Effect of Tsunami Damage on Passenger and Forestry Transportation in Pacific County, Washington

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The outer coast of Washington State is exposed to significant seismic and tsunami hazards. A Cascadia subduction zone (CSZ) event is expected to cause high earthquake intensities and tsunami inundation, resulting in considerable infrastructure loss, inundation of developed land, and degraded functioning of coastal communities. One area of particular concern is Pacific County, in southwest Washington, where more than 85% of the population is expected to experience severe shaking intensities. This paper establishes the predisaster passenger and freight transportation patterns and the predicted damaged postdisaster road network in Pacific County. The hazard used in the analysis was a CSZ magnitude 9.1 earthquake with Washington asperity and resulting tsunami. The anticipated change in trip distance and the percentage of trips that could no longer be completed were used to compare passenger travel and forestry freight travel. Because passenger and freight travel have different purposes and patterns, understanding how they are affected differently can serve as a foundation for community-based disaster recovery planning to increase community resilience in earthquakes and tsunamis.

The outer coast of Washington State is exposed to significant seismic and tsunami hazard. A Cascadia subduction zone (CSZ) event is expected to cause high earthquake intensities and tsunami inundation, resulting in considerable infrastructure loss, inundation of developed land, and degraded functioning of coastal communities (*1*). One county of particular concern is Pacific County, located in southwest Washington and home to the towns of Long Beach, Ilwaco, Raymond, and South Bend. The county is home to 20,920 permanent residents, according to the 2010 census (*2*), but the seasonal population can swell to many times this number because of the strong coastal tourism economy.

According to recent modeling conducted by federal, state, and private collaborators, the estimated losses from the ground shaking of a CSZ earthquake would be significant in Pacific County, with more than 85% of the population expected to experience severe shaking intensities. More than 1,700 buildings are expected to be heavily damaged, with an additional 2,690 buildings experiencing moderate damage (*3*). In addition to severe shaking, nearly half of Pacific County's residents and more than half of all county businesses are located in a tsunami inundation zone (*4–6*).

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Estimated damage to transportation infrastructure is also particularly notable in Pacific County. Seismic shaking is expected to heavily damage 10% of the county's highway bridges and to moderately damage an additional 55% (*3*). Tsunami inundation is estimated to compound the damage from seismic shaking on the major highways and state routes in Ilwaco, Long Beach, Shoalwater Bay, Raymond, and South Bend (*5*). Damage to the transportation network will affect personal daily tasks and limit the movement of commodities in and out of the county. Restoring critical infrastructure for passenger travel is vital as Contreras et al. found that the distance and travel time from relocation settlement to city center accounts for 55% of residents' preference to move to a new settlement (*7*). With forestry as one of the major economic drivers in Pacific County, the roadways this industry relies on should also be prioritized. Understanding how passenger and forestry travel are affected can serve as a foundation for community-based disaster recovery planning to increase community resilience in earthquakes and tsunamis.

LITERATURE REVIEW AND PAST WORK

The current state of earthquake and tsunami recovery planning builds on several years of significant work in Washington State. State agencies, academic institutions, and local communities have worked together to characterize coastal seismic and tsunami hazards, develop tsunami inundation maps, model marine environment impacts, and engage in hazard-related community planning. In 2010, the Washington State Department of Emergency Management commissioned the estimation of human and infrastructure losses resulting from 20 scenario or historic seismic events in Washington State. These loss estimations used scenario ground motion hazard maps in the ShakeMap format as higher accuracy input to the Federal Emergency Management Agency's multihazard loss and estimation tool, HAZUS-MH (*3*). The ShakeMaps are also used in this analysis as a basis for the estimation of ground shaking.

The use of four-step travel demand models to gain an insight into transportation patterns that deviate from the baseline is well established in the literature. The general idea is to use trip demand data (e.g., census data) for various types of trips as a basis for creating origins and destinations on the network (i.e., trip generation and attraction). Next, the mode is assigned, and finally the route is determined according to some criteria. The result is an overview of how the network is used in aggregate (*8*). The travel demand model is a useful tool when trying to understand the demand before and after a change, in this case a disaster.

