A RETRO-ANALYSIS OF THE JANUARY 7^{TH}, 2022 FLOOD CLOSURE OF I-5

By

GEORGIANNA STROBIN

MASTER OF SCIENCE
GEOGRAPHIC INFORMATION SYSTEMS TECHNOLOGY
FINAL PROJECT

THE UNIVERSITY OF ARIZONA

2022

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ABSTRACT

Floods pose an acute risk to transportation networks and impose large costs on travelers. A twenty-mile section of Interstate 5 (I-5) was forced to close on January 7th, 2022, when rising floodwaters from the Chehalis, Skookumchuck, and Newaukum Rivers threatened to cover the highway. Many travelers and residents were unable to reach their destinations and alternate routes quickly became congested. This retroactive analysis investigated the total cost of the flood closure using traffic counts from permanent traffic recording stations, AAA's estimated cost per mile of operating a vehicle for 2021, and the standard velocity equation—time equals distance divided by velocity—to solve for time cost. Through a GIS-based network analysis, two unique alternative routes are identified and time and mileage costs for travelers are calculated. Route One costs $151.97 while Route Two costs $160.67 in time per vehicle. Respectively, the routes cost $103.65 and $114.20 in mileage costs for each vehicle. Additionally, two historic Washington State Department of Transportation (WSDOT) detour routes are compared in time and mileage costs. Historic Route One costs $266.10 in mileage and $703.94 in time. Historic Route Two is much more expensive at $338.10 in mileage and $1,136.47 in time. The total cost of the flood closure was $924,950. With only one direct route to access so many destinations, it continues to be vitally important to increase access to urban and rural destinations during flood disasters.

Keywords: transportation network, flooding, road closure, travel costs, Interstate 5, I-5, Chehalis River

ETHICS STATEMENT

Maps and data are powerful tools that shape the way we view the world and its inhabitants. Each GIS practitioner must wholeheartedly understand the weight of responsibility that rests upon their shoulders. GIS has an inherent need to carefully consider the ethics of each map made or piece of data manipulated. While each situation is different, there are several commonly accepted ethical guidelines that GIS practitioners can follow to ensure that they are not knowingly or unknowingly producing harmful information. Carefully considering the ethical implications of GIS work will improve the relationship between consumers and GIS professionals, thus promoting trust in the discipline.

One of the most important principles of the GIS code of ethics is to treat others with respect. GIS practitioners can do this by clearly highlighting the purpose of their map, representing the data in an accurate way. Not only does this show respect to the viewer by presenting them with factual information, but it also demonstrates that the GIS practitioner is aware of their responsibility to the integrity of the profession. Additionally, GIS professionals should know their audience and make maps that communicate effectively to them. A group of real estate executives would not want a map designed for a local municipality’s Parks department, for example, because the overall message of the map would be different. Essentially, understanding the map’s audience and purpose shows the viewers that their message is being represented correctly by the GIS practitioner. Finally, the GIS professional must not misrepresent their experience or skill. Doing so can create a ripple effect of negative impacts that not only harm the individual but expand outward to harm the client and the profession. Mutual trust and respect are the cornerstones of ethical GIS.

This project focuses on the costs of flooding for a 20-mile section of Interstate 5 (I-5). Time costs and mileage costs are investigated. Alternative routes are developed using Network Analyst in ArcGIS Pro. There are ethical challenges with this project that must be addressed. First, I am operating under an assumption that all travelers will take an alternative route when calculating costs. Through firsthand knowledge I understand that such extensive alternative routes are rarely taken by travelers—many prefer to stay where they are until the flood has abated. This can misrepresent the true cost of the flood by not accounting for abandoned trips. To mitigate this concern, this fact is clearly stated within the project methodology. Also, while I have conducted many Network Analyst analyses, I have not done one on this scale before. This knowledge limitation can lead to mistakes in my methodology.

CHAPTER 1
INTRODUCTION

Washington State is bisected by Interstate 5 (I-5). I-5 is the state's busiest highway and the primary route to traverse the state from the Oregon border to Canada (Hallenbeck et al., 2014). If disaster strikes and closes the highway, many people will be cut off from their destinations, alternate routes will receive more traffic than they are meant to, and smaller towns and cities could be isolated from resources and supplies. Transportation networks, such as I-5, "support the safety and wealth of communities" (Pregnolato et al., 2017, 67). In urbanized areas in particular, heavy rainfall coupled with a high percentage of impervious surfaces can lead to high flood risk.

Disaster did strike on January 7th, 2022. An atmospheric river, a relatively narrow stream of moisture "usually around 250-400 miles wide. . .thousands of miles long…[and] low in the atmosphere" (Marriott, 2022, paras. 2, 4-5) had been depositing snow and rain on the Pacific Northwest. The rainfall only added to a precarious situation, as Lewis County had received 13.34 inches of precipitation (NOAA, 2022), much of that snowfall, only a week prior that was just beginning to melt. The atmospheric river dumped up to 6 inches of rain from January 6th to January 7th (Samenow, 2022, paras. 1, 6), with a total of 12.83 inches for the month (NOAA, 2022). Roads were flooded, travelers could not reach their homes or further destinations, and the water kept on rising. Twenty miles of I-5 would be closed for five hours (Horne, 2022, para. 1) while anxious travelers waited to see how high the floodwaters would rise.

Floodwater impacting roads is not a new occurrence. According to a paper published in 2015, "Flood disaster has become one of the most damaging natural disasters for the highway transportation [network] all around the world" (Ou-Yang et al., 381). The Federal Highway Administration (FHA) states that precipitation can have varied effects to the roadway and traffic flow (FHA, 2022, Table 1). Impacts to the road can include reduced visibility, loss of traction on the road, and lane blockage; while heavy precipitation can alter the capacity of the roadway, reduce traffic speed, increase travel times, and increase accident risk (FHA, 2022, Table 1; Rogelis et al., 2016, 3). Ou-Yang et al. state that "Strong rainfall also heightens the water level of flood disaster and makes the pavement flooded" (2015, 384). Pregnolato et al. (2017) agree and mention that "Flooding, especially as a result of intense precipitation, is the predominant cause of weather-related disruption to the transport sector" (67). This was especially evident on January 7th, 2022.

Literature Review

The cost of flooding on transportation networks can be measured with a variety of methods. Some approaches focus on the cost to the traveler, several investigate the flood impact on infrastructure, while still others evaluate the effectiveness of commonly accepted methodology. This analysis is primarily based on evaluation of traveler costs.

In their 2017 paper titled *The impact of flooding on road transport: A depth-disruption function*, Pregnolato et al. analyzed the behavior of travelers on flooded roadways in the United Kingdom. They argued that the current approaches to "assess the disruptive impact of flooding on road transport" (67) ignore one important reality: roads are often not fully operable or fully inoperable. Stating that "The relationship between adverse weather, traffic flow and congestion is acknowledged but poorly understood" (68), they claim that roads may be driveable despite flooding, and that if the traveler believes that they can traverse the roadway they will do so (73-76; Rogelis et al., 2016, 3). Pregnolato et al. developed a “depth-disruption” function to determine the relationship between water depth and speed (67, 73). This equation provides greater insight into the time costs of flooding. This deviation from the common “closed or open” mentality presents an interesting change to the normal time cost evaluation.

Infrastructure concerns and disruptions to traffic flow are the focus of several studies. Rogelis et al. highlighted the impacts of flooding to infrastructure such as bridges, telecommunications, and emergency vehicle access (2016, 3). Disruptions to the transportation network, such as a flood or major infrastructure failure will alter the transportation and infrastructure landscape (Aydin et al., 2012, 380). The road network, and each segment individually, is designed to work close to capacity with little reserve (Das, 2020, 586). This “renders transportation networks sensitive to…extreme weather, natural disasters…” (Das, 2020, 586). The impact of a singular event, such as a flooded roadway, can ripple far further into the overall network than was previously thought (Aydin et al., 2016, 387). Aydin et al. argue that conventional models of transportation networks do not adequately estimate the effects of a disaster on the network; in their study, effects from an infrastructure failure encompassed an entire freeway and were felt across the United States (2016, 387-394). Similarly, flood impacts to roadways were discussed by Ou-Yang et al. (2015). They stated that “Rainstorm and flood may induce geological disaster such as collapse and further sabotage the highway roadbed, pavement, and other infrastructures” (Ou-Yang et al., 2015, 382). Their analysis discussed a three-pronged approach to evaluation flood risk to highways, which include factors that cause disaster, a disaster-prone environment, and the subject that bears the force of the disaster (2015, 381). The 20-mile section of I-5 covered in this analysis represents the subject of the disaster, while the heavy rainfall and proximity to rivers produced the disaster-prone environment. To mitigate the effects of floods on the transportation network and the disaster-prone environment itself, Das suggested a resilience-based approach (2020, 591). This type of approach would enable the network to “return to a normal state after a major disruption” (Das, 2020, 591), which would allow for all trips along the network to be completed. Transportation network infrastructure failure and recovery is an important aspect to calculating traveler costs.

Transportation network costs appear to be standardized among the literature. Rogelis et al. defines multiple indices that measure cost; two of these indices are similar to methodology used in this analysis. The Generalized Travel Cost index compares “the difference between the least cost path with the network intact and the least cost path without the link” (2016, 12), demonstrating the increase in cost after the link is compromised due to flooding. The Importance Measure “assumes that all drivers are forced onto a more expensive route when an event causes the disruption or closure of a link” (2016, 12), highlighting expenses as both time and distance of detours. In addition to infrastructure, time costs heavily impact the total cost of flood closures to the traveler. Rogelis et al. delved deeply into flood impacts on the road network as it relates to congestion (2016, 3). They claim that indirect impacts, defined as “the costs of interruption and logistics disruptions” (3; Das, 2020, 591) often have consequences such as lost trips or long, arduous detours that increase the costs of trips (6).

The length of the detours can be directly tied to the road segment affected by flooding (11). Road segments that are the singular link between nodes on the transportation network are considered weak by Rogelis et al. because “the length of the connection (detour route) …would grow substantially" (2016, 11) if that segment were to be closed due to flooding. Das proposed a method that utilized origin-destination travel patterns to create an index that "results in a situation where all travelers will reach their destination" (2019, 587). The primary step in any travel analysis is trip generation (Chang and Dresser, 1990, 13), where "the number of trips to and from geographical areas" (13) is determined based on urban factors. In the case of this analysis, urban centers are used for origin and destination points. The origin-destination framework is applied in this retro-analysis. It functions under the assumption that there is an alternative route and that all travelers will be able to reach their destinations (Hallenbeck et al., 2014).

In a report commissioned by the Washington State Department of Transportation in 2014, Hallenbeck et al. conducted a study on flood closure impacts to the same 20-mile section of I-5 covered in this analysis (3). In it, the researchers focused on 100-year flood conditions (3) and their impact on the "travel costs associated with the closure of roads in the greater Centralia/Chehalis, Washington, region" (2014, 10). Costs are calculated to include "added costs of time and vehicle mileage associated with available detour routes" (Hallenbeck et al., 2014, 10) but do not incorporate loss of commerce due to flood closures (10). They found that the estimated closure lasted for five days and costed approximately $8,508,000 in detour mileage and time, with a total closure cost of $11,872,000 (12). Their analysis showed "only about 42 percent of trips normally occurring on I-5 in the Centralia/Chehalis area are estimated to take alternative routes when I-5 is closed" (15) but noted that the majority of the costs incurred through the closure were used in detours (15). Hallenbeck et al. identified two primary detour routes around the flood closure with origin-destination points set at Portland, Oregon and the Puget Sound region (Seattle, Olympia, and others) (2014, 29). The first route follows I-84, then “takes US 97 north to I-82…follows I-82 to I-90, and then takes I-90 west” (29), while the second route travels via I-84 to Oregon, then north on I-82 (29). Respectively, they add 134 detour miles and 254 detour miles to any trip (29). They note that congestion along I-5 can often double travel time under normal conditions and highlight the fact that this may impact travel time on detour routes (31). The analysis done by Hallenbeck et al. is, to my knowledge, the only flood risk and cost analysis on this 20-mile segment of I-5.

