Impact of Forest Road Maintenance Policies on Log Transportation Cost, Routing, and Carbon-Emission Trade-Offs: Oregon Case Study

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Abstract: Wood transportation costs have significant impacts on timber investment returns. To optimize transportation costs, a practical design of the route network is necessary for log trucks that ship wood material from timberlands to wood mills. Road conditions resulting from various road maintenance policies dramatically affect speed limits, log-truck route networks, and transportation costs. The effects of road maintenance policies on truck route selection and user/agency cost trade-offs have not been deeply researched. By considering forest-road maintenance policies, this study intends to provide accurate information on timber-processing service coverage and log-truck route selections for forest companies or subcontracted fleets of log trucks. This research also conducts an environmental analysis to assess the effects of various road maintenance policies on consumed energy and greenhouse gas emissions of log trucks. With current maintenance policies, the results indicate that only between 33% and 51% of timber areas in Oregon can be accessed or harvested by existing nearby wood mills. However, application of the proposed road maintenance policy in this paper would increase accessibility to timberlands by up to 104%. The cost of log transportation also decreases by 16%–34%. The methodology developed in this study can lead to improvements in forest road preservation management systems to achieve the full benefits of reducing log-truck emissions and total transportation costs. **DOI: 10.1061/JTEPBS.0000335.** *© 2020 American Society of Civil Engineers.*

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Introduction

Timberland is defined as the part of forestland that is fully stocked by natural stands of trees, not withdrawn from timber utilization, and with the potential to produce at least 566.3 L (20 cu ft) per acre, per year of industrial wood (Alig et al. 2003). The wood manufacturing industry draws raw material from timberlands to produce various types of products, for example, paper, wrapping, building materials, and furniture. The most important natural factors affecting timber productivity are soil, climate, and topography. These factors make Oregon one of the world's great tree-growing areas (Alig et al. 2003; Roony 2016). According to the Oregon Employment Department (Roony 2016), forests cover almost half of the state's landmass. The Oregon Department of Forestry (ODF) estimates that logging produced 8967001 cubic meter (3.8 billion) board feet of wood material in 2015.

Lopez et al. (2010) indicated that wood transportation costs have significant impacts on timber investment returns. Therefore, research to create greater understanding of log-truck routing and log-processing service coverage is critical to wood product companies, especially in Oregon. Using supply chain management to improve operations is critical for forest companies, and one important forest supply chain link is transportation from forests to factories. In this regard, each (wood) load transported from a forest area to a processing plant is accompanied by information about wood type assortment, volume, origin, and destination at the processing plant, contractual distance, time stamps, carrier, and wood owner, for example. Computing the contractual distance is a key issue in estimating transportation costs because it forms the basis for invoicing and payment. Determining the distance between a pair of nodes in a log transportation network may not be the most challenging task if information regarding speed limits, conditions, and the availability of routes is available. Shortest-path algorithms, such as Dijkstra, can be used to estimate the contractual distance for log transportation networks (Bertsekas 1998). Efficient implementations of Dijkstra's algorithm are described in Zeng and Church (2009). The availability of forest road segments and forest route speed limits is affected by road maintenance levels. These effects modify each route's travel time and route selections from forest to processing plant. Optimized selected routes (routes having the least travel time) from forest to processing plants provide a basis for estimating contractual distances. To the authors' knowledge, no studies have been conducted to investigate the effects of forest road maintenance levels on estimating the contractual distance and log transportation costs.

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Log-truck scheduling problems (LTSPs) aim to identify a set of feasible routes for a given number of log trucks to transport products from supply points (timberlands) to demand points (wood mills) so that the total cost is minimized (Palmgren et al. 2004). Several methods exist for solving LTSPs. A column generation scheme for tackling LTSPs was proposed by Palmgren et al. (2004). Gronalt and Hirsch (2007) applied Tabu search (TS) heuristics to solve a restricted variant of the LTSP. Flisberg et al. (2009) and Andersson et al. (2008) proposed a linear programing and TS two-phase approach to solve the problem. Rönnqvist and Ryan (1995) and Rönnqvist et al. (1998) proposed a procedure for building a route one trip at a time. Rey et al. (2010) addressed the problem of forest product delivery at different destinations by assigning a limited number of trucks daily. El Hachemi et al. (2015) presented a two-phase method to solve weekly LTSPs, including routing and scheduling, in a full truckload transportation situation. Amrouss et al. (2017) presented a mathematical model based on a time-space network to solve forestry real-time transportation problems considering unforeseen events affecting transportation operations, such as delays, changes in the demand topology of transportation networks, and loader breakdowns. A number of studies focused on information supply and the provision of Geographic Information System (GIS)-based applications to support truck drivers in finding storage locations and to further support wood transport. For instance, Martin et al. (2001) used the ArcView network analyst program to estimate the shortest timber transportation path.

In a LTSP problem, harvesting points and wood mills are usually defined as supply and demand points, respectively. Because the forest road network is the primary part of the problem network, its limitations, such as route weight limits (Gronalt and Hirsch 2007), accessibility, turning radius, route speed limits, and barriers (Andersson et al. 2008), play key roles in the problem resolution. Maintenance level is a road characteristic that specifies the limitations of forest road segments. Maintenance level is designated by five levels. It is also widely accepted that various maintenance treatments will have different effects on road conditions (Gao et al. 2011; Lu and Tolliver 2012) and, in return, may provide different operational road conditions for vehicles. Arcand et al. (2008) worked on the theoretical relationships between macroeconomic drivers and forest clearing. Moreover, Nicholls et al. (2006) indicated the results measuring the impact of improved road quality and forest clearing through shorter transport time to market and lower vehicle maintenance costs.