By using a travel demand model for potato and diesel supply chains, Goodchild et al. found that the effect of I-90 closures in

Washington State led to different impacts on transportation for the commodities (*9*). Given the origins, destinations, and modes, the two commodities exhibited very different usage patterns, with a closure of I-90 having large impacts on potato trips, and much smaller impacts on diesel trips. In addition, because potatoes are low value and the cost of a detour was relatively costly, trips were reduced. The nature of the differences was because of the value and time sensitivity of the cargo, origins and destinations, and the modes available (*9*). This paper will use a travel demand model to gain an insight into whether and how passenger and forestry freight travel differ.

CSZ EARTHQUAKE

A subduction zone is an area in which one tectonic plate slides under another, less dense, plate. In the case of the CSZ, the bottom plate is the oceanic Juan de Fuca plate and the top plate is the continental North American plate. As the plates slide past each other, friction causes the top plate to be locked, causing the North American plate to lift as the Juan de Fuca plate slides beneath it. When the stress in the locked zone becomes too high, the top plate slips past the bottom plate creating an earthquake, which results in subsidence near the shore and uplift offshore. The subsidence causes inundation on land, and the offshore uplift can create a tsunami (*10*).

The hazard scenario considered in this study is the CSZ earthquake Scenario 1A with a Washington asperity, referred to hereafter as Scenario 1A with asperity, first developed by Priest et al. (*11*) and Myers et al. (*12*) in the late 1990s. The scenario assumes a magnitude 9.1 CSZ earthquake with a rupture length of 650 mi, a rupture width of 45 mi, and an average slip of 17.5 m. An event of this type will create significant ground shaking, which can cause roads to crack, split, buckle, and form mounds, dips, and potholes. Subsidence can cause roads to completely collapse (*13*).

Ground shaking damages infrastructure, liquefies saturated sandy soils, and triggers landslides (*14*). When liquefaction occurs, soil loses its strength and stiffness and cannot support the infrastructure built atop it. When the soil resolidifies, it may not do so evenly; this is called differential settlement. When the soil beneath buildings, bridges, and roads experiences differential settlement, it can cause structural damage. Another effect of liquefaction is lateral spreading on gentle slopes, where sections of soil separate horizontally as a result of the loss of shear stress. Lateral spreading can cause roadways to break apart.

The Scenario 1A with asperity earthquake would also produce a tsunami that would reach the North American coast in as little as 30 min at a height of 7 to 8 m (*15*). The model of the National Oceanic and Atmospheric Administration, which times the tsunami at high tide, predicts that Pacific County will experience extensive inundation in all areas along the western coast of Long Beach, with depths averaging between 1 and 3 m (*16*). Inundation may affect the road infrastructure through several forces, including buoyant, impact, hydrostatic, drag, and surge forces. Roads that are inundated become saturated and lose strength.

For this study, it is assumed that roads that are affected by both ground shaking and tsunami inundation are impassable. In the transportation model (Figure 1), the affected roads are simply removed from the intact network to create the damaged road network.

PASSENGER TRAVEL

The goal of the passenger travel model is to understand the total nonconcurrent demand on the network by passengers. The result of the model shows the critical links and the areas of activity. The passenger travel simulation consists of multiple steps: creating a network, generating households and facilities such as work and school,

