PASCO	mean	261.6	667284.8	820924.9	153640.2
PULLMAN	mean	115.5	247435.6	252151.9	4716.3
PUYALLUP	mean	71.0	151499.8	202697.9	51198.1
RICHLAND	mean	50.5	123500.4	147972.3	24471.9
ROCK ISLAND	mean	152.4	355376.3	357204.0	1827.7
SEATTLE	mean	2055.4	4462111.0	5915019.0	1452908.0
SHELTON	mean	122.5	245027.6	265244.1	20216.6
SNOHOMISH JCT	mean	379.0	820753.1	1120902.0	300148.9
SPOKANE	mean	254.1	489540.4	504120.2	14579.9
SUMAS	mean	289.9	672819.3	851717.8	178898.5
SUNNYSIDE	mean	96.0	222286.8	291876.2	69589.5
TACOMA	mean	228.1	494154.6	580220.0	86065.4
TOPPENISH	mean	243.8	605383.8	753100.7	147716.8
UNDERWOOD FRUIT	mean	123.6	240565.9	266573.6	26007.8
VANCOUVER	mean	164.2	401122.9	467891.4	66768.5
WALLA WALLA	mean	50.0	136200.0	139350.0	3150.0
WALLULA JCT	mean	135.8	223593.3	263352.3	39759.0
WENATCHEE	mean	195.6	345083.8	399156.4	54072.6
WISHRAM	mean	220.8	495302.3	581478.1	86175.8
YAKIMA	mean	295.2	640109.5	703526.5	63416.9
Totals	mean	555.5	1078488.0	1317941.0	239452.2
	std.dev.	3926.8	7792880.0	10600000.0	2834346.0
	sum	203325.0	395000000.0	482000000.0	87600000.0