According to the Malheur National Forest Report (USDA 2004), because of large funding shortfalls, there is a need to identify and prioritize the minimum primary road system necessary for access and management of national forestland. This lack of funding and the need to prioritize a minimum road system is also the drive for this study's focus. Limited previous research studied log-truck route selection performance by considering road maintenance policies (e.g., El Hachemi et al. 2011; Lin et al. 2016). However, investigation into the effects of different forest road maintenance policies on consumed energy and carbon emissions is clearly underresearched and has in fact never been studied. In this research, the authors hope to fill the research gaps by providing a complete road-maintenance-policy effect assessment on environmental and operational performance for log-truck route selections.

Growing energy use increases carbon dioxide (CO_2) emissions, which are threatening the global ecology (Eklington 1998). World energy consumption and CO_2 emissions grew by 75% from 1980 to 2016 (USEIA 2016). Over the same period, US primary energy consumption increased by 25% and CO_2 emissions increased by 8%, from 4,777 million metric tonnes (MMT) to 5,174 MMT (USEIA 2016). Moreover, according to the International Energy Outlook (USEIA 2010), CO_2 emissions are estimated to be 43% higher in 2035 than in 2007 (USEIA 2016). If these emissions are not controlled, they will pose a greater danger to the environment by increasing air pollution and accelerating climate change (Benjaafar et al. 2013; Sobhani and Wahab 2017; Sun et al. 2018; Sobhani et al. 2019). These carbon emission consequences may have negative long-term effects on the availability of timberlands used by wood processors to produce wood products (Stern 2007). For this reason, companies have initiated sustainable development efforts to manage their energy consumption, resulting in a reduction in their carbon emissions and energy costs (Black 1996; Richardson 2005; Slaper and Hall 2011; Cheng et al. 2015; Ji et al. 2016; Haji Esmaeili et al. forthcoming). Among manufacturing sectors, the wood product industry has been a pioneer in evaluating carbon emissions through its manufacturing and supply chain processes (Wang et al. 2016). Previous studies demonstrated the contribution of wood product industries in consuming fossil fuels and emitting carbon (Kong et al. 2016). For instance, the pulp and paper industry accounted for 15% of final energy use in the European Economic Area's industrial sector in 2010 (Laurijssen et al. 2012). This high level of energy consumption makes the paper and pulp industry the fourth highest greenhouse gas (CO_2) emitter among worldwide manufacturing sectors (Gielen 2007). In addition, a few studies have assessed carbon emissions produced in the transport of timber used by biomass power plants and wood product companies (Oberscheider et al. 2013). These studies were intended to develop practices to reduce CO_2 emissions caused by timber transportation activities. As previously mentioned, route maintenance policies may change route selections for log trucks. However, to the authors' knowledge, based on a review of the literature, no studies consider the effects of forest road maintenance policies on energy consumed by timber transport vehicles (log trucks) and the associated CO_2 emissions.

To bridge this research gap, this study will consider the effects of forest road maintenance policies on log-truck routing while minimizing travel time between wood mills and timber areas. GIS tools will be applied to investigate the impacts of different forest road maintenance policies and corresponding speed limits on (1) truck-route travel times, (2) the selection of harvesting areas and the volume allocation of corresponding wood mills to each harvesting location, (3) log transportation costs, (4) energy consumed by log trucks, and (5) CO_2 emitted by log trucks while transporting wood from timberlands to wood mills in Oregon.

The remainder of this paper is organized as follows. The "Data and Methodology" section describes the methodology of the research by explaining GIS data collected for this study, the framework of the research, and the algorithm used for route selections. The section "Numerical Results" presents the numerical results for different forest road maintenance scenarios. The sections "Discussion" and "Conclusions" present a discussion of the research and conclude the paper, respectively.

Data and Methodology

This section introduces data resources used for GIS analysis. It also explains the research framework developed to assess the effects of road maintenance policies. The data classification, quantification, and analysis were subdivided into seven steps (Fig. 1):

1. Quantify the study area including forest area and a complete transportation network.
2. Quantify and classify the main network analysis elements including a complete transportation network, timber area, and wood mill locations according to geometric parameters.
3. Classify the methodology based on three scenarios.

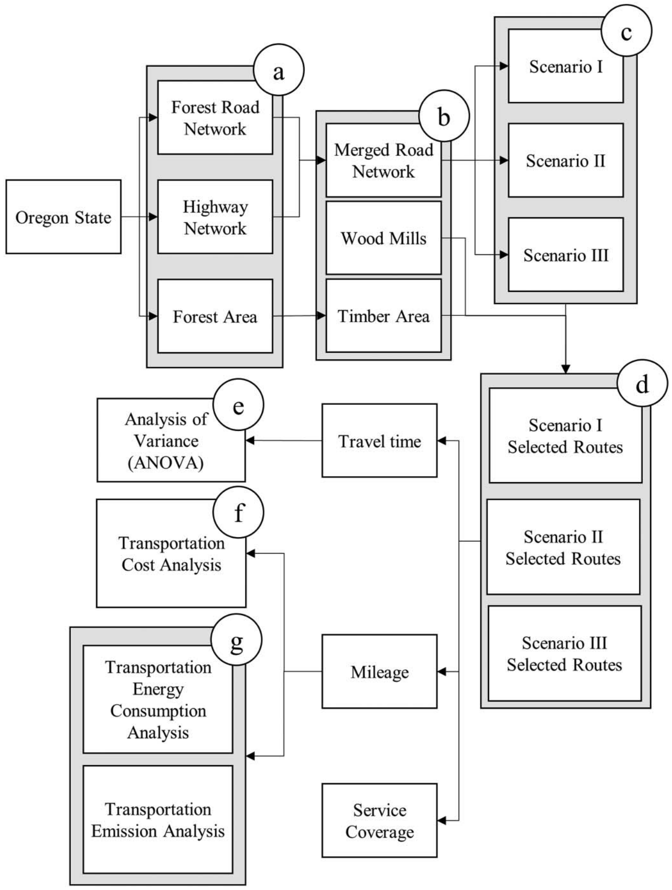

Fig. 1. Research step flow charts.