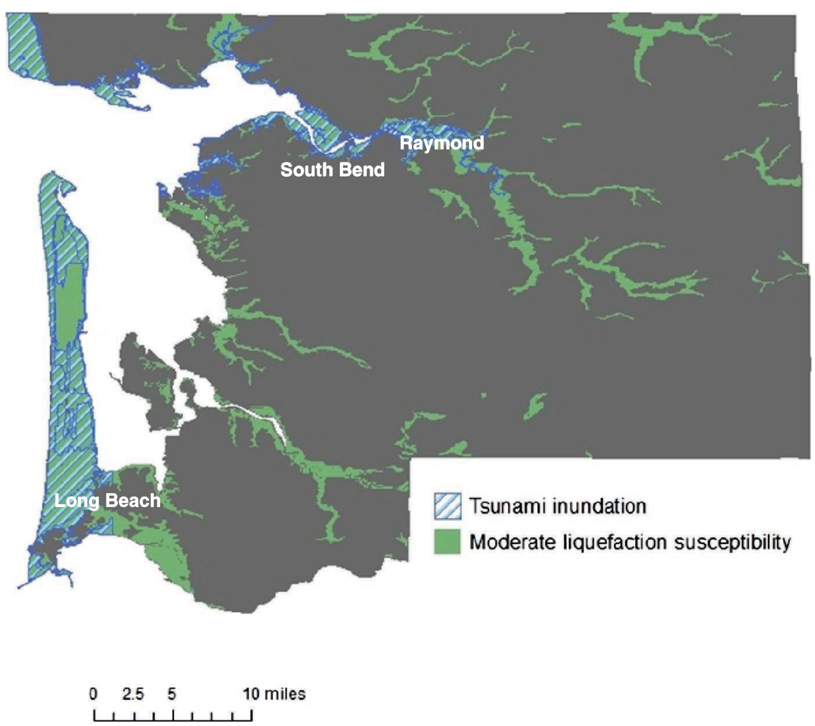


FIGURE 1 Areas expected to be inundated by tsunamis generated by Scenario 1A with asperity and areas with moderate liquefaction susceptibility.

assigning trips, and calculating the shortest trips. The Washington road network data were obtained as a shapefile from the OpenStreetMap data extract site Geofabrik (*17*). The network, as shown in Figure 2, was used to create the network data set in ArcGIS for use in the network analyst extension.

The household characteristics come from the 2009–2013 American Community Survey (ACS) 5-year estimates (*18*), but are randomly applied to each household. The simulation input parameters are total population (initial total population = 20,920) and total housing units (initial total housing units = 15,575), which are currently set to the 2013 ACS estimates. The number of occupied housing units is a percentage of the total housing units. From the 2013 ACS estimate, this percentage is 60.1%. These numbers can be updated to the estimated population and housing units at times during the recovery. For the occupied households, the following characteristics are determined: household size, number of household members under age 5, number of household members between the ages of 6 and 10, number of household members between the ages of 11 and 17, number of working adults, number of adults who work in the county, number of adults who work outside the county, and address.

Household size is calculated using 2013 ACS estimates to assign household size to each occupied household unit. Household size can be one person (28.9%), two people (46.3%), three people (11.8%), or four or more people (13.0%). Household size is coded as a percentage of the total occupied units, so the absolute numbers will change if the total housing units change.

Children are split into three groups according to age: 5 and under (4.6%), between 6 and 10 (4.74%), and between 11 and 17 (7.12%). Each percentage is of the total population. To assign children to households, first the household size is reduced by one (assuming every household has one adult). If the remaining number of household members is greater than 0, children between 6 and 10 are assigned, then children between 11 and 17 are assigned, and finally children under 5 are assigned, each according to an appropriate Bernoulli distribution. Each time a child is assigned to a household, one household member is removed from the remaining available household members so that the overall household size is unchanged. School-age children are assigned to the closest appropriate school to their address.

The number of employed adults is applied simply as a percentage (49.2%) of adults. The ACS reports this percentage for all residents 16 and older. The ACS also reports, however, that those residents aged 15 to 17 have 100% school enrollment in high school. Therefore, the employment percentage is applied only to adults. First, all children are removed from a list of household size and then the Bernoulli distribution using the employment probability is applied to the remaining adults. Working adults are divided between in-county (79.3%) and out-of-county workers.

Any household with at least one elementary school–aged child is assigned one elementary school trip to the closest school, and any household with at least one middle or high school–aged child is assigned one trip to the closest middle school or high school. Any household with an in-county working adult is assigned a trip to the closest central business district (CBD), and any household with an out-of-county working adult is assigned a trip to the closest out-of-county node: U.S. Route 101 south, U.S. Route 101 north, SR-4, or SR-6. Each household is assumed to make one grocery shopping trip (*19*) to the closest CBD once a week (*20*).