Objectives

The breadth of research that surrounds the impacts of floods on transportation networks provides a tried-and-true framework for conducting a retroactive analysis. Much of the research investigated singular or hypothetical events. Modeled closely after a study done by Hallenbeck et al. in 2014 on the same stretch of I-5, this analysis aims to investigate the costs associated with the flood event on January 7th, 2022, that closed the roadway. While Hallenbeck et al. used a 100-year flood event as the basis for closure, the scope of this analysis is much smaller; the closure lasted for only five hours. Though the combination of a retrospective lens and an origin-destination framework this analysis:

- Identified the overall cost of the flood event using average (mean) vehicle miles traveled and time cost,

- Evaluated potential alternative routes taken during the closure using ArcGIS Pro Network Analyst and assigned a rank based on time and mileage costs, and
- Investigated historical detour routes presented by Hallenbeck et al. (2014) and adjusted their cost estimates for inflation to promote accurate comparison between historical and Network Analyst-identified routes.

The costs of flood events on travelers and identifying effective detour routes around I-5 is the focus of this project. With only one route to access so many destinations, it continues to be vitally important to increase access to urban and rural destinations during flood disasters.

CHAPTER 2
METHODS

Data

Several key pieces of data are required to complete this analysis. Data was acquired from the Washington State Department of Transportation (2022) and the Washington State Geodata (2022) spatial repositories. To build the Network Dataset, I used the Open Street Map North America layer to ensure that my network would have proper connectivity to run my analyses. The Washington State Department of Transportation maintains their own open geospatial portal where I have downloaded permanent traffic recorders. I also downloaded quarterly traffic reports as an Excel spreadsheet to determine average traffic counts.

Permanent traffic recorders monitor daily trends of travel along many of Washington's roadways. This point feature class contains the ID of the recorder, which will be used to join it to a WSDOT spreadsheet of yearly data from each traffic recorder. Table 2-1 and Figure 2-1 contain more information about the data.

Table 2-1. Metadata for permanent traffic recorders in Washington (WSDOT 2022).

<table>
<tr><th colspan="5">WSDOT_Traffic_Volume_Trend</th></tr>
<tr><td>Year Published</td><td colspan="4">2022; updated 1/20/2022</td></tr>
<tr><td>Author/Owner</td><td colspan="4">Washington State Department of Transportation (WSDOT)</td></tr>
<tr><td>URL</td><td colspan="4">https://gisdata-wsdot.opendata.arcgis.com/maps/wsdot-traffic-volume-trend/about</td></tr>
<tr><td>Description</td><td colspan="4">Permanent traffic recorder daily travel trends for Washington State. Data is updated daily at 10AM Pacific time.</td></tr>
<tr><td rowspan="2">Coordinate System</td><td colspan="4">NAD 1983 HARN StatePlane Washington South FIPS 4602 (US Feet)</td></tr>
<tr><td>Geodesic Model: WGS 1984</td><td>Horizontal Datum: D WGS 1984</td><td>Vertical Datum: D WGS 1984</td><td>EPSG Code: 4326</td></tr>
<tr><td>Projection</td><td colspan="4">Lambert Conformal Conic</td></tr>
<tr><td>Geometry</td><td colspan="4">Point</td></tr>
</table>

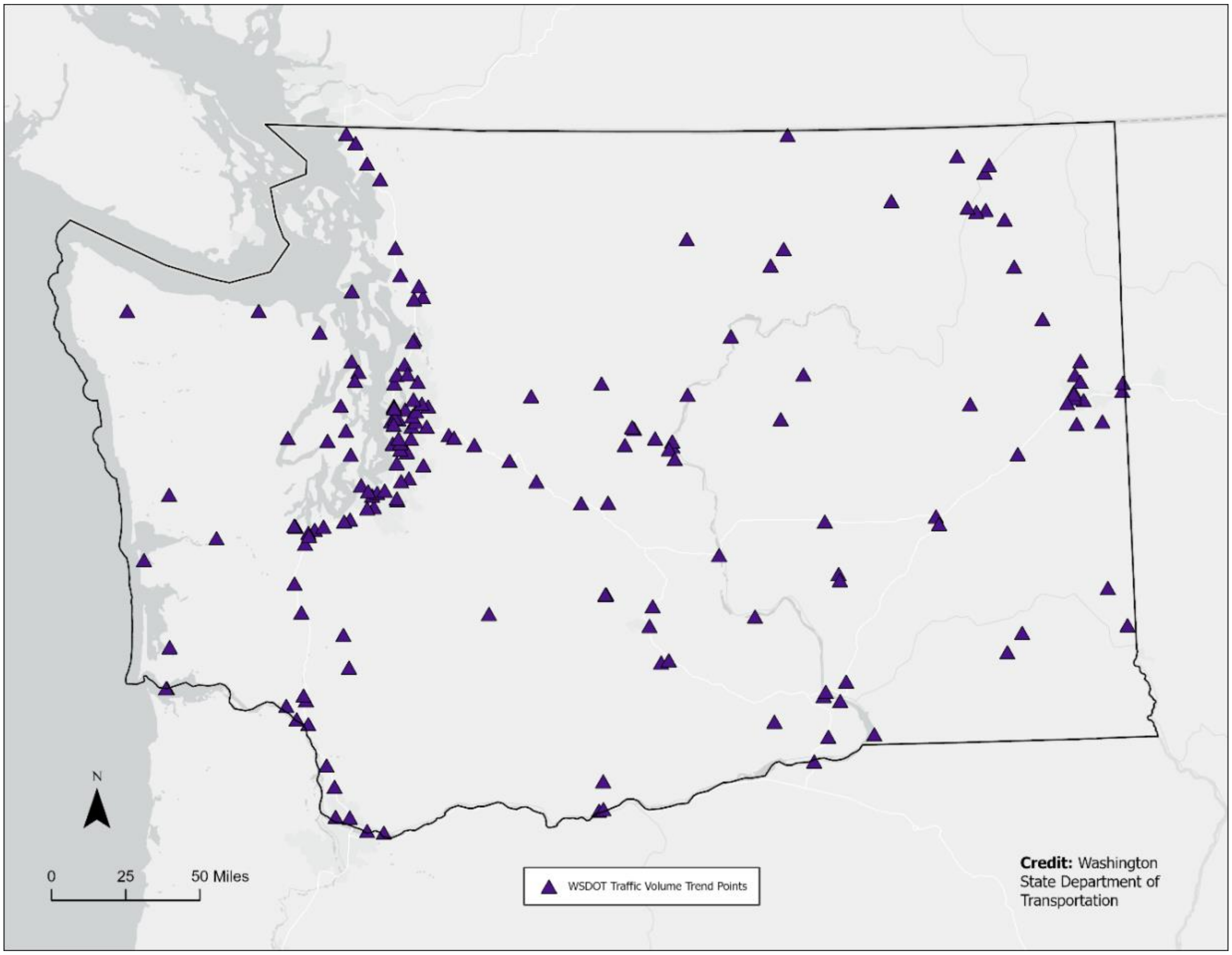

Figure 2-1. Permanent traffic recorders (volume trend points) in Washington (WSDOT 2022).

Washington State County boundaries were downloaded from the Washington State Geodata portal (2022). These boundaries will be used to define the study area and clip data to the proper extent (Table 2-2, Figure 2-2). In addition to county boundaries, this dataset also contains Department of Natural Resources regions, districts, local units, natural area preserves, natural resource conservation areas, and recreation areas.

Table 2-2. Metadata for Washington State County boundaries (WA DNR 2021).

<table>
<tr><th colspan="5">WA County Boundaries (Cadastre.Jurisdiction)</th></tr>
<tr><td>Year Published</td><td colspan="4">2021, updated weekly</td></tr>
<tr><td>Author/Owner</td><td colspan="4">Washington State Department of Natural Resources</td></tr>
<tr><td>URL</td><td colspan="4">https://fortress.wa.gov/dnr/adminsa/gisdata/datadownload/WA_County_Bndys.zip</td></tr>
<tr><td>Description</td><td colspan="4">County boundaries in Washington, as well as Department of Natural Resources Regions, Districts, Local Units, Natural Area Preserves, Natural Resource Conservation Areas, and DNR Recreation Areas.</td></tr>
<tr><td rowspan="2">Coordinate System</td><td colspan="4">NAD 1983 HARN StatePlane Washington South FIPS 4602 (US Feet)</td></tr>
<tr><td>Geodesic Model:
GRS 80</td><td>Horizontal Datum:
D North American 1983 HARN</td><td>Vertical Datum:
North Americna Vertical Datum 1988</td><td>EPSG Code:
2927</td></tr>
<tr><td>Projection</td><td colspan="4">Lambert Conformal Conic</td></tr>
<tr><td>Geometry</td><td colspan="4">Polygon</td></tr>
</table>