4. Select and then quantify routes based on geospatial analysis, including optimized route selection, route travel time, travel distance, and service coverage calculations.
5. Conduct travel time analysis for three scenarios.
6. Conduct total transportation cost analysis for three scenarios including both user costs and agency costs.
7. Conduct energy consumption and environmental impact analysis for three scenarios.

Study Area (Step a)

The state of Oregon is the case study considered in this paper because of its large logging industry, huge forested areas, and extensive network of forest roads. The authors first filtered timber (harvesting) areas out from the overall 30 million acres of forests, resulting in 3.3 million acres of timber areas, which is explained in more detail in the next section. In this study, 189 Oregon wood mills are considered. The road network between timberlands and wood mills includes about 14,464 km (8,987.51 mi) of highways including total state highway system miles, interstate miles, and some other state mileage, such as state forests miles, and 656,623.617 km (408,007 mi) of forest roads. This road network was generated by merging the Oregon highway and forest road networks in the next step.

GIS Database (Step b)

In this study, several spatial databases that include merged forest and highway road networks and timberland areas that include timber spots were used to complete GIS analysis and select routes with minimum travel time between timberlands and wood mills. Topographic maps, forest management maps, and timber locations were generated and analyzed in ArcGIS version 10.1. To collect the required GIS data, boundaries and counties with the geographic coordinate system of "GCS North America 1983" were obtained from the Oregon Spatial Data Library website (Oregon Spatial Data Library 2015). The forest layer for the state of Oregon was obtained from the Forest Service, an agency of the USDA (Forest Service 2016). This GIS layer provides valuable data and information regarding the usage of different forest areas in Oregon. There are in total 30 million acre forests, and each area is assigned a function by the Forest Service to indicate whether the forest area is open to timber cutting or not. Based on such information, about 3.3 million acres of area suitable for timber production, named *harvesting areas*, is identified for this study. In terms of wood mills, the authors collected data related to all western US sawmills from the USDA website (US Wood-Using Mill Locations 2005). These data specify mills that only purchase logs or chips. These mills exclude paper or any other wood products that require secondary processing or rely entirely on recycled fiber. The data on roads (forest roads and highways) that connect different forest areas and mills were collected from national forest-system roads (Forest Service 2016) and the Oregon highway network (Data.gov 2013).

Road Maintenance Scenarios and Speed Limits (Step c)

This section explains the research framework (methodology) developed to evaluate the effects of road maintenance policies. The three maintenance policies in the research are based on the road maintenance classifications defined by USDA. Forest roads are classified into five categories based on USDA's five maintenance levels, which reflect the road conditions (Apodaca et al. 2012):

1. Level 1 roads are inactivated and managed as stored or closed for more than 1 year.
2. Level 2 roads are suitable for high clearance vehicles and are not maintained for passenger cars.
3. Level 3 roads are maintained for passenger cars. Roads are typically low speed and single lane.
4. Level 4 roads are maintained for passenger cars and provide a moderate degree of user comfort and convenience. Roads are double lane and aggregate surfaced.
5. Level 5 roads are maintained for passenger cars and provide a high degree of user comfort and convenience. Roads are normally double lane.

Note, according to the USDA Forest Service (Forest Service 2016), roads maintained at Level 3 and above will provide unrestricted access and serve a compelling public need. Therefore, those forest roads are open to all traffic, including log trucks. Level 2 roads are not maintained for passenger cars, indicating those roads are not suitable for passenger car use. However, USDA does not restrict those roads to passenger cars. Only Level 1 roads are closed to motor vehicle use.

The maintenance level of a given road can be increased or decreased depending on road needs. Therefore, USDA defined two types of maintenance levels for a given road: operational and objective. The operational maintenance level (OML) is at the level at which the road (road segment) is currently maintained, while the objective maintenance level (ObML) is the desired level of maintenance for the road (road segment) in consideration of future needs, budget constraints, and environmental concerns (Forest Service 2016). The ObML can be greater than, less than, or the same as the OML. According to national forest-system roads data, both operational and objective maintenance levels are assigned to each forest road segment. For this study, another type of maintenance level is introduced and assigned; it is referred to as the rehabilitation maintenance level. This type of maintenance level indicates the authors' suggested maintenance policy for a given forest road segment.

Three scenarios are defined to assess the effects of road maintenance levels. These scenarios were analyzed separately to (1) determine the routes that provide the shortest travel time between timberlands and wood mills, (2) estimate forest area service coverage, and (3) calculate log transportation costs and, finally, carbon emissions and fuel consumption of log trucks. The three maintenance scenarios (policies) are defined as follows:

Scenario 1: Operational maintenance policy. According to this scenario, all forest roads are maintained with respect to the current maintenance levels (OMLs) specified by the USDA.

Scenario 2: Objective maintenance policy. According to this scenario, all forest roads are maintained with respect to the desired level of maintenance (ObMLs) specified by the USDA.

Scenario 3: Rehabilitation policy. In this scenario, it is assumed that all forest road conditions were improved by maintenance and rehabilitations with respect to their OML and ObML. For instance, if the OML of a road is currently designated as being Level 2 and USDA defined Level 3 as the road's ObML, then Level 3 is considered to be the road condition improvement goal for the numerical analysis in this paper.