Addresses are taken from the Pacific County geographic information system database. All addresses with a land-use code corresponding to residential housing were kept, and then this list was randomly sampled with replacement to create the list of occupied housing units (see Figure 3). This step is appropriate because a subset of the addresses are not single family homes but multiunit buildings.

All persons going to the same location from one household unit will be assumed to travel together in one vehicle. All working adults and school-aged children are assumed to work or attend school Monday through Friday and travel during the morning and afternoon peak periods. Pacific County school addresses are used.

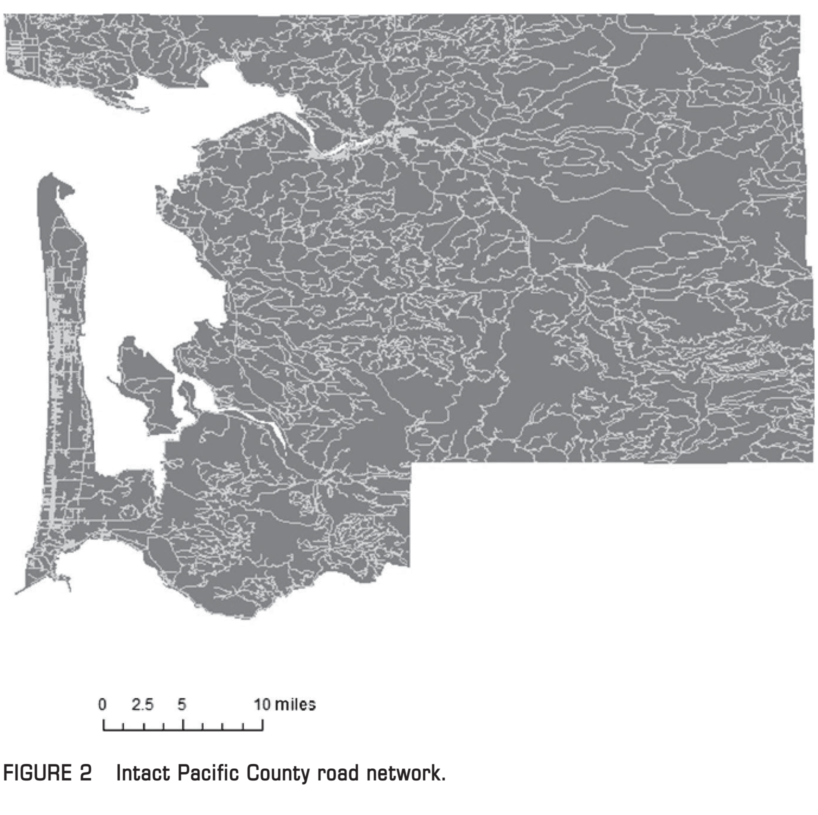


FIGURE 2 Intact Pacific County road network.