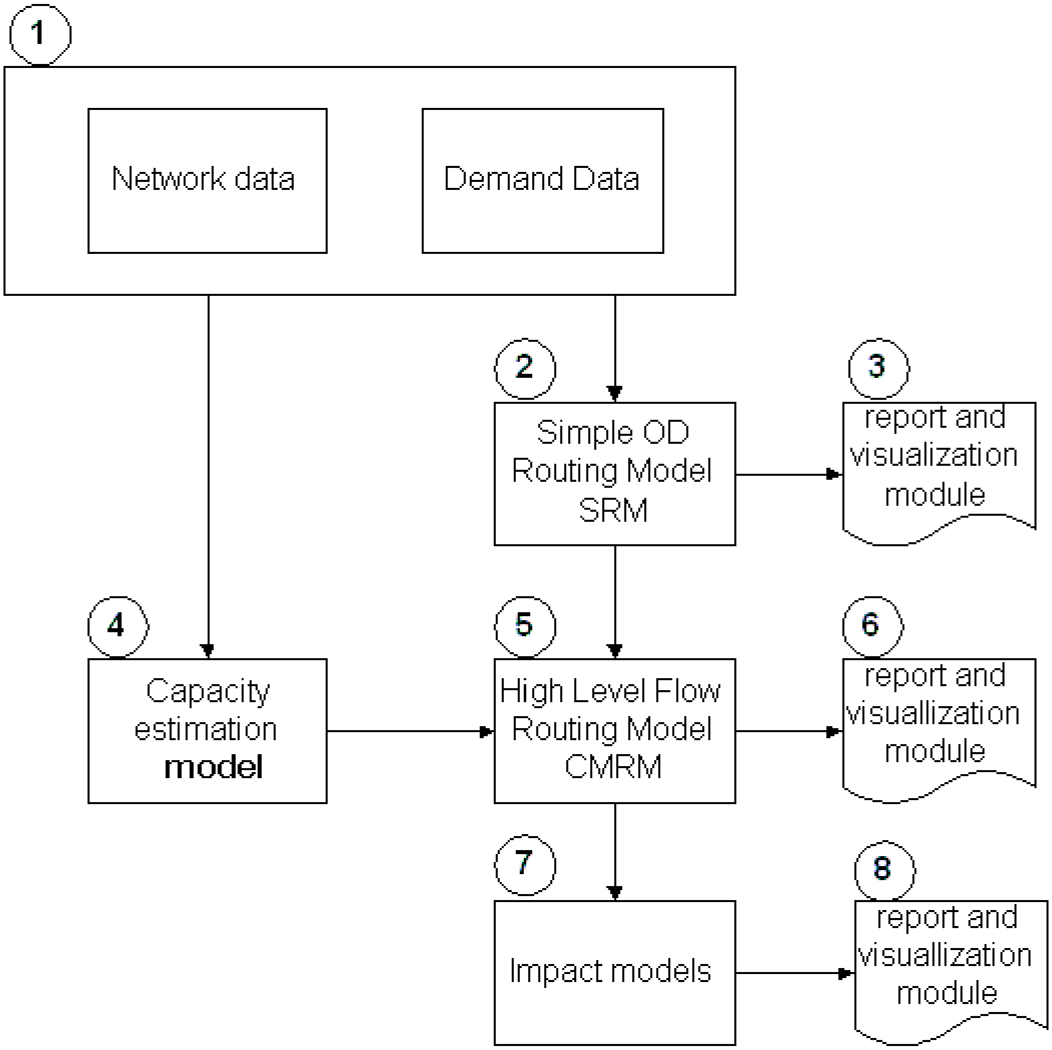

FIGURE 1. Framework for modeling the impacts of rail network disruptions

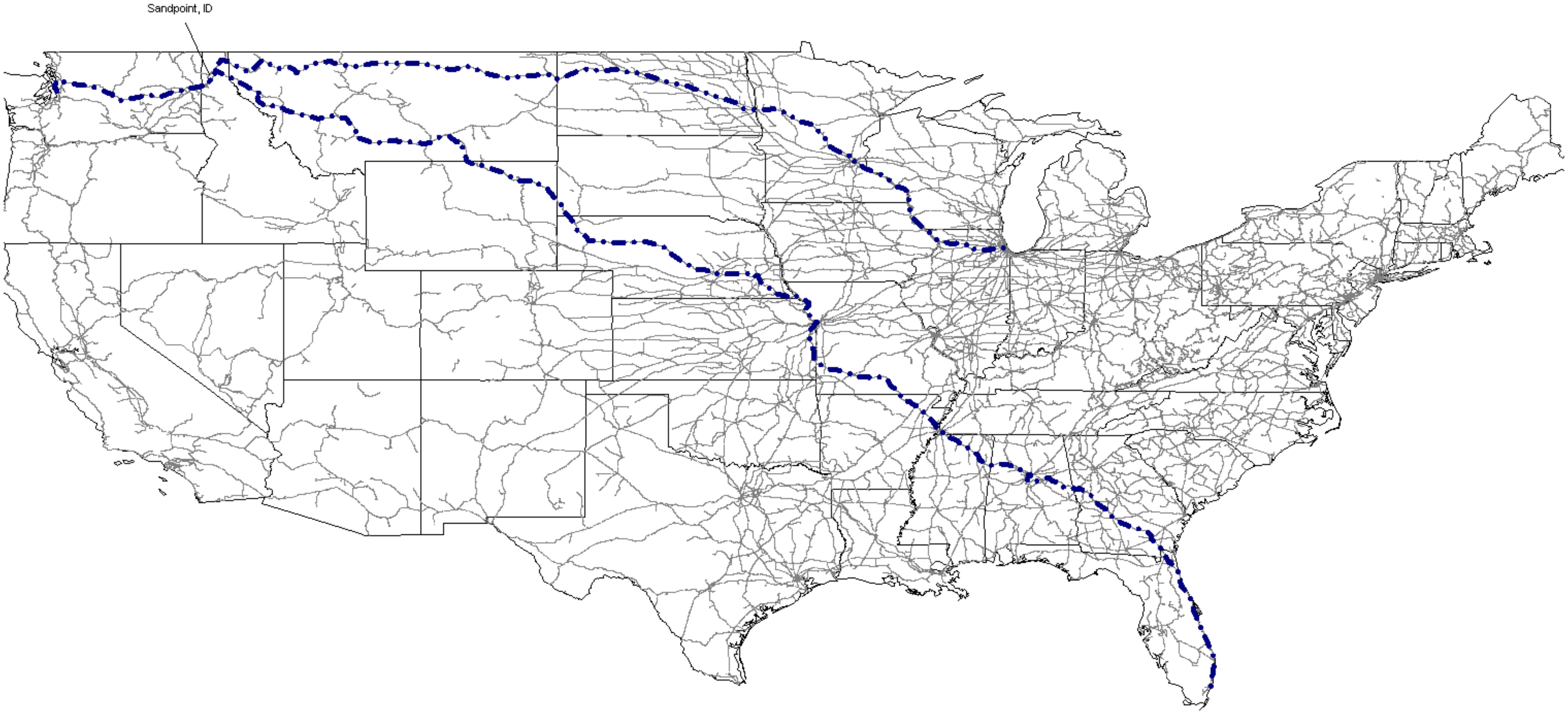