To minimize log-truck transportation costs, it is essential to consider maximum speed limits of forest roads and highway segments in each scenario. With respect to these speed limits, an analytical algorithm, a p-median location model (Church 1999), is used to find routes that provide the shortest demand-weighted travel time between origins (timberlands) and destinations (wood mills). The maintenance levels of forest roads are an indicator of road conditions, which in turn affect speed limits. Consequently, the speed limit of each forest road was estimated according to its maintenance-related condition (characteristics) as specified by the USDA and its route classification as reported by Oregon's statutory speed limits (Brustlin 2009). Consequently, the speed limits on forest roads with Maintenance Levels 2, 3, 4, and 5 are 32.2, 40.2, 88.5, and 88.5 km/h (20, 25, 55, and 55 mi/h), respectively. These speed limits are used directly in Scenarios 1 and 2 to complete the numerical analysis. In Scenario 3, the maintenance level of a given forest road was specified after rehabilitation. If the OML and ObML maintenance levels of a forest road were greater than one, the higher maintenance level was assigned to the road. Subsequently, the corresponding speed limit (defined earlier) was considered for that road. For the roads with Maintenance Level 1 (closed segments) for their both OML and/or ObML, the following situations can be deduced:

1. OML is 1 (closed route) and ObML is greater than 1.
2. ObML is 1 (closed route) and OML is greater than 1.
3. Both ObML and OML are 1.

In the first situation, the speed limit associated with ObML was assigned to the forest road. In the second situation, the speed limit associated with OML was assigned to the forest road. In the last situation, the speed limit of a forest route was estimated according to its functional classification, as specified by the USDOT (USDOT/Federal Highway Administration 2000). Road functions are classified into three categories: arterial, collector, and local. The maximum speed limit for each functional classification is 104.6, 88.5, 32.2 km/h (65, 55, and 20 mi/h), respectively. For example, if a forest road's ObML and OML are 1 and its functional classification is determined as local, its speed limit becomes 32.2 km/h (20 mi/h).

The maximum speed limit of log trucks on highways is 88.5, 96.6, or 104.6 km/h (55, 60, or 65 mi/h) depending on the road segment. Two references are considered in this paper to determine the maximum speed of log trucks in highways: the Insurance Institute for Highway Safety website [Freight management and operation report (Schmitt et al. 2008)] and the Oregon DOT website (Oregon DOT 2016). According to the first reference, the maximum speed of trucks is 55 mi/h for all highways in the state of Oregon. However, the second reference set the maximum speed of trucks at 60 or 65 mi/h for some highway segments. In this study, a speed limit of 55 mi/h was assigned to all highway segments except the segments defined as 60 or 65 mi/h according to the Oregon DOT.

Road Network Analysis (Step d)

The final road network was scaled as 2.54 cm (1 in.) is equal to 76.2 km (47.35 mi) on scaled topographic maps. The travel time of a log truck for each road section was estimated and added to the attribute table of the GIS road network database as a new field. The travel time for each road segment was computed based on road segment length and its assigned speed limit according to the section "Road Maintenance Scenarios and Speed Limits (*Step c*)." The following formula indicates the travel time for each road segment:

$$t_i = \frac{l_i}{v_i} \tag{1}$$

where t_i = travel time of road segment I; l_i = length of road segment i (mi); v_i = speed limit of log truck for road segment i (mi/h); and 60 was used to convert unit of travel time from hours to minutes.

Network analysis is widely used in solving transportation problems that usually include various parameter values, such as length, cost, and travel time assigned to the network links. The optimal path (usually shortest) is selected by searching the route and minimizing the sum of the total link parameter values (Zhan 1997; Akay and Sesions 2005).

To employ real-world transportation data, this paper considered one-way restrictions, turn restrictions, junction impedance, and side-of-street constraints while minimizing a user-specified cost attribute (travel time) for route networks. From different techniques available in estimating the shortest path, the new closest facility method, a *Network Analyst extension* of ArcGIS tools (ArcGIS 2019), was used for each scenario separately to estimate the fastest routes between wood mills and timber spots. The fastest route was calculated by ArcGIS network analysis based on Dijkstra's algorithm (Zeng and Church 2009). Some road segments might be closed because their maintenance level is identified as Level 1. Hence, their associated links were hypothetically excluded from the network system by placing barriers on those links (bold lines in Fig. 2 map extent).

The service coverage for each road maintenance scenario (policy) is defined as the number of wood mills assigned to timber locations within each timber area (district). For instance, the zoomed area in Fig. 1 shows that only 2.7% of all wood mills were assigned to the timber locations in the timber area named Chiloquin Ranger District. In this research, the authors assume that each wood mill can only serve one timber location or area, but one timber location can be served by multiple wood mills.

Statistical Analysis (Step e)

ANOVA was completed to determine whether there is a (statistically) significant difference between estimated log-truck travel times resulting from maintenance policy scenarios. To compare the results of three road maintenance scenarios, the