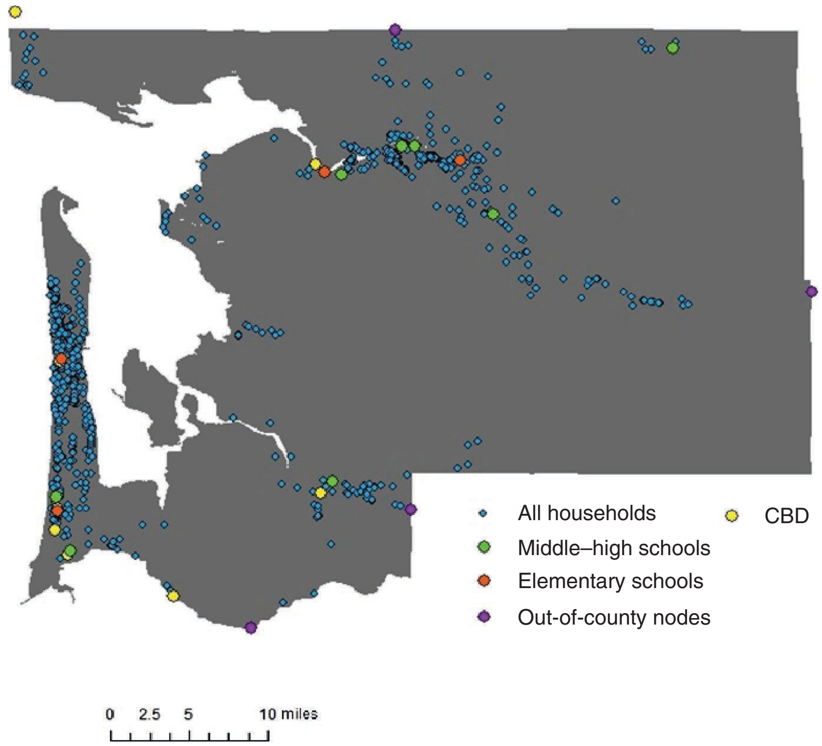
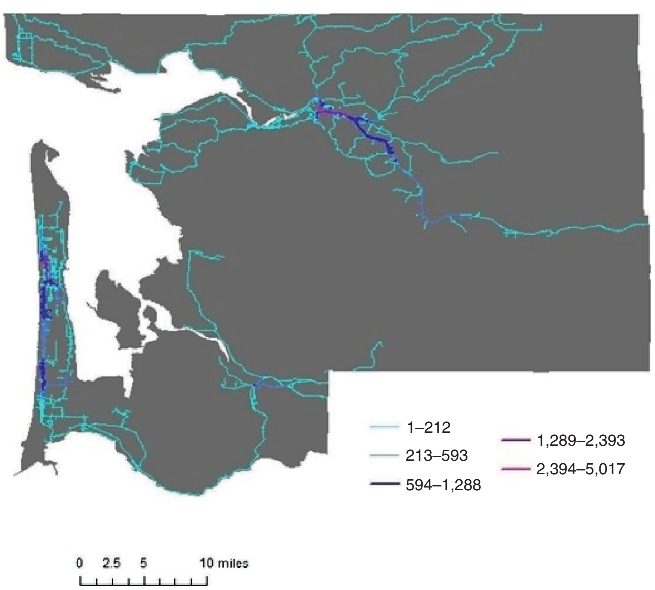


FIGURE 3 Passenger travel nodes; residences are clustered in Raymond and South Bend area and Long Beach Peninsula.

The ArcGIS closest facility tool is used to determine the roads used and total distance traveled for each trip that occurs. In the context of this tool, the residences are incidents and the schools, workplaces, and CBDs are treated as facilities. The shortest trip is measured by shortest distance. Congestion is not accounted for because all roads in Pacific County operate at Level of Service A (*21*).

To determine the most-used road segments, all passenger trips taken on one given work day morning under normal operating conditions during the school year are combined. Spatially joining the route segments with the network data set yields counts of how many times each network segment was used. Only segments used for a trip are shown on the map.

The overlay is not meant to describe any specific instance of time, but rather overall use of the network in 1 day. In Figure 4, pink and purple road segments appear in the areas of Long Beach, Raymond, and South Bend, meaning that the highest number of trips occur in



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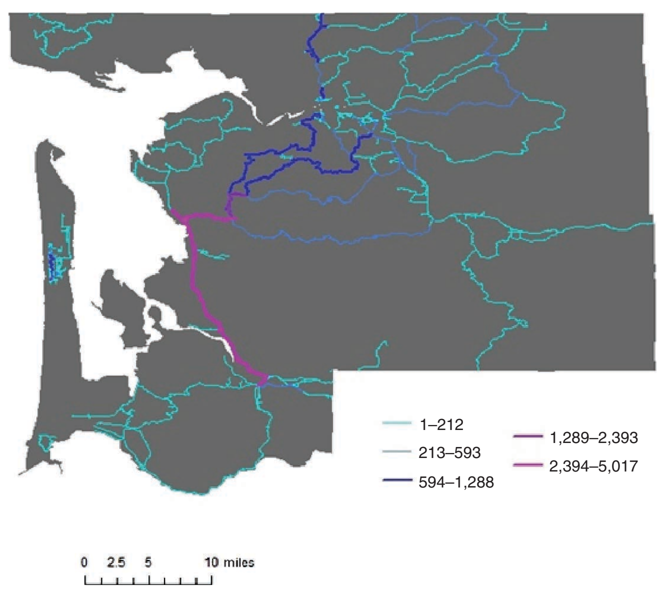


(b)

FIGURE 4 Destruction of road network results in 40% reduction of all passenger trips: (*a*) trips on intact network and (*b*) trips on damaged network.