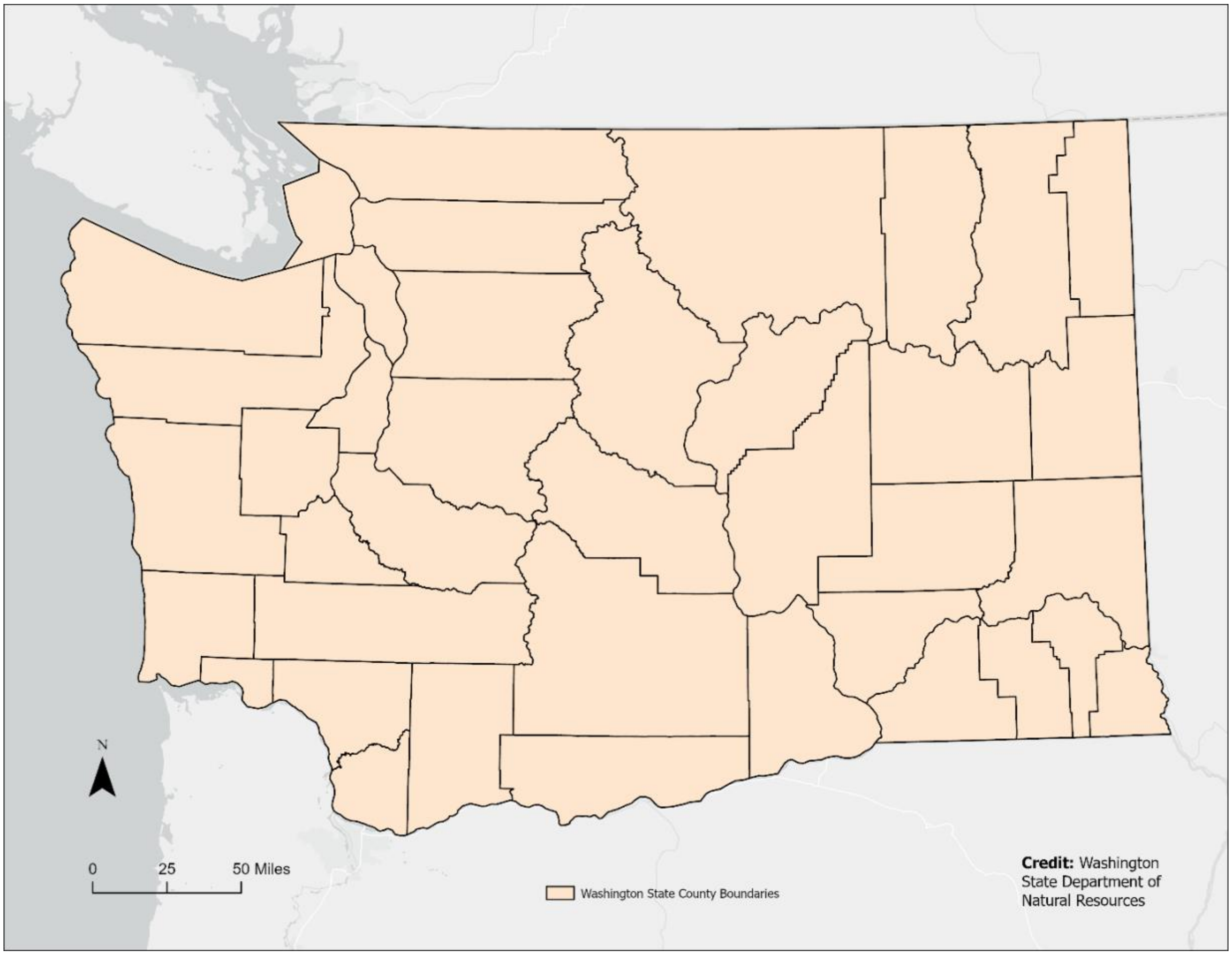

Figure 2-2. County and DNR boundaries in Washington State (WA DNR 2021).

The Open Street Map North America layer was brought in using the Living Atlas in ArcGIS Pro. This dataset spanned the entirety of North America and was clipped to my study area before I began performing analysis on it. This layer contains highways, local roads, pathways, and more. Table 2-3 and Figure 2-3 present a comprehensive look at the data.

Table 2-3. Open Street Map layer metadata (OSM, 2022).

<table>
<tr><th colspan="5">OSM_Highways_NA</th></tr>
<tr><td>Year Published</td><td colspan="4">2022</td></tr>
<tr><td>Author/Owner</td><td colspan="4">Open Street Map</td></tr>
<tr><td>URL</td><td colspan="4">https://services6.arcgis.com/Do88DoK2xjTUCXd1/arcgis/rest/services/OSM_Roads_NA/FeatureServer</td></tr>
<tr><td>Description</td><td colspan="4">The Open Street Map Highways North America shows highways, local roads, trails, paths, bike lanes, and more in North America.</td></tr>
<tr><td rowspan="2">Coordinate System</td><td colspan="4">WGS 1984 Web Mercator (auxiliary sphere)</td></tr>
<tr><td>Geodesic Model: WGS 1984</td><td>Horizontal Datum: D WGS 1984</td><td>Vertical Datum: D WGS 1984</td><td>EPSG Code: 4326</td></tr>
<tr><td>Projection</td><td colspan="4">Mercator Auxiliary Sphere</td></tr>
<tr><td>Geometry</td><td colspan="4">Line</td></tr>
</table>

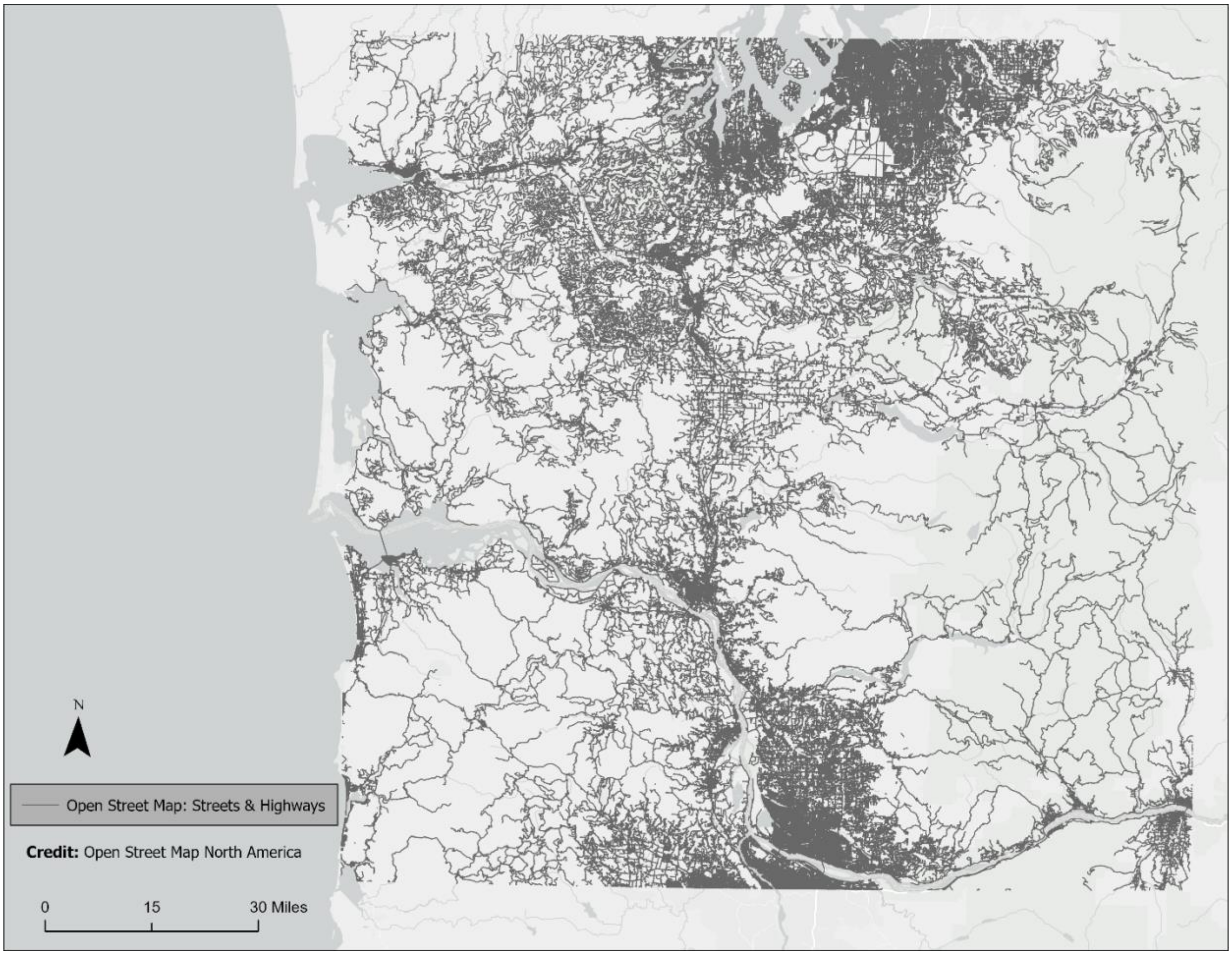

Figure 2-3. Clipped OSM layer to study area of analysis (OSM, 2022).

Approach

There are three main questions this analysis seeks to answer: what are the mileage and time costs resulting from the 20-mile closure of I-5 due to flooding, what are the fastest routes around the 20-mile closure area, and how do the two historic alternative routes presented by Hallenbeck et al. (2014) compare to the generated alternative routes in both time and mileage costs? Methodology for each is discussed in further detail below. Additionally, a workflow is presented in Figures 2-4 and 2-5 that outlines all the steps taken to achieve the results.

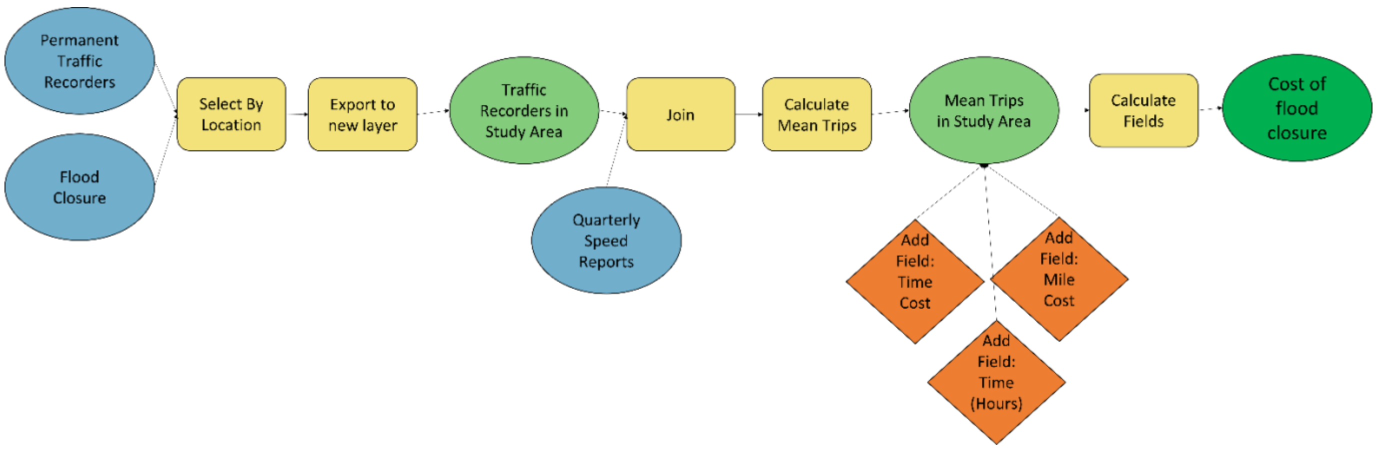

Figure 2-4. Flood closure cost workflow.

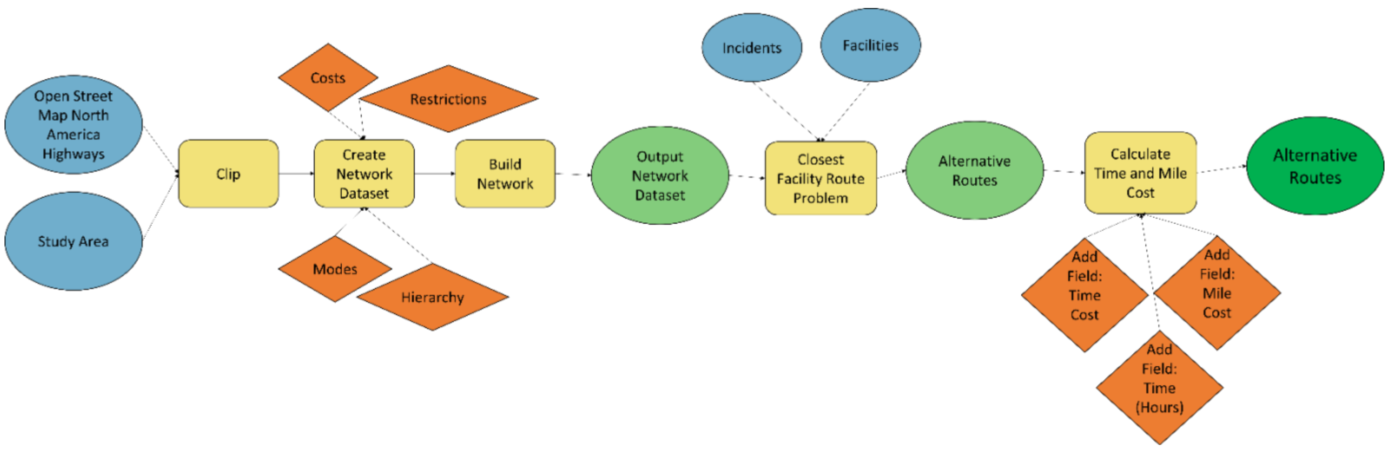

Figure 2-5. Alternative routes workflow.