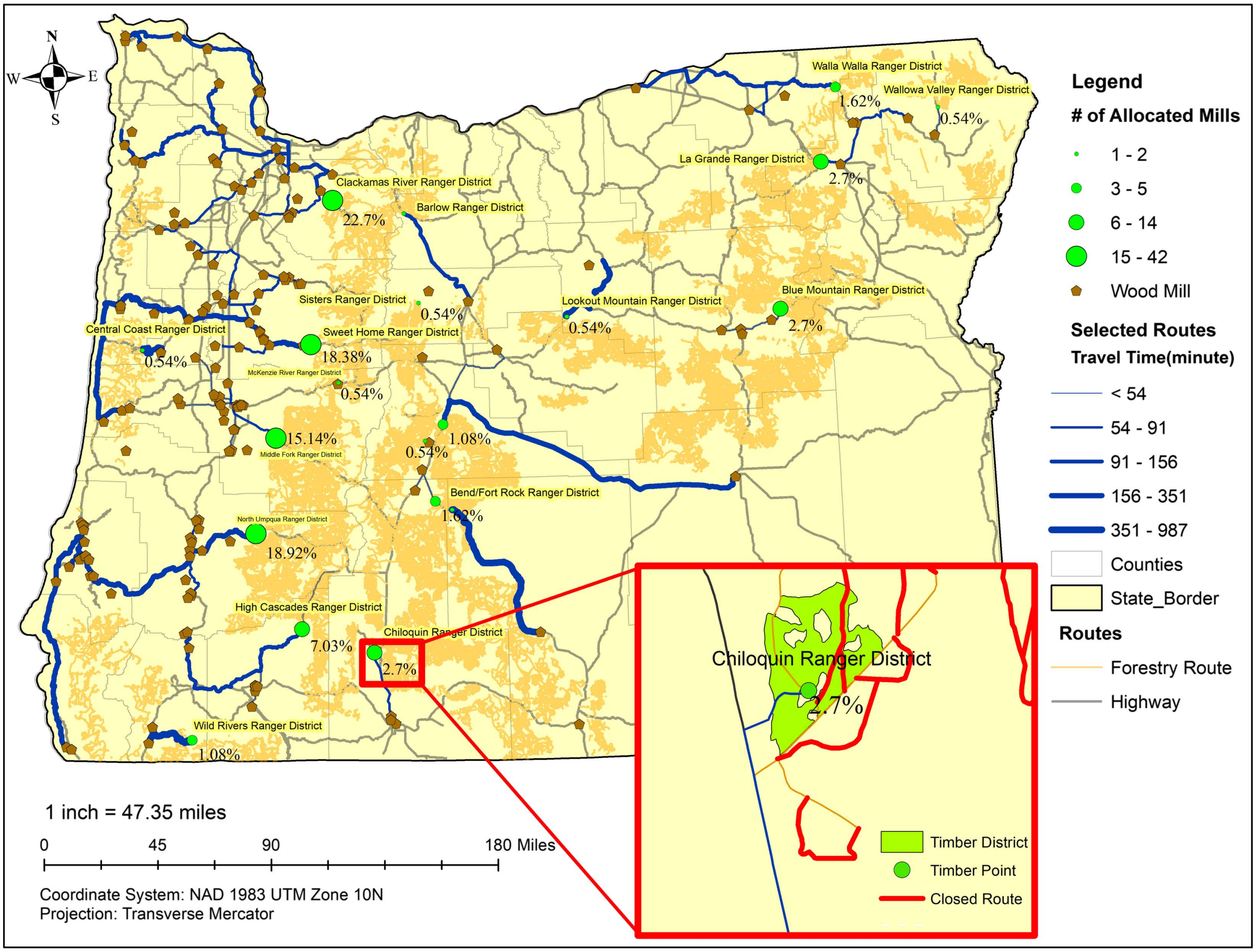

Fig. 2. Routing solution of operational maintenance policy (Scenario I). Map generated using ArcGIS software.

Student–Newman–Keuls (SNK) technique (Student 1927; Newman 1939; Keuls 1952) employed the ANOVA of every two scenarios. This statistical technique is a post hoc test specifying which scenario's average travel time is significantly different from the others. In this way, the optimum routing solution (maintenance scenario with the lowest log-truck travel time) can be determined from the three scenarios.

Cost Analysis (Step f)

Total log-truck transportation cost includes two major items: user cost and agency cost. The user cost considers operating expenses (e.g., fuel), whereas agency cost considers maintenance and capital improvement expenses. These cost items were approximated with respect to the length of routes selected in each road maintenance scenario and unit operating and agency cost per mile.

Energy Consumption and Emission Analysis (Step g)

For the purpose of this study, the consumed energy (fuel) and CO_2 emissions of a given log truck were estimated for each road maintenance scenario and the results compared. Similar to the approach used to estimate transportation cost items, both consumed energy and emitted CO_2 were computed according to the length of routes selected in each road maintenance scenario.

Numerical Results

Route Selection and Service Coverage

This section provides the details of the route selection and service coverage resulting from each maintenance scenario.

Fig. 2 illustrates the routing results (paths with shortest travel time) for the first road maintenance scenario (OML policy). The red lines in the smaller map demonstrate an example of closed forest roads (OML $= 1$) resulting from the operational maintenance policy. Fig. 2 shows the routable network including both highway and forestry roads. The blue lines on the map are the resulting fastest routes connecting the nearest timber harvesting areas (green circle) to each wood mill (brown pentagon) under the first scenario. Note that a route with a thicker line has a longer travel time. The maximum travel time is about 987 min for travel between the Wild Rivers Ranger District and Rough and Ready Lumber Company. The average travel time of all routes with the shortest travel times in the first scenario (OML policy) is 96.70 min (Table 3). The size of the green circles indicates the number of mills supplied by each timber area.

The timber area allocated to the maximum number of mills is the Clackamas River Ranger District with 42 assigned wood mills, which is about 23% of the total mills. Furthermore, on average, 9.2 (4.86% of total mills) mills are supplied by each timber area, while 49% of harvesting areas are inaccessible to all of the wood mills (Table 1).

Figs. 2 and 3 indicate the results for objective maintenance policy (Scenario 2) and rehabilitation policy (Scenario 3), respectively. The average travel time is 97.490 min for Scenario 2, which is about the same as Scenario 1. However, travel time is reduced to 65.893 min for Scenario 3. For each timber area, the average number of assigned service mills is 9.63 for Scenario 2, which is again about the same as Scenario 1, which had 9.2 mills. However, the number of mills is reduced significantly to 6.93 for Scenario 3.