TABLE 1 Summary of Trips on Intact Predisaster Network

Reason for Trip	Average Trip Length (mi)	Maximum Trip Length (mi)	Total Number of Trips
Elementary school	3.01	25.72	913
Middle–high school	5.32	25.51	1,248
Grocery store	3.14	19.22	1,850
Work in county	3.18	19.43	9,201
Work out of county	15.62	26.11	76

these areas. Table 1 presents the average and maximum travel distance for passenger trips, as well as the total number of trips taken. Workers who travel out of the county have the longest commute, but they represent a very small portion of all travelers. Note that the trip length reported for out-of-county workers accounts only for travel inside Pacific County; the worker may travel an additional distance in neighboring counties.

SCENARIO 1A WITH ASPERITY PASSENGER TRAVEL

The analysis for Scenario 1A with asperity follows the same steps described for the intact analysis with only one change: the network. The damaged network is created by removing all road segments that are in the areas with high to moderate liquefaction susceptibility and the area of tsunami inundation.

It is assumed that all trips generated in the intact analysis are attempted in the damaged scenario. In other words, the model assumes all households, places of work, CBD, and schools are functional and that residents will attempt to travel between them. This approach represents the maximum passenger transportation load the network is expected to carry after the disaster.

Running the analysis with the damaged network results in an increase in travel distance and a decrease in trips (see Table 2). The decrease in trips is caused by either the origin or destination being inaccessible on the damaged network. Comparing the intact and damaged results in Figure 4, one can see that in the intact scenario, travel is centralized in the Long Beach Peninsula and farther north in the area of Raymond and South Bend. The critical links in the intact scenario fall within the tsunami inundation area. Therefore, in the damaged scenario, residents have to travel to neighboring schools and CBDs, thereby increasing their travel distance. Intact travel is localized and remains within zip codes; damaged travel is spread out and occurs between zip codes. Intact travel is generally along the coast and avoids the forest areas inland, whereas damaged travel makes use of inland roads because the coastal roads are impassable.

FORESTRY TRAVEL

More than 90% of Pacific County is forested (*22*); the types of wood that are harvested in Pacific County include western hemlock, Douglas fir, cedars, ponderosa pine, red alder, and other pines and conifers. The total amount of timber harvested in Pacific County in 2014 was 340,533 thousand board feet (MBF), making Pacific County the sixth largest timber producer in Washington State by MBF (*23*).

The forestry supply chain starts in the forest where trees are grown. Each year, a portion of the forest is chosen for harvest. The felled logs are transported from their stump to a landing site. A landing site is an area in which trees are collected, processed, and stacked to be put onto a logging truck. The trip between the stump and the landing site takes place on skid roads; these trips are not included in the model. From the landing site (which is placed near a forest road), logs are transported to either a mill or an export facility on forest roads and public roads. Trucks are the primary mode for transporting timber from the landing site to the mill; the model assumes that trucks are the only mode. From the mill, wood products are transported to secondary markets (*24*). Timber and wood products are the largest commodity transported in and out of Pacific County, accounting for 23% of trucks with loads and 41% of total tonnage in 1998 (*25*).

The areas that are considered forest land in the model are the five forest areas coded as forest lands with long-term commercial significance in Pacific County's comprehensive plan (*21*). Assuming that 1% of the forest is harvested in 1 year (*26*), random landing sites were created within the forest areas using the ArcGIS tool for creating random points; one landing site per 100 harvested acres tool, for a total of 41 sites. The landing sites were generated in each of the five forest areas proportionately:

Forest Area 1. 35,428 acres, 8.6% of total forest, four landing sites;
Forest Area 2. 120,749 acres, 29.3% of total forest, 12 landing sites;
Forest Area 3. 214,894 acres, 52.2% of total forest, 21 landing sites;
Forest Area 4. 32,125 acres, 7.8% of total forest, three landing sites; and
Forest Area 5. 8,484 acres, 2.1% of total forest, one landing site.