Regarding the first, Select by Location was used to isolate all permanent traffic recorders within the flood closure area. The selected features were exported into a new feature class and joined one-to-one with the Quarterly Speed Reports spreadsheet from the Washington State Department of Transportation (2022). This spreadsheet contains quarterly and yearly traffic counts for all permanent traffic recorders in the state, as well as counts of speeds that each vehicle was traveling as it passed that recorder. Next, the average number of trips through the study area was calculated using the mean. Several fields were added to the study area traffic recorder feature class: Time (in hours), Time

Cost, and Mile Cost. Time was calculated using the standard velocity equation: time = distance / speed. The traffic recorder feature class already had a speed value for each recorder, and the distance was the length of the flood closure—20 miles. For mileage costs, Hallenbeck et al. (2014) gave cars the cost of 21 cents per mile and trucks the cost of $1.10 per mile. Since it is impossible to determine the vehicle type with the data available, the mileage cost per car was used.

However, these costs from Hallenbeck et al. were from 2014, and inflation, rising gas prices, and rising costs of car maintenance have subsequently increased the costs of owning and operating a vehicle. So, I utilized AAA's 2021 Cost of Driving table and calculator to determine current costs. I calculated each metric based on a midsize sedan, to be in line with Hallenbeck et al.'s (2014) methodology. In addition, I used the cost of gas for my study area as of February 2022, $3.98 a gallon (AAA, 2022). AAA's Cost of Driving calculator requires the following information as inputs: total miles driven, gallons of gas used, total cost of gas, maintenance, repair, tires, miscellaneous costs, depreciation, insurance, taxes, license, and registration (AAA, 2021, p. 2-3). Fuel cost was calculated using an average of 15k miles per year over 5 years, a total of 75k miles. Average miles per gallon was calculated by averaging the city and highway miles per gallon of the AAA top 5 midsize sedans for 2021. These included the Chevrolet Malibu, the Honda Accord, the Hyundai Sonata, the Nissan Altima, and the Toyota Camry (AAA, 2021, p. 1). Table 2-4 shows the average miles per gallon for both city and highway for each of these vehicles, as well as the overall mean miles per gallon. To get the number of gallons of gas used, I divided 75k by the average miles per gallon. I then calculated the total cost of gas by using the AAA average cost per gallon for WA in

2022. Next, I divided it by 75k to get the gas cost per mile. (Table 2-5). The maintenance, insurance, license, registration, taxes, depreciation, and finance changes were all adjusted for inflation from 2021 to 2022 (Figure 2-6, Table 2-5). The resulting cost per mile was used in the analysis to calculate the cost of the flood closure and the costs of the alternative routes.

Table 2-4. Summary of Average MPG for midsize sedans.

Midsize Sedan	City MPG	Highway MPG
Chevy Malibu	29	36
Honda Accord	30	38
Hyundai Sonata	28	38
Nissan Altima	28	39
Toyota Camry	28	39
Sum	143	190
Mean	28.6	38
Sum of Means	66.6	
Mean Combined MPG	33.3	

Driving Costs

Please note the figures in each vehicle category are the average costs for five top-selling 2021 models selected by AAA for this year's Your Driving Costs study.

	Small Sedan	Medium Sedan	Subcompact SUV	Compact SUV (FWD)	Medium SUV (4WD)
Operating Costs					
fuel	6.84¢	7.79¢	8.32¢	7.87¢	10.23¢
maintenance	8.83¢	10.43¢	9.91¢	9.93¢	10.01¢
cost per mile	**15.67¢**	**18.22¢**	**18.23¢**	**17.79¢**	**20.25¢**
Ownership Costs					
full-coverage insurance	$1,353	$1,403	$1,298	$1,292	$1,296
license, registration, taxes	$421	$603	$487	$541	$705
depreciation (15k mi/yr)	$2,687	$3,996	$3,004	$3,432	$4,186
finance charges	$419	$632	$494	$561	$744
cost per year	**$4,880**	**$6,633**	**$5,283**	**$5,825**	**$6,931**
cost per day	**$13.37**	**$18.17**	**$14.47**	**$15.96**	**$18.99**
Total Cost – 10k mi/yr					
operating cost	$1,567	$1,822	$1,823	$1,779	$2,025
ownership cost	$4,880	$6,633	$5,283	$5,825	$6,931
depreciation[1]	-$217	-$241	-$233	-$286	-$371
total cost per year	**$6,229**	**$8,214**	**$6,873**	**$7,319**	**$8,584**
total cost per day	**$17.07**	**$22.50**	**$18.83**	**$20.05**	**$23.52**
total cost per mile[2]	**$0.6229**	**$0.8214**	**$0.6873**	**$0.7319**	**$0.8584**
Total Cost – 15k mi/yr					
operating cost	$2,350	$2,733	$2,734	$2,669	$3,037
ownership cost	$4,880	$6,633	$5,283	$5,825	$6,931
total cost per year	**$7,230**	**$9,366**	**$8,017**	**$8,494**	**$9,968**
total cost per day	**$19.81**	**$25.66**	**$21.96**	**$23.27**	**$27.31**
total cost per mile[2]	**$0.4820**	**$0.6244**	**$0.5345**	**$0.5663**	**$0.6645**

Figure 2-6. AAA Cost of Driving numbers (AAA, 2021).

Table 2-5. Calculated costs of owning and operating a midsize sedan.

Medium Sedan	
Operating Costs	
Fuel	$0.12
Maintenance	$0.11
Cost Per Mile	$0.23
Ownership Costs	
Full Coverage Insurance	$1,455.70
License, Registration, Taxes	$625.65
Depreciation (15k mi/yr)	$4,146.09
Finance Changes	$655.74
Cost Per Year	$6,883.18
Cost Per Day	$18.86
Total Cost - 15k mi/yr	
Operating Cost	$3,423.00
Ownership Cost	$6,883.18
Total Cost Per Year	$10,306.18
Total Cost Per Day	$28.24
Total Cost Per Mile	$0.69

To determine the time cost, values from Hallenbeck et al. (2014) were adjusted for inflation from 2014 dollars to 2022 dollars. They assign local trips a time cost per car of $12 an hour and intercity trips a time cost per car of $16.70 an hour. I adjusted each value for inflation and averaged them together to get the mean cost of time per car per hour. Then, to calculate the total cost of the flood closure I employed two methods: cost per mile and cost per vehicle. Cost per mile was determined using the methodology from the previous paragraph. Cost per vehicle, however, was not. From the 87 permanent traffic recorders within the study area, I calculated the mean number of cars that passed through that area during January: approximately 2,077,786 cars. I divided that average by 31 days to get the number of vehicles per day, 67,035. I then calculated the total cost of the flood closure by multiplying the cost per mile by the total number of miles closed, then multiplied that number by the number of vehicles per day. I divided that resulting value by the mean number of vehicles that drove that section in January and determined the cost of the closure per vehicle.

To generate alternative routes around the flood closure, I created a Network Dataset in ArcGIS Pro 2.9 using the Open Street Map North America Highways service layer clipped to my study area. I used drive time and drive distance as modes. Costs were set up for both mileage and time; and two restrictions were added: driving over the flood closure and driving on pedestrian paths, which were included in the Open Street Map dataset. A hierarchy was set up to prioritize main roads. I built the network using the Build Network tool, then ran a Closest Facility route problem. I loaded the southern destinations in the Incidents layer and the northern destinations in the Facilities layer. I ran the route problem to solve for the shortest routes using time and mileage. I added the fields discussed above and calculated the costs using those methods. In addition, I mapped the two alternative routes presented by Hallenbeck et al. (2014) using the Trace tool to follow the routes along the Open Street Map dataset. I then calculated time cost and mileage cost using the average speed limit for the roads along the route.

CHAPTER 3
RESULTS

To properly understand the impact of the flood closure on the traveler, two costs must be established: the cost of time and the cost per mile Hallenbeck et al. (2014) had previously stated that the cost of local trips was $12.00 an hour and the cost of intercity trips was $16.70 an hour, in 2014 dollars. After adjusting for inflation and averaging those costs together, the cost of time was determined to be $17.04 (Table 3-1).

Table 3-1. The value of time, in cost per hour of travel time.

Year	**2014**	**2022**
Local Trips	$12.00	$14.25
Intercity Trips	$16.70	$19.83
Average Cost Per Hour	$14.35	$17.04

The cost per mile incorporated a variety of metrics to determine the most accurate cost. Table 3-2 details each metric, adjusted for inflation to 2022 dollars. This cost was based on AAA's proprietary yearly report (2021) on the cost of owning a vehicle. The fuel cost was adjusted from a nationwide average of $2.50 per gallon to a local average of $3.98 per gallon to reflect the cost of travel more accurately in the flood closure area. Additionally, this calculation assumed that individuals travel an average of 15,000 miles per year. Values were also calculated for a medium sedan to mirror AAA as much as possible.

Table 3-2. The cost per mile, mirrored after AAA's yearly report.

Medium Sedan	
Operating Costs	
Fuel	$0.12
Maintenance	$0.11
Cost Per Mile	$0.23
Ownership Costs	
Full Coverage Insurance	$1,455.70
License, Registration, Taxes	$625.65
Depreciation (15k mi/yr)	$4,146.09
Finance Changes	$655.74
Cost Per Year	$6,883.18
Cost Per Day	$18.86
Total Cost - 15k mi/yr	
Operating Cost	$3,423.00
Ownership Cost	$6,883.18
Total Cost Per Year	$10,306.18
Total Cost Per Day	$28.24
Total Cost Per Mile	$0.69

The Cost of Flooding

The cost of flooding in the 20-mile closed section of I-5 amounted to $0.45 per vehicle, while the cost per mile was $0.69. Those numbers are not particularly large but considering the amount of vehicles that drive through that section it amounts to a much greater overall cost in terms of lost trips and resulting loss in commerce. When the total cost is calculated using the cost per mile, it amounts to approximately $924,950. An average of 67,025 vehicles passed through the closed section of I-5 daily in January; over two million traversed that section during the month (Figure 3-1). When calculating the cost of the flood closure using the cost per vehicle, the total does become much lower, at only $30,161.41

Table 3-3. Cost of flood closure.

Mean Observed Vehicles in January *(from 87 Permanent Traffic Recorders)*	2,077,786.50
Vehicles per Day	67,025.37
Cost per Mile	$0.69
Length of Flood Closure (miles)	20
Total Cost of Closure (cost per mile)	$924,950.12
Cost per Vehicle	$0.45
Total Cost of Closure (cost per vehicle)	$30,161.41

Figure 3-1. Permanent traffic recorders along the closed section of I-5.

Alternative Routes

Four alternative routes around the closure were identified using Network Analyst. Each route goes from the south, with an origin at either Portland, Oregon or Vancouver, Washington. These routes terminate in the north at major cities including Olympia, the capitol city; Tacoma, a major shipping port; Tumwater, home to many State offices; and Aberdeen, a major logging and shipping port. Both mileage and time costs were calculated for each route (Table 3-4). Every route was told to avoid the direct area of the flood closure, the 20-mile stretch between milepost 68 and milepost 88.

Table 3-4. Mileage and time costs for each alternative route.