FIGURE 2: Example routes from Seattle and Spokane, Washington

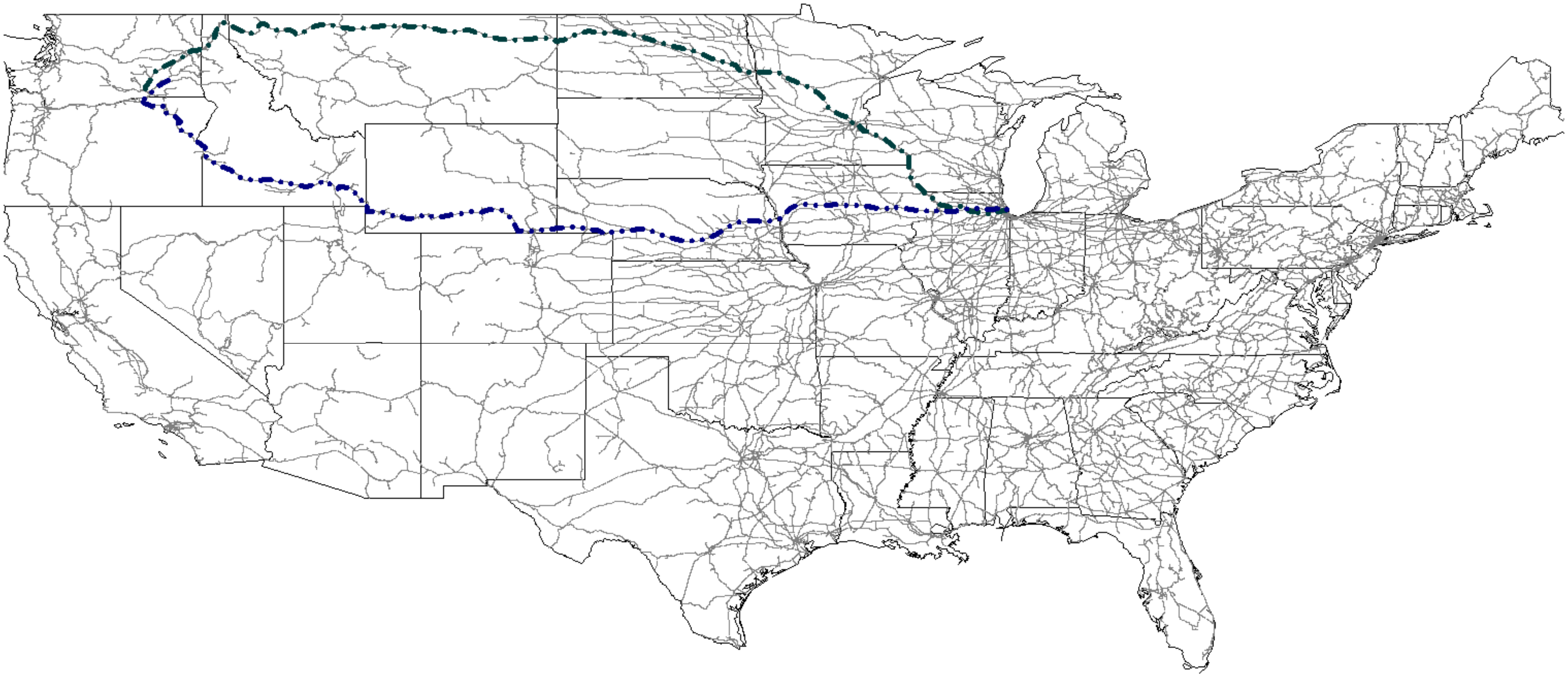

FIGURE 3. BNSF (northern) and UP (southern) routes from Ayers Junction, WA to Chicago, IL.