The only sawmill in Pacific County is the Raymond lumber mill. This mill processes (*a*) all wood that is produced and processed in Pacific County and (*b*) all wood that is transported from other counties to Pacific County for processing. Pacific County processes wood

TABLE 2 Summary of Trips on Damaged Postdisaster Network

Reason for Trip	Average Trip Length (mi) (% increase)	Maximum Trip Length (mi) (% increase)	Total Number of Trips (mi) (% decrease)
Elementary school	10.63 (252.79)	79.44 (208.80)	609 (33.30)
Middle–high school	10.45 (96.35)	54.65 (114.23)	636 (49.04)
Grocery store	15.85 (396.56)	42.66 (122.00)	1,157 (37.46)
Work in county	20.83 (554.70)	42.66 (119.56)	5,641 (38.70)
Work out of county	19.13 (22.48)	41.35 (58.37)	37 (51.32)

TABLE 3 Incoming Timber from Washington State Destined for Pacific County Mill

County of Harvest	Amount (MBF)	No. of Trips
Clallam	39,109	11,174
Clark	1,488	426
Cowlitz	6,813	1,947
Grays Harbor	41,507	11,860
Jefferson	13,895	3,970
King	2,663	761
Kitsap	2,663	761
Lewis	71,727	20,494
Mason	2,663	761
Pacific	52,671	15,049
Thurston	17,604	5,030

SOURCE: Washington State Department of Natural Resources.

from Clallam, Clark, Cowlitz, Grays Harbor, Jefferson, King, Kitsap, Lewis, Mason, and Thurston Counties (see Table 3). Random points in these counties serve as origins for a portion of the wood destined for the Raymond lumber mill.

Wood harvested in Pacific County is processed in mills in Pacific County, on the Olympic Peninsula, in the Puget Sound region, and in Clark and Cowlitz Counties (see Table 4). Mills in these counties will act as destinations for a portion of the timber with origins at Pacific County landing sites. The ports of Longview and Grays Harbor export logs, with Longview handling the most MBF of all ports in Washington and Oregon. Weyerhaeuser, a wood products company, maintains its own port facilities as well. The port locations, however, are close to the mills in these counties; therefore, for simplicity, only mills will be used.

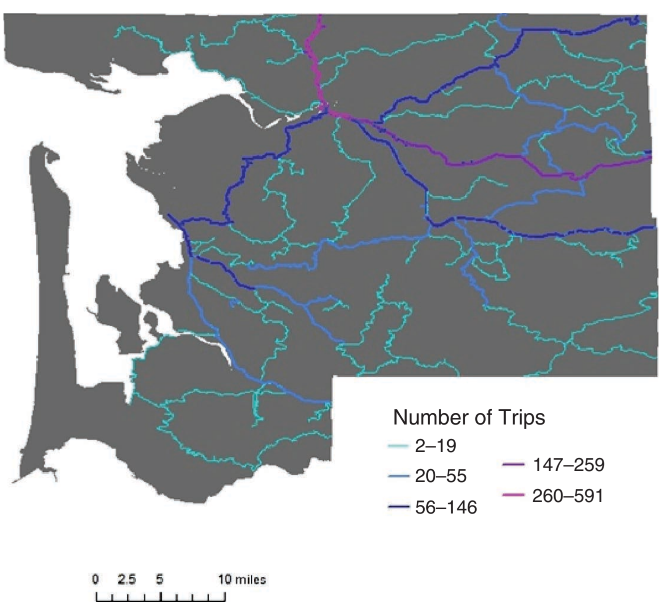
TABLE 4 Outgoing Timber from Pacific County Landing Site Destined for Washington State Mills

Area of Processing	Amount (MBF)	No. of Trips
Puget Sound Mills	12,488	3,568
Grays Harbor Mills	58,329	16,666
Lewis County Mills	26,168	7,477
Clark County Mills	26,628	7,608
Cowlitz County Mills	19,985	5,710

Taking the amount of Pacific County wood processed in the various counties in Washington from the 2014 mill survey and assuming the average logging truck trip can carry 3.5 MBF (*27*), Table 3 shows the number of trips leaving landing sites in Washington State destined for the Pacific County mill during the year 2014.