Miles				
	Route One	***Route Two***	***Route Three***	***Route Four***
Origin	Portland, Vancouver	Portland, Vancouver	Vancouver	Vancouver
Destination(s)	Tacoma	Olympia, Tacoma	Tumwater, Olympia	Olympia, Tacoma, Aberdeen
Miles	150.214239	165.5104477	114.975565	245.566977
Cost per Mile	$0.69	$0.69	$0.69	$0.69
Total Cost per Vehicle	$103.65	$114.20	$79.33	$169.44
Time				
Time (Hours)	2.986366581	3.070694763	2.368188774	4.872360655
Minutes	179.1819948	184.2416858	142.0913265	292.3416393
Average (mean) Speed	50.3	53.9	48.55	50.4
Cost per Hour	$50.89	$52.32	$40.35	$83.03
Cost per Minute	$0.85	$0.87	$0.67	$1.38
Total Cost per Vehicle	$151.97	$160.67	$95.57	$404.53

Route One

Route One begins in Portland, Oregon and terminates in Tacoma, Washington (Figure 3-2). The route travels very close to the closed section of I-5 but does not run along it (Figure 3-3). Once the traveler is past the closure, they can take any road to reach other northbound destinations. Route One encompasses 150 miles and has a total cost per vehicle of $103.65 in mileage costs. It takes 2.9 hours to drive using the average speed limit of 50.3 miles per hour along the entire route. The average accounts for differences when switching from highways to local roads. It costs $50.89 per hour and $0.85 per minute, with a time cost to each vehicle of $151.97.

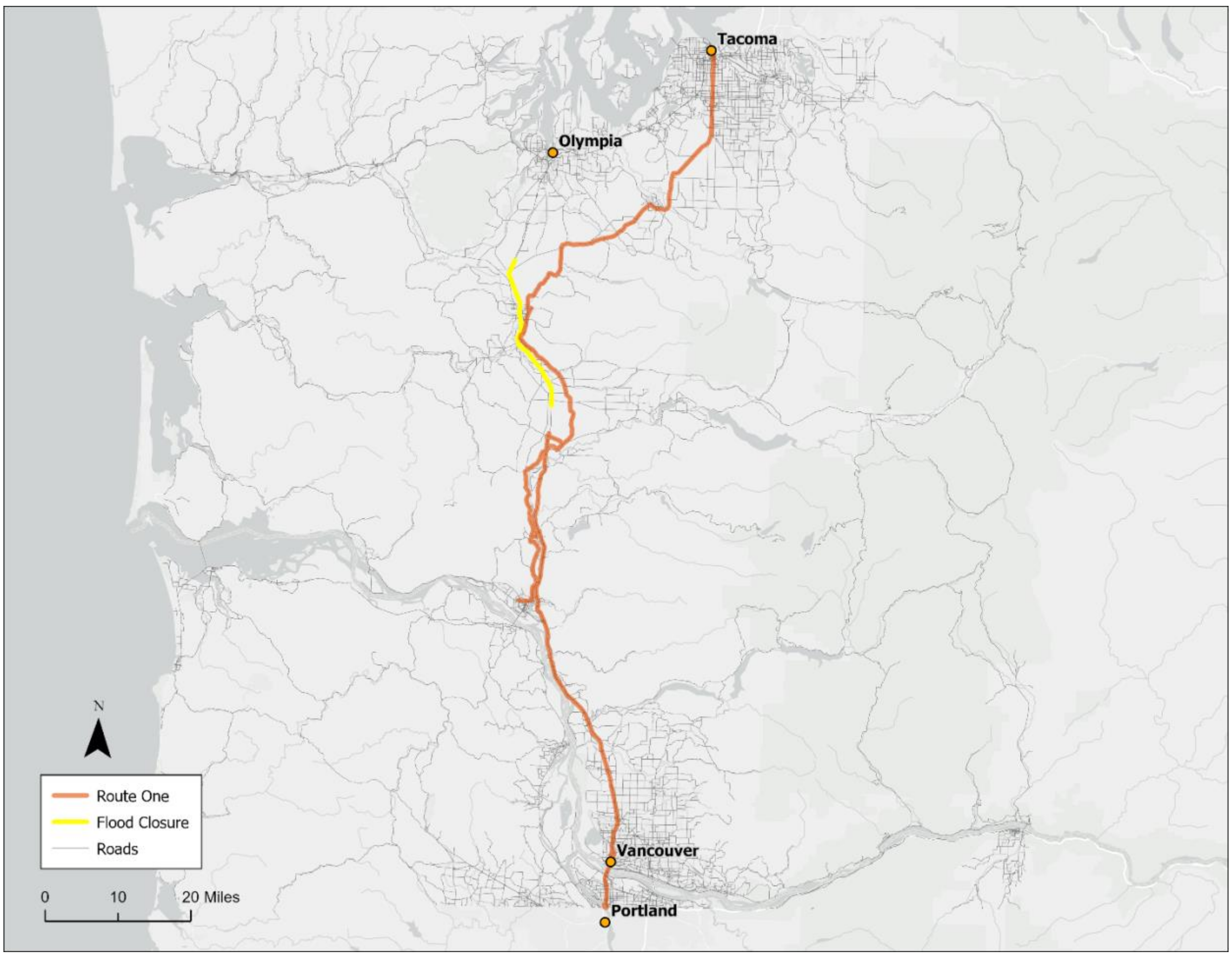

Figure 3-2. Route One, Portland to Tacoma.

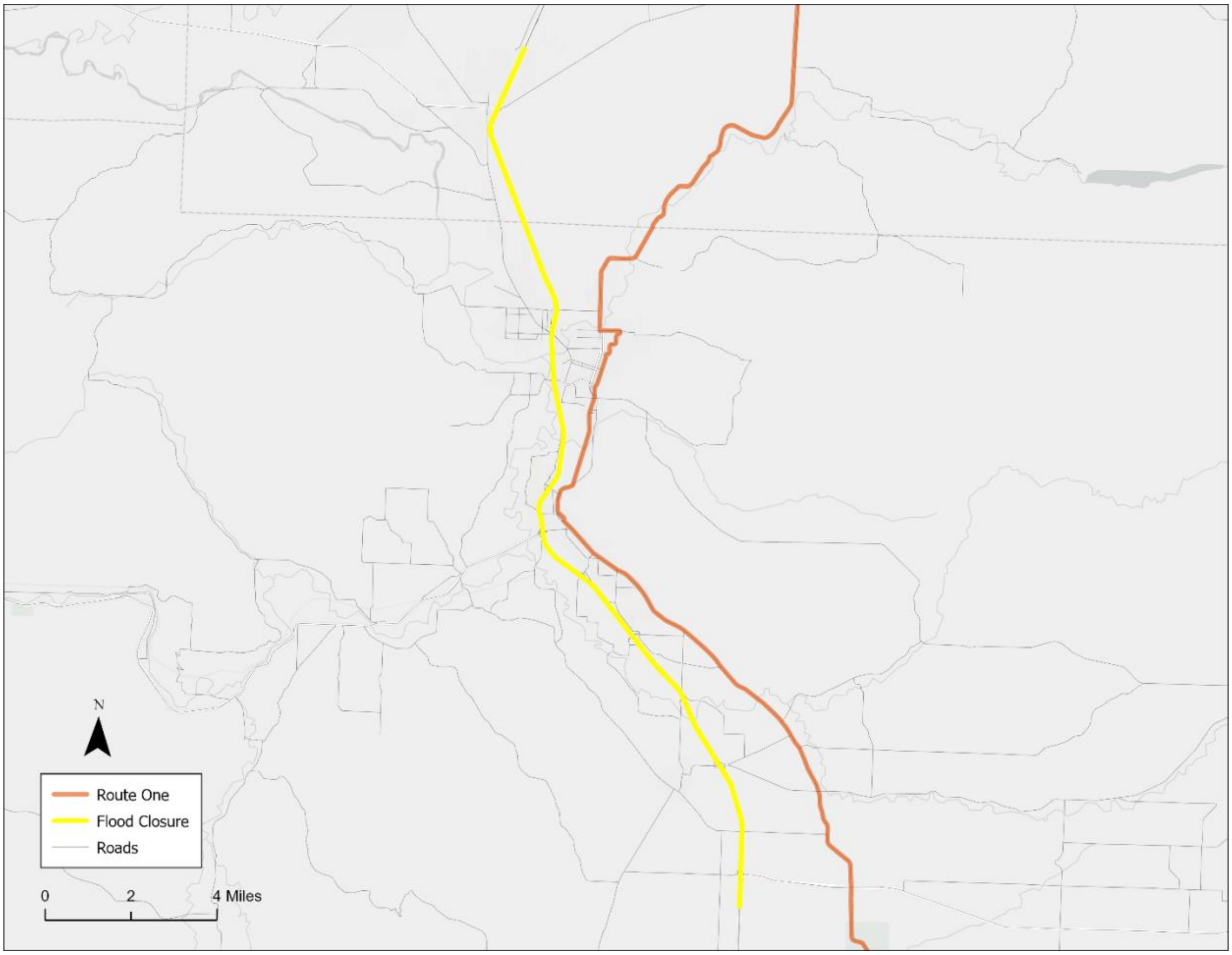

Figure 3-3. Zoomed in view of Route One as it passes the flood closure.

Route Two

Route Two shares the origin point of Route One and has two end points, in Olympia and in Tacoma (Figure 3-4). It covers 165.5 miles and costs each vehicle $114.20 to drive. It takes a different path, swinging wide in some areas (Figure 3-5). This route takes about 3 hours to drive at an average speed of 53.9 miles per hour. For each vehicle that chooses this route, it would cost $52.32 an hour or $0.87 a minute, culminating in a time cost of $160.67.