Note that even though the average number of mills is about the same for Scenarios 1 and 2, the percentage of assigned mills can be dramatically different for a specific timber area. For instance, fewer mills (0.54% of mills) will be able to meet the demand for McKenzie River Ranger District under the first scenario. However, this percentage increased dramatically to 41.53% under the second scenario. This means that as neighboring mills become inaccessible to the district, more distant mills will be selected to partially meet the demands of the district. This is because more forest roads will be closed to traffic under the objective maintenance policy compared to

Table 1. Statistical information on allocated mills for the three scenarios

Scenario	Number of connected timber harvest points	Percentage inaccessible timber harvest areas (%)	Average percentage of mills/timber harvest areas (%)	Standard deviation of percentage of mills/timber harvest areas (%)	Percentage maximum served mills (%)
1	20	49	5.00	7.33	22.70
2	19	67	5.26	10.64	40.98
3	27	0	3.70	5.66	19.79

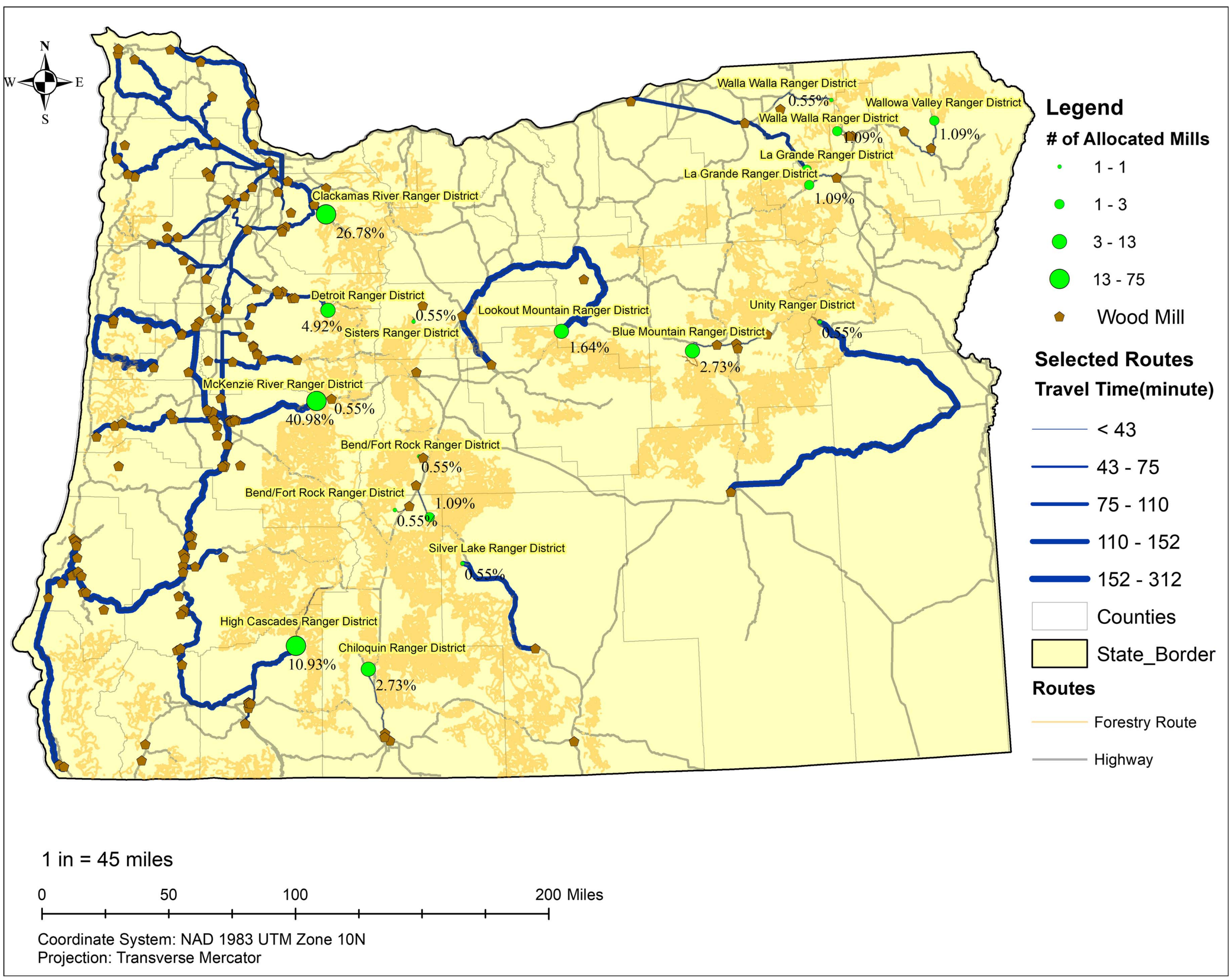

Fig. 3. Routing solution of objective maintenance policy (Scenario II). Map generated using ArcGIS software.

Table 2. ANOVA results

Source	DF	Sum of squares	Mean square	F-value	Pr > F
Model	2	139,377.440	69,688.720	8.44	0.0001
Error	629	5,194,227.108	8,257.913	—	—
Corrected total	554	5,333,604.548	—	—	—

Note: DF = degrees of freedom.

Table 3. Student–Newman–Keuls test for travel time

SNK grouping	Average travel time (min)	Number of assigned routes	Scenario
A	97.490	183	2
A	96.705	185	1
B	65.893	187	3

Note: alpha = 0.1; error degrees of freedom = 629; error mean square = 8,257.92; and harmonic mean of cell sizes = 209.11.

operational maintenance policy, which will result in more mills being inaccessible from neighboring districts. Thus, mills far from the district have to be selected to serve the district. In total, 67% of timber harvest areas became inaccessible to wood mills under the second scenario compared to 49% in the first scenario (Table 1). However, 100% of timber harvest areas are accessible to their neighboring mills under the third scenario. This finding indicates that average travel time and average number of mills assigned to a timber area might not be dramatically different between the two current maintenance scenarios. However, for each specific timber area, the assigned service mills can change dramatically. Moreover, travel time and average number of mills assigned to timber area are both reduced dramatically under Scenario 3 compared with the other scenarios.

Scenario 3 provides the best route selection and operational costs among the three scenarios because under this scenario the fewest forest roads are closed, making the network more routable.

Statistical Comparison Results

The scenario statistical results are given in Tables 1 and 3; the average travel time of a log truck and the average number of mills per timber harvesting area is about the same for Scenarios 1 and 2, even though the individual routes show great differences. Moreover, there is a large loss of timber forest coverage in the first two scenarios, 49% and 67% respectively, indicating that both maintenance policies need to be reevaluated. In addition, Tables 1 and 3 demonstrate that the lower the standard deviation of supplied mills percentage per each timber harvest area, the higher the number of connected timber harvest areas and the lower the maximum supplied mills percentage. With respect to these findings, it can be concluded that Scenario 3 has a more suitable timber area wood allocation pattern.