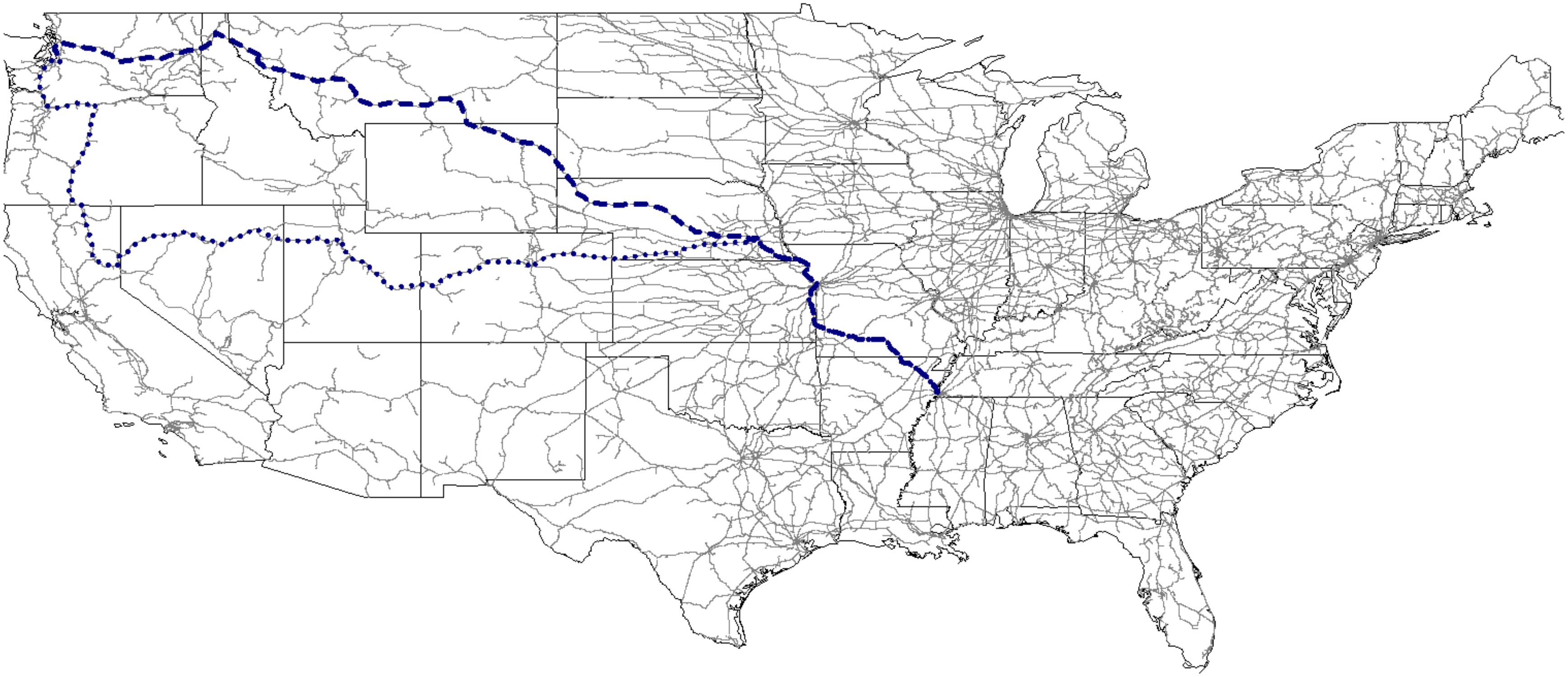

FIGURE 4. Rerouting of Seattle to Memphis trip based upon interdicted bridge at Sandpoint, ID. Original route is a dashed line and the detour route is a dotted line.