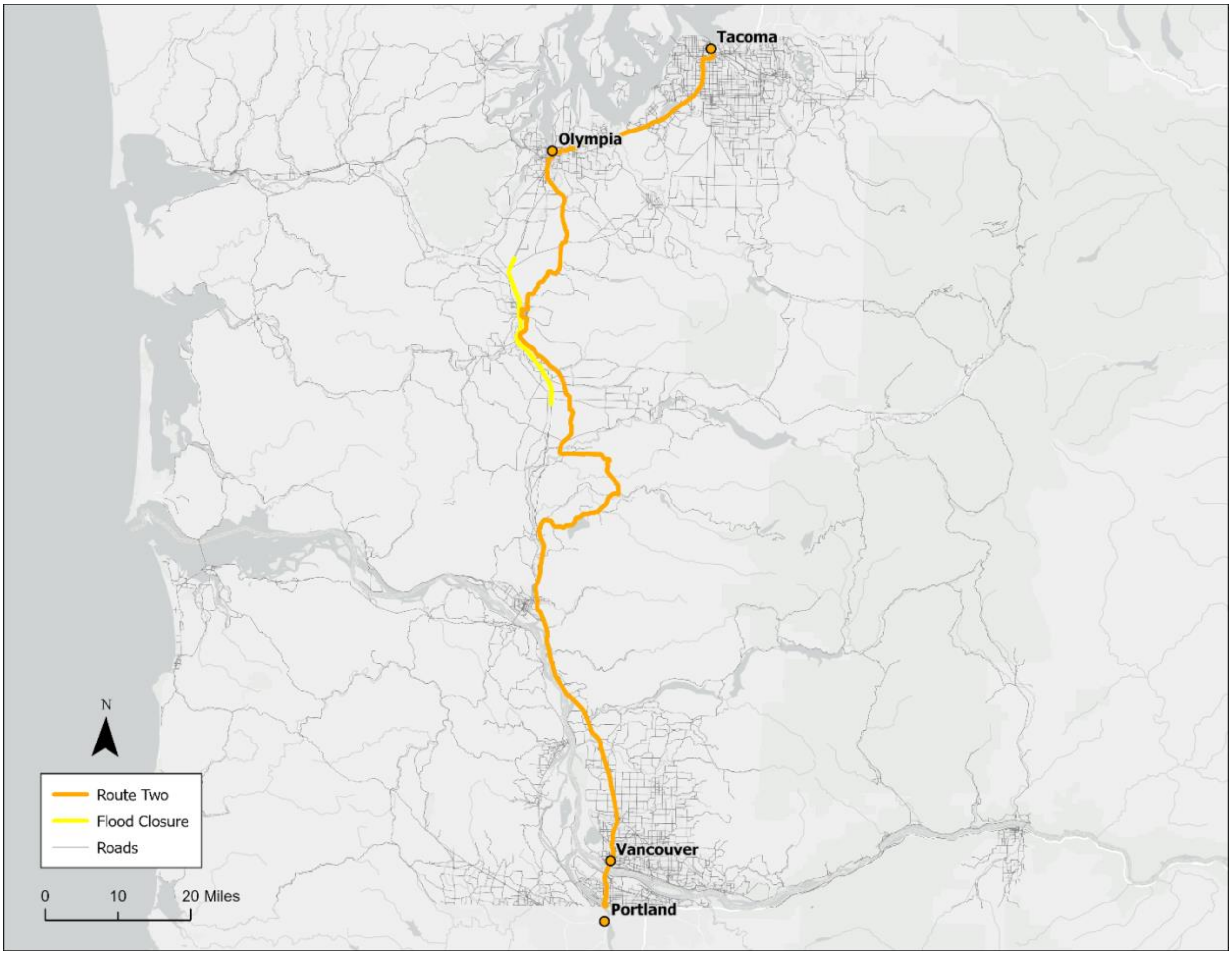

Figure 3-4. Route Two, from Portland to Vancouver to Olympia to Tacoma.

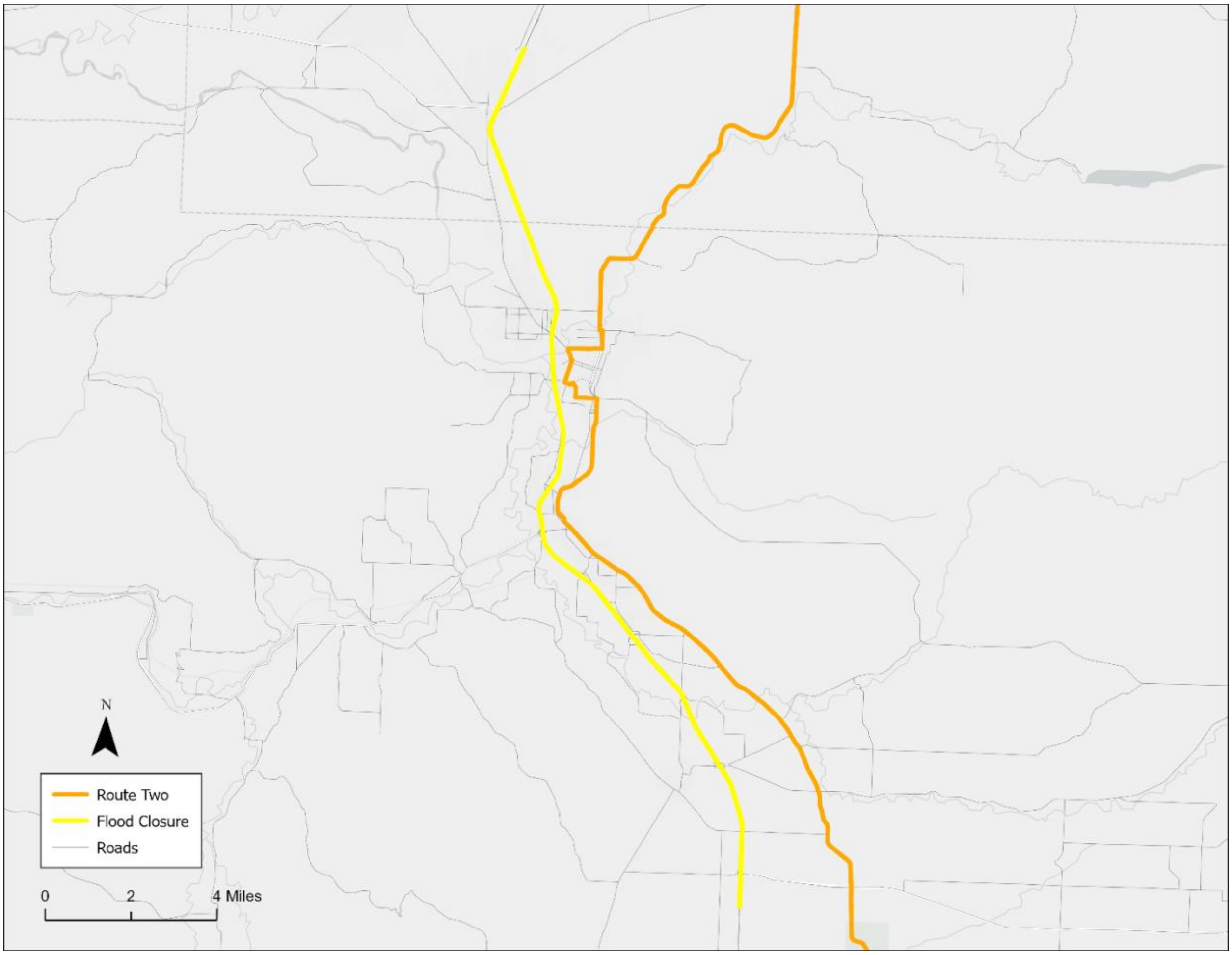

Figure 3-5. Route Two takes a slightly different path than Route One.

Route Three

Route Three is the shortest route of the four created through Network Analysis. It stretches only 114.9 miles from Vancouver to Tumwater and further north to Olympia (Figure 3-6 and Figure 3-7). It has the lowest cost per vehicle for mileage at only $79.33 per vehicle. Additionally, the time cost when computed at an average speed of 48.55 miles per hour and 2.3 hours of drive time is only $95.57 an hour and $0.67 a minute to traverse the entire route. The low cost is most likely due to the relatively short distance between the origin and destination points.

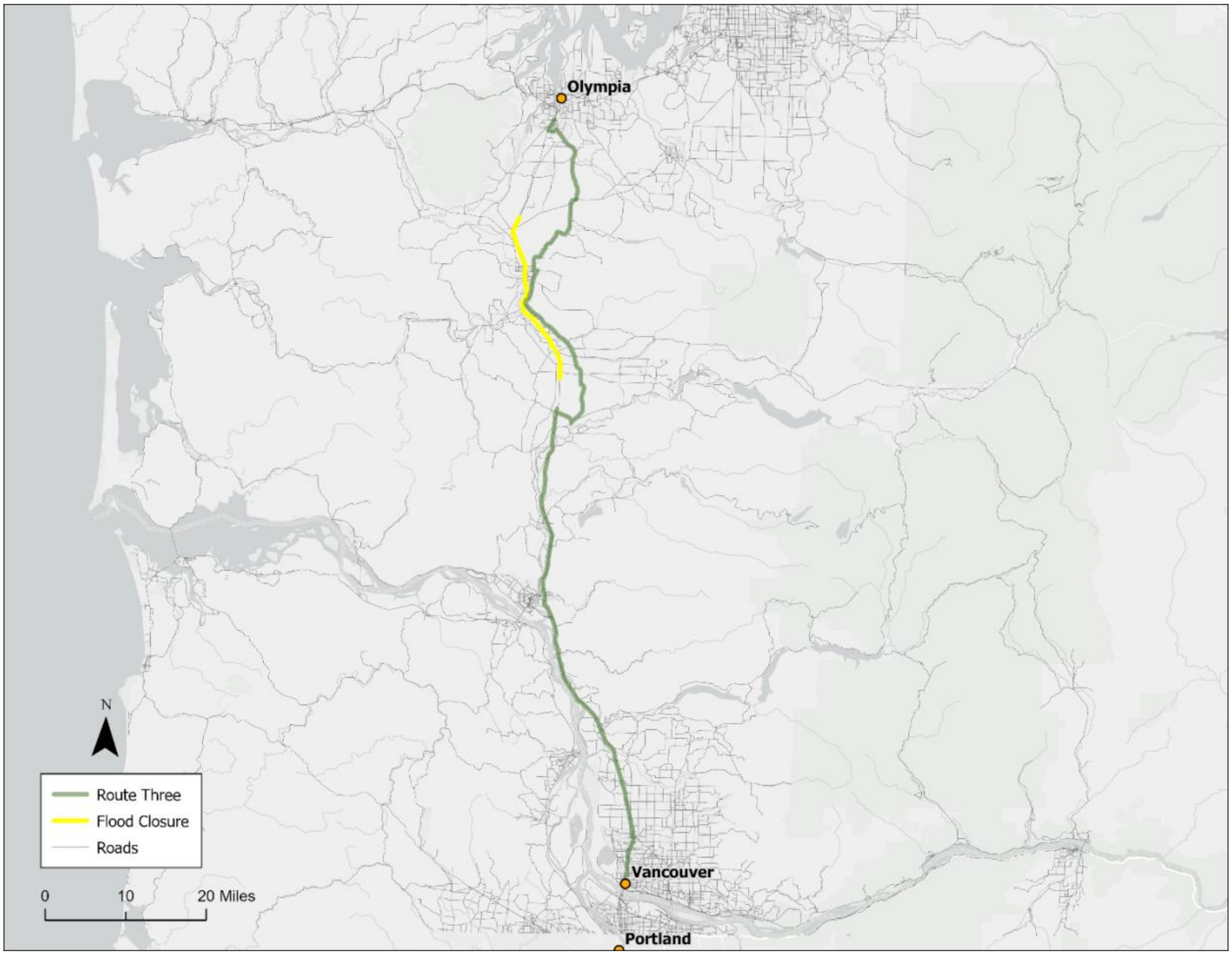

Figure 3-6. Route Three, with an origin in Vancouver and a destination in Tumwater and Olympia.