Table 2 shows a statistical summary of the ANOVA test. Because the p-value is less than 0.05, the null hypothesis in ANOVA, the impact of the three scenarios on average route travel time was the same for all three road maintenance policies, is rejected.

The SNK technique is often used as a post hoc test whenever a significant difference between three or more sample means has been revealed by an ANOVA (De Muth 2014). To further support the findings of the ANOVA test, the, SNK post hoc test was used to assess the differences between each scenario in terms of the average duration of assigned paths (average travel time) and the number of assigned routes. The results of the SNK test are shown in Table 3.

The SNK test with a significance level of 0.1 indicates that the average travel time of log trucks under both operational and objective maintenance policies (Scenarios 1 and 2) is not significantly different. However, the average travel time under the rehabilitation policy (rehab scenario) is significantly different from the other two policies. The difference proves that rehabilitation policy significantly decreases the average travel time of log trucks (by about 31.6 min), but the objective maintenance policy (Scenario 2) is not useful for decreasing the average travel time of log trucks because the corresponding improvement is not significantly different compared to the operational (current) maintenance policy (Scenario 1).

Cost Analysis

Total log-truck transportation costs include agency (maintenance and capital improvement) and user (operating) costs. Tables 4–7 provide details about the estimated forest road maintenance cost, highway maintenance cost, total agency cost, and total user cost, respectively. These cost items were estimated according to the

Table 4. Estimated total forest road maintenance cost

Policy	Maintenance level	Total forest road mileage [km (mi)]	Average maintenance [costs/km (costs/mi)]	Total maintenance cost	Percentage change compared to rehab policy (%)
1 (OML)	1	0 (0)	\$658.39 (\$1,060.00)	\$0.00	−14
	2	107.11 (66.557448)	\$1,583.85 (\$2,550.00)	\$169,721.49	
	3	233.70 (145.216436)	\$20,074.53 (\$32,320.00)	\$4,693,395.21	
	4	28.81 (17.901451)	\$117,080.74 (\$188,500.00)	\$3,374,423.51	
	5	0 (0)	\$117,080.74 (\$188,500.00)	\$0.00	
	All	370.15 (230)		\$8,237,540.22	
2 (ObML)	1	0 (0)	\$657.28 (\$1,058.23)	\$0.00	−7
	2	86.51 (53.753257)	\$1,583.85 (\$2,550.00)	\$137,070.81	
	3	381.25 (236.897071)	\$20,074.53 (\$32,320.00)	\$7,656,513.33	
	4	7.45 (4.629443)	\$117,080.74 (\$188,500.00)	\$872,650.01	
	5	0.43 (0.266314)	\$117,080.74 (\$188,500.00)	\$50,200.19	
	All	476.37 (296)		\$8,716,434.33	
3 (Rehab)	1	0 (0)	\$658.39 (\$1,060.00)	\$0.00	—
	2	161.31 (100.235895)	\$1,583.85 (\$2,550.00)	\$255,601.53	
	3	243.80 (151.49285)	\$20,074.53 (\$32,320.00)	\$4,896,248.91	
	4	34.47 (21.41991)	\$117,080.74 (\$188,500.00)	\$4,037,653.04	
	5	1.40 (0.87242)	\$117,080.74 (\$188,500.00)	\$164,451.17	
	All	440.96 (274)		\$9,353,954.65	

Table 5. State highway maintenance cost

Policy	Highway mileage [km (mi)]	Highway maintenance [cost/km (cost/mi.)]	Total maintenance cost	Percentage change compared to rehab policy (%)
1 (OML)	17,698.25 (10,992.70515)	$16,719.87 ($26,919)	$295,912,630	+17
2 (ObML)	22,544.379 (14,002.7201)	$16,719.87 ($26,919)	$376,939,222	+35
3 (Rehab)	14,724.544 (9,145.679816)	$16,719.87 ($26,919)	$246,192,555	0

Table 6. Estimated total agency cost

Policy	Overall maintenance cost	Capital improvement cost	Total agency costs	Percentage change compared to rehab policy (%)
1 (OML)	$304,150,170	$0.00	$304,150,170	+16
2 (ObML)	$385,655,657	$0.00	$385,655,657	+34
3 (Rehab)	$255,546,510	$151,467	$255,697,977	0

implementation of each road maintenance policy (Scenarios 1–3). They were calculated according to the length of the selected routes in each road maintenance policy and the corresponding maintenance unit cost per mile for each maintenance level adopted, according to the Oregon DOT report (USDA 2004).

As shown by Table 4, total forest road maintenance cost was estimated according to the different maintenance levels for each road maintenance policy. This cost item includes annual maintenance and deferred maintenance expenses. Table 4 also shows the mileage of forest roads with the given road maintenance levels. The results show that the implementation of the suggested rehabilitation policy increases forest road maintenance expenses by about 7% and 14% compared to current operational and objective maintenance policies. This cost increment in Scenario 3 demonstrates that improving forest road maintenance levels will increase the number of accessible forest roads to neighboring timber spots and mills and reduce unnecessary detours. This, in turn, will considerably decrease state highway usage [14,725.06 km (9,146 mi) under Scenario 3 compared to 17,698.73 km (10,993 mi) and 22,544.83 km (14,003 mi), respectively], which will substantially decreases state highway maintenance costs. Table 5 shows the estimated total highway maintenance cost for each road maintenance scenario. These findings show that the implementation of the suggested rehabilitation policy increased the usage of forest roads but reduced state highway mileage and resulted in reductions in total agency costs (by up to 34%).