As in the passenger model, the ArcGIS closest facility tool is used to determine the roads used and total distance traveled for each trip. The shortest trip is measured by shortest distance. Congestion is not accounted for because all roads in Pacific County operate at Level of Service A.

Carrying out the analysis for both the intact and damaged road network yields the results shown in Figure 5. The main change is the use of an alternative route in the damaged scenario that minimally increases travel distance. Because forestry is not located by the shore, where inundation will damage the roads, it is not highly affected by the transportation disruption, and all predisaster trips can be completed on the postdisaster network. The average intact forestry trip length is 77.87 mi, whereas the average damaged forestry trip length is 84.18 mi. Likewise, the maximum trip length on the intact network is 183.76 mi, and the maximum trip length on the damaged network is 184.96 mi.



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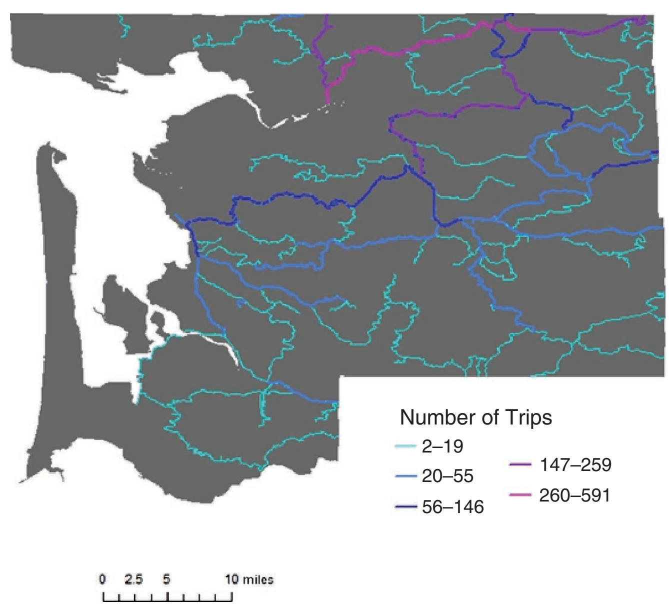

(b)

FIGURE 5 Destruction of road network does not prohibit any forestry trips from taking place: (*a*) trips on intact network and (*b*) trips on damaged network.

CONCLUSIONS

The models created in this paper are large-scale, total demand pictures of transportation before and after a CSZ earthquake and tsunami. With the majority of the county dedicated to forestry, the residential areas are clustered in low-lying coastal areas. Before the disaster, the majority of passenger travel is contained within each residential cluster. After the disaster, many of the coastal roads are impassable, forcing residents to travel inland to the smaller CBDs in the interior of the county.

Forestry travel, however, takes place on interior roads before the disaster and therefore does not suffer major disruptions after the disaster. The Pacific County mill, however, is close to the water, where some roads are damaged by the tsunami; Figure 5 shows that, postdisaster, trucks must travel inland and then back west to reach the mill rather than travel directly. The mill is located in Raymond, which is also a population center. Therefore, the models in this paper suggest that Raymond is a key regional transportation center.

With the damaged network, U.S. Route 101 becomes a key transportation corridor for passenger trips, but it is less essential for forestry trips. A key difference is the location of the origins and destinations, with passenger nodes being localized in the tsunami inundation zone. Forestry, however, is located inland and on higher ground. Transportation recovery plans that address passenger travel demands only will not serve the key economic engine of the state. Likewise, only planning for forestry will leave many passengers stranded.

This analysis highlights the potential that key segments of a county's economy use the road infrastructure in significantly different ways and that the different segments may not be equally served by an earthquake recovery plan that focuses on only one segment. By understanding the subnetwork in use by the various segments, communities will be better able to predict a hazard's impact and focus resources on the most effective solutions.

ACKNOWLEDGMENT

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