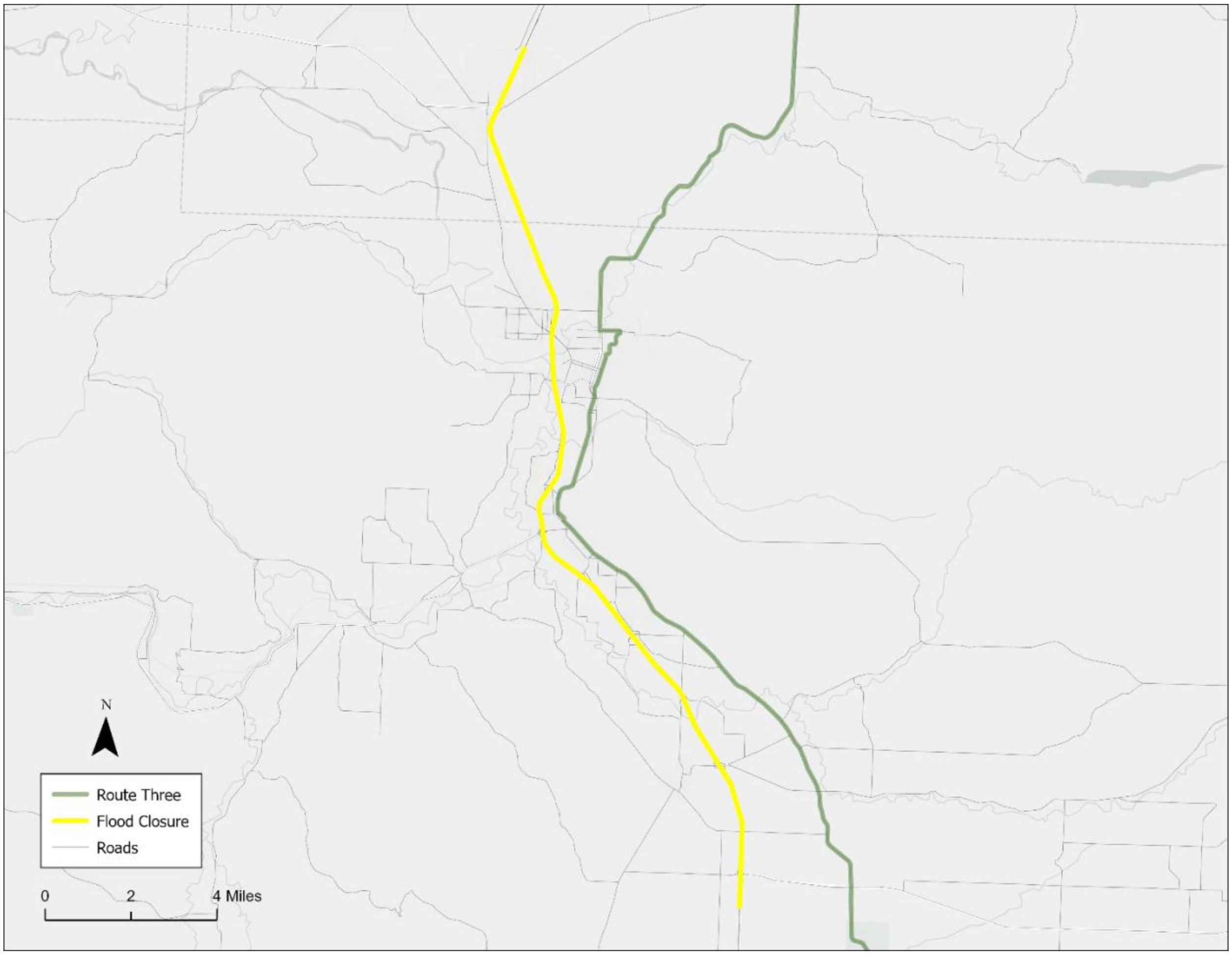

Figure 3-7. Zoomed view of Route Three. This route is nearly identical to Route One.

Route Four

Route Four begins in Vancouver and continues to Aberdeen in the west and Olympia and Tacoma in the north (Figure 3-8). It runs close to the flood closure (Figure 3-9). This is the longest route by far, though many travelers will not need to reach every destination along the route. It encompasses 245.5 miles and costs $169.44 per vehicle to travel the entire route. It takes 4.8 hours to drive at an average speed of 50.4 miles per hour. Per minute, it costs $1.38 and in sum this route has the highest time cost of $404.53.

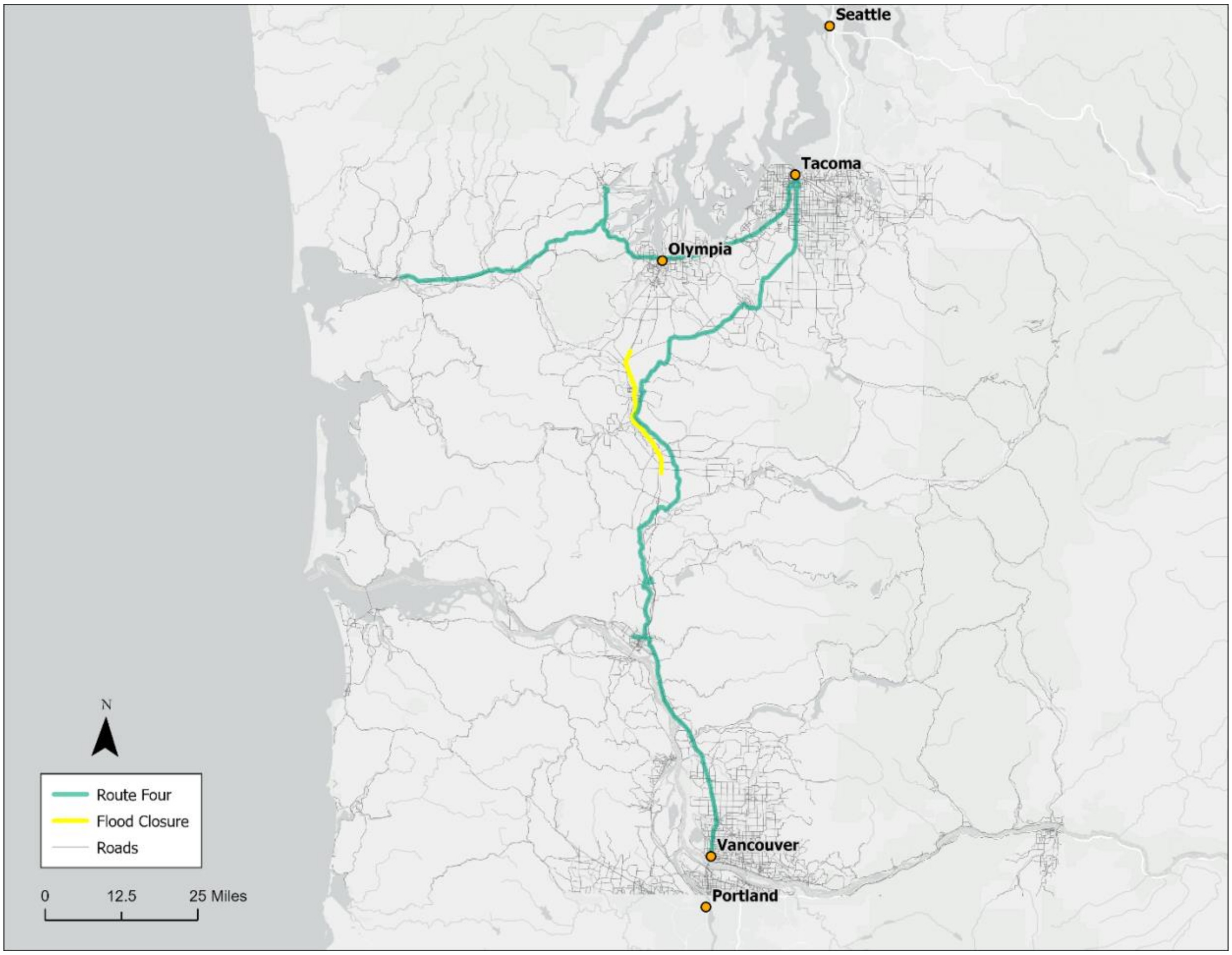

Figure 3-8. Route Four, the longest route in the analysis. This route stretches over 245 miles and takes almost 5 hours to drive.

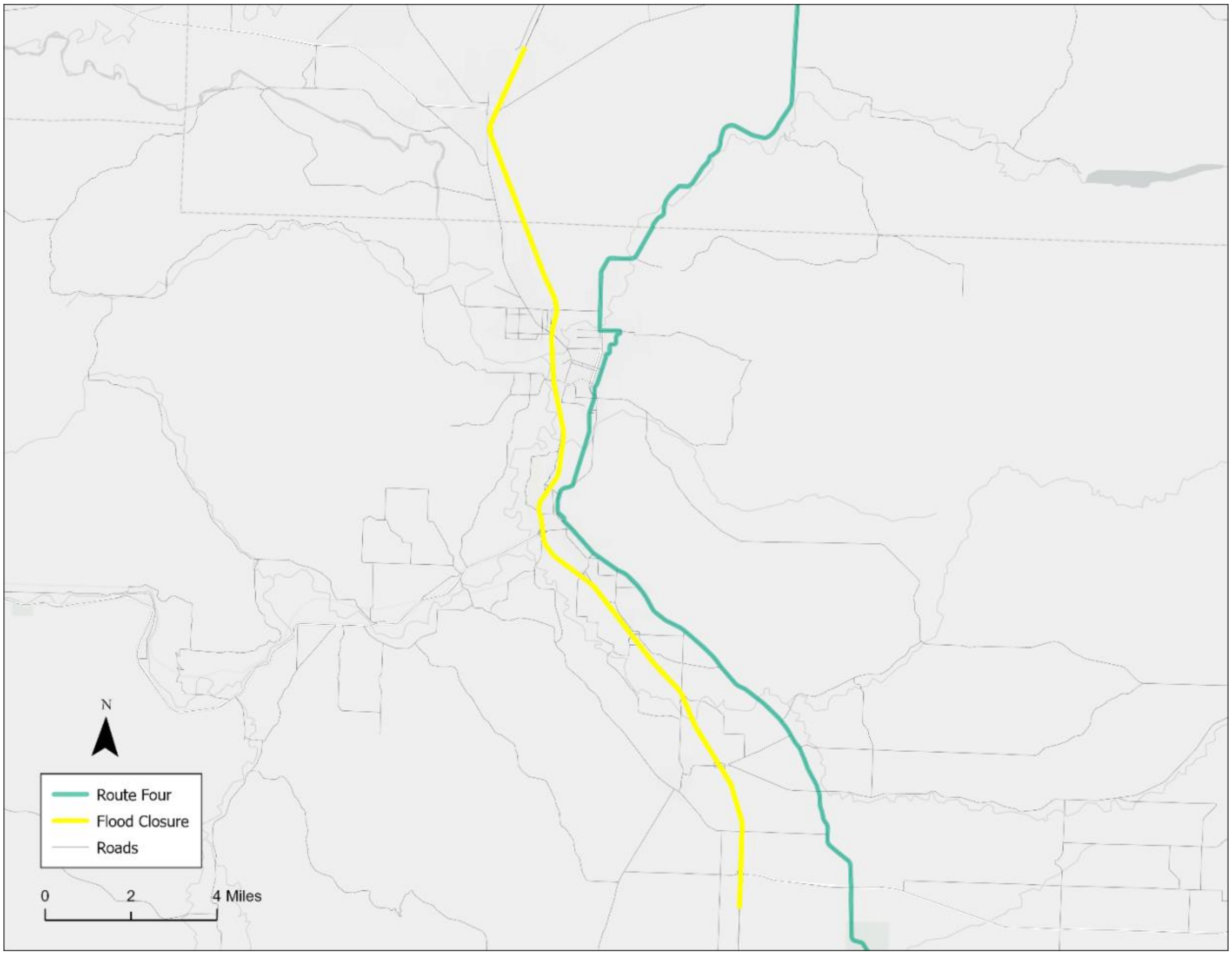

Figure 3-9. Route Four follows a similar path around the flood closure as most other routes produced by this analysis.

Historic Alternative Routes

Hallenbeck et al. (2014) defined two historic alternative routes that could be used to circumvent the flood closure area. Route 1 follows Interstate 84 (I-84) east, then north to Interstate 82 (I-82), then takes Interstate 90 (I-90) to Seattle and follows I-5 to terminate in Olympia. Route 2 begins on I-84 east, turns north on I-82, and terminates in Olympia following I-5.

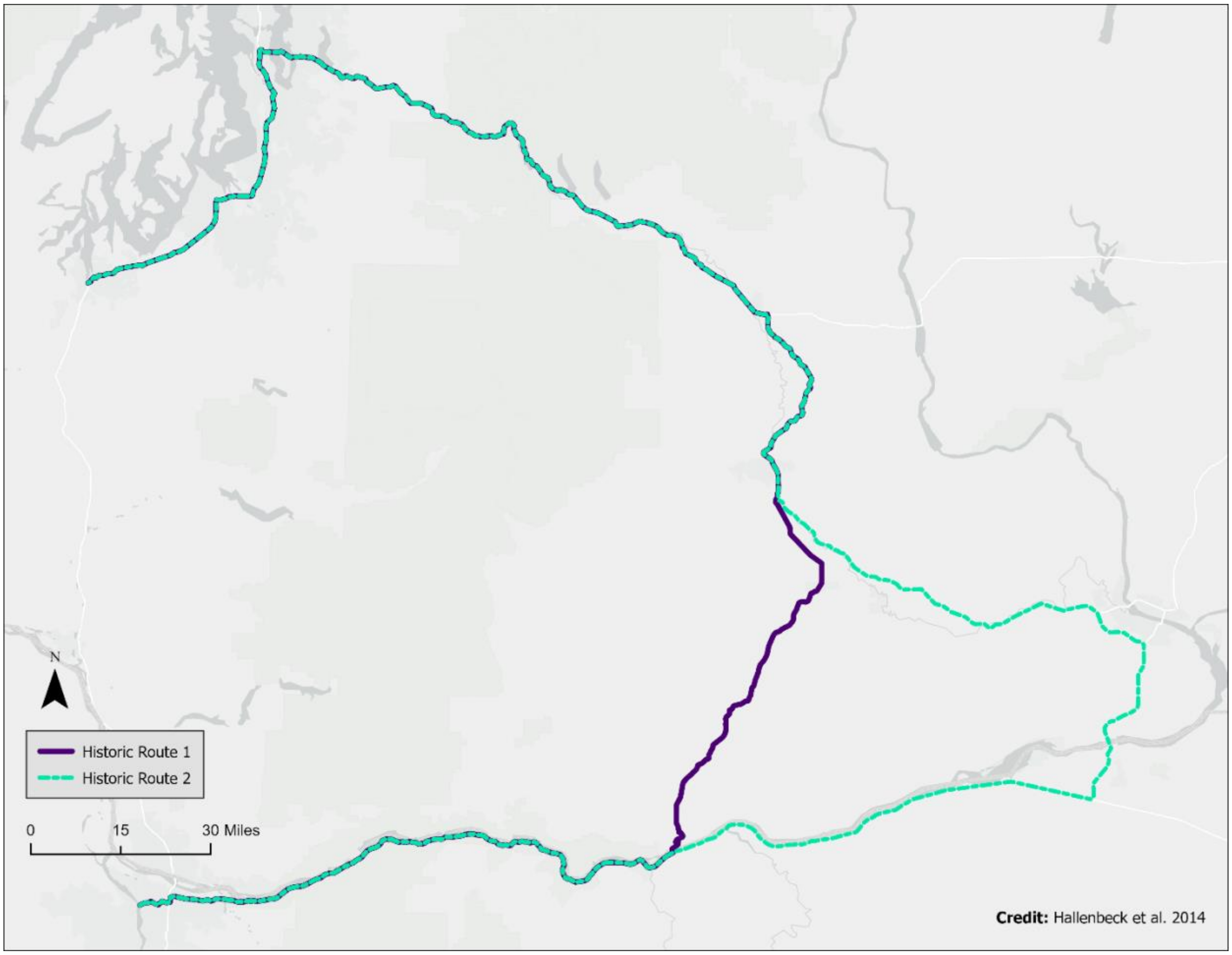

Figure 3-10. Two historic detour routes presented by Hallenbeck et al.

The two historic detour routes had the highest mileage and time costs of all the routes presented in this analysis. Table 3-5 shows a detailed breakdown.

Table 3-5. Mileage and time cost for historic alternative routes.

	Miles	
	Historic Alternative Route 1	Historic Alternative Route 2
Origin	Portland	Portland
Destination(s)	Olympia	Olympia
Miles	385.652659	490.000501
Cost per Mile	$0.69	$0.69
Total Cost per Vehicle	$266.10	$338.10
	Time	
Time (Hours)	6.427544	8.166675
Minutes	385.65264	490.0005
Average (mean) Speed	60	60
Cost per Hour	$109.52	$139.16
Cost per Minute	$1.83	$2.32
Total Cost per Vehicle	$703.94	$1,136.47

Discussion and Limitations

Discussion

Nearly every route used the same path to avoid the flood closure (Figure 3-11). Routes One, Three, and Four mirror each other exactly, while Route Two deviates by making use of local roads that see significantly less traffic. The fact that three of the four routes generated share the same path to avoid the closure results in heightened congestion, which lowers their value considerably. Additionally, none of the routes fall on the west side of I-5. There is less connectivity among the road network on the west side of I-5, which can account for this.

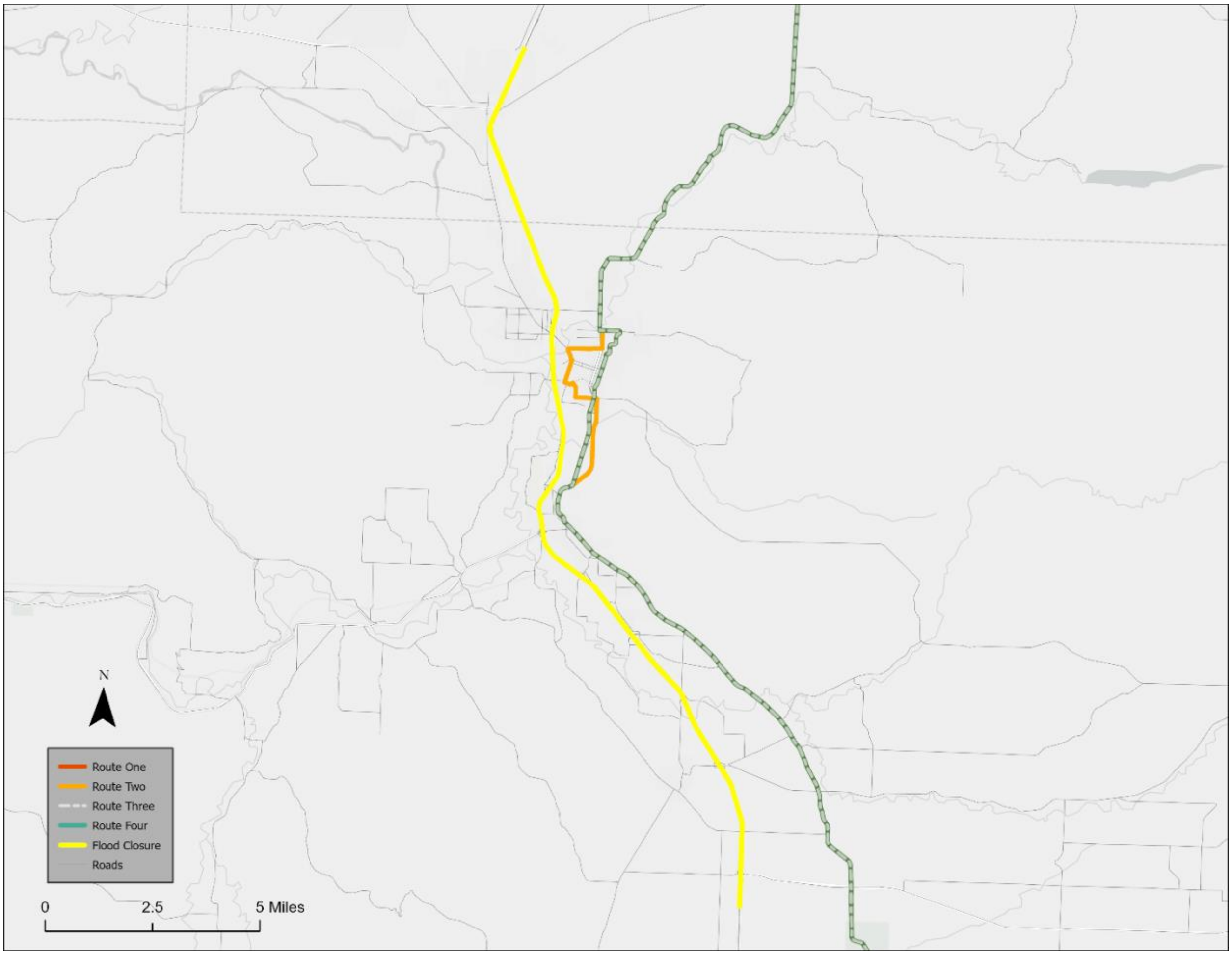

Figure 3-11. Three of four routes share the same path around the flood closure, creating congestion.

However, congestion can be slightly mitigated by including the two historic detour routes presented by Hallenbeck et al. (2014). These routes can offset the congestion on the generated detour routes if travelers are willing to absorb greater traveling costs to reach their destinations.

Limitations

This study had several limitations due to data availability and scope. The traffic counts from the permanent traffic recorders are from 2020; they represent the most recent available data. Traffic through the flood closure area is realistically higher now than it was in 2020. When Hallenbeck et al. (2014) did an analysis on flooding in 2014 on this same section of I-5, they took a survey to determine usual traffic patterns and common origins and destination points. Due to time constraints, I was not able to conduct a survey of travelers to determine patterns of travel. Additionally, three of the four routes I generated using Network Analysis followed the same path which would create congestion. Past studies recommend detour routes that cross the mountain passes and utilize I-90 and I-84 (Hallenbeck et al., 2014). These routes cost more in both time and mileage. Additionally, the start and end of the historic routes is the same, so congestion is still likely to be present in these areas.

CHAPTER 4
CONCLUSIONS

Using retrospective analysis techniques and commonly accepted origin-destination frameworks, this analysis investigated the costs of the January 7th, 2022, flood closure on I-5. There were three objectives: to identify the overall cost of the flood event using vehicle miles traveled and time cost, to evaluate possible alternative routes taken by travelers during the closure, and to investigate two historic detour routes for usability and cost comparison. Out of four possible detour routes generated by Network Analyst, only two had route variances around the flood closure; the others followed identical paths to the first route. The cost of flooding on I-5 was $924,950 when using cost per mile, and $30,161 when using cost per vehicle. Of the two unique alternative routes, Route 1 was the cheapest in both time and mileage cost. Similarly, the first Historic detour route was the cheapest of the two. However, if possible, the best route to use to avoid the flood closure would be Route 1.

The calculated detour routes showed that there are not enough feasible routes around I-5 in the event of a flood closure. There is not much network connectivity on the west side of I-5, and thus no detour routes were able to be generated for that side. If the floodwaters covered the surrounding areas, the only possible route around the closure would be over the mountain passes and would take several hours. This underscores the need to develop better flood mitigation practices for the three rivers, such as levee walls, or to increase the network connectivity so that I-5 is not the singular main route through the state. Additionally, the limited number of detour routes will lead to increased congestion and increased time costs for travelers.

If I were to repeat this project, I would explore placement of an additional route through the state north to south. Adding a route such as this to bisect the state would decrease the present congestion on I-5, facilitate additional traffic, and ease the pressure on the transportation network during flood events or other major disruptions. Additionally, I would update the hierarchy in the Network Dataset and place a higher value on local roads as alternative routes around the flood closure. There are many local road networks that surround the area of the flood closure, and these could be key to mitigating congestion and travel delays during a flood event.

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