Table 6 shows the total agency costs, which include total road maintenance costs for both state highway and forest roads and capital improvement costs. Therefore, total agency costs for each scenario are estimated based on the following equation:

$$Total\,agency\,cost = Total\,maintenance\,cost + Capital\,improvement\,cost \quad (2)$$

According to the definition of the rehabilitation maintenance policy [section "Road Maintenance Scenarios and Speed Limits (*Step c*)"], all road segments with OML = 1 or ObML = 1 (closed routes) will be rehabilitated to higher maintenance levels. Furthermore, a forest road with OML = 1 and ObML = 1 is rehabilitated to the maintenance level of local roads (according to the forest network analysis, the functional classification of forest road segments is local, meaning that forest road segments are low-speed roads, single-lane roads). With respect to the definition of road maintenance levels and local road characteristics, the maintenance level of forest road segments is determined to be Level 3. According to the literature, the unit capital improvement cost to improve forest road maintenance conditions to Level 3 is about $16,405/mi (USDA 2004). Finally, the total capital improvement cost for Scenario 3 (rehabilitation maintenance policy) was estimated to be $151,467.38. This extra cost in Scenario 3 results in an average travel time reduction of 31.597 min and improved timber harvest area accessibility to 100%. The total agency costs of the rehabilitation policy were estimated to be $255,697,977. This is about 16% and 35% lower than the corresponding costs estimated under the operational and objective maintenance policies.

According to the literature, operating expenses of log-truck transportation are influenced by various cost items, such as average fuel price, hourly wage of drivers ($16.09 for the first 40 h/per week and $24.14 for overtime hours), estimated costs of health insurance for driver and spouse, Social Security, industrial insurance, drug test charges, and others (Mason et al. 2008). Note that employment benefits, such as retirement plans and paid vacations, are not included in proposed operating costs. With respect to these items, the state literarure estimated the unit cost of operating expenses as $1.76/km ($2.83/mi) for a single truck and $1.85/km ($2.98/mi) for multiple trucks (Mason et al. 2008).

Table 7 shows the total operating costs (total use expenses) for each forest road maintenance policy by considering single and multiple log trucks. The total operating cost in Scenario 3 for a log truck averages $5,000 (16%) and $15,000 (34%) less than those estimated in Scenarios 1 and 2. This cost reduction is mainly due to a lower mileage of routes selected after rehabilitation of forest roads in Scenario 3. As discussed earlier, this lower mileage decreases the average travel time between timberlands and wood mills.

Carbon Emissions and Consumed Energy Analysis

This section describes a comparison of the energy consumed by a log truck to transport logs under the three defined route

Table 7. Estimated total operation cost (user cost)

Policy	Total miles [km (mi)]	Operating cost/mile (single truck company) (cost/km)	Total operating cost (single truck company)	Percentage user's cost versus rehab policy	Operating cost/mile (multiple truck companies) (cost/km)	Total operating cost (multiple truck companies)	Percentage user's cost versus rehab policy (%)
1 (OML)	18,067.4 (11,222)	$2.83 ($1.76)	$31,759.34	−16	$1.85 ($2.98)	$33,443	+16
2 (ObML)	23,019.7 (14,298)	$2.83 ($1.76)	$40,464.09	−34	$1.85 ($2.98)	$42,609	+34
3 (Rehab)	15,166.2 (9,420)	$2.83 ($1.76)	$26,657.75	0	$1.85 ($2.98)	$28,071	0

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Table 8. Energy consumption versus different routes, maintenance policy

Maintenance policy scenario	Total miles	Total kilometers	Truck capacity	MJ/ton-km	Total consumed energy (MJ)	Percentage change versus Scenario 3 (%)
1	11,222	18,061	41	1.35	999,656	19
2	14,298	23,011	41	1.35	1,273,646	52
3	9,420	15,160	41	1.35	839,078	0

Table 9. Carbon emission versus different routes, maintenance policy

Maintenance policy scenario	Total miles	Total kilometers	Truck capacity	$\mathrm{kg\,CO_2/ton\text{-}km}$	Total $\mathrm{kg\,CO_2}$	Percentage change versus Scenario 3 (%)
1	11,222	18,061	41	0.117	86,637	19
2	14,298	23,011	41	0.117	110,383	52
3	9,420	15,160	41	0.117	72,720	0

maintenance policies. The section also includes an evaluation of the effects of route maintenance policy changes on CO_2 emitted due to log transportation. The parameters and assumptions made to estimate energy consumption and carbon emissions were set according to previous empirical studies (e.g., Zhang et al. 2015). Eq. (3) demonstrates the total energy consumed by a log truck. It is measured in megajoules (MJ):

$$Total\,consumed\,energy = Energy\,factor \times Truck\,capacity \times Timber\,transport\,distance \tag{3}$$

The energy factor determines how much energy is consumed by a log truck per ton of timber (log) per kilometer. It is estimated as 1.35 MJ/ton-km (Zhang et al. 2015). The log-truck capacity is set equal to 41 t (Zhang et al. 2015). The timber transport distance is determined by the GIS road analysis according to the given route's maintenance policy. Table 8 shows the total energy consumed while transporting timber. The results show that the truck consumes the least amount of energy (839,078 MJ) in Scenario 3 (rehabilitation maintenance policy) because it travels the fewest kilometers in transporting timber to wood mills. Changing the route maintenance policy to Scenario 2 (objective maintenance policy) and Scenario 1 (operational maintenance policy) leads to increases in energy consumed by 52% and 19%, respectively, because the associated transportation distance increases to 23,019.78 and 18,067.42 km (14,298 and 11,222 mi), respectively. Eq. (4) demonstrates the total carbon emission of a log truck:

$$Total\,CO_2\,(\mathrm{kg}) = Emission\,factor \times Truck\,capacity \times Timber\,transport\,distance \tag{4}$$

The emission factor is a parameter that determines how much carbon is emitted by a log truck per ton of timber per kilometer. It is estimated to be 0.117 $\mathrm{kg\,CO_2/ton\text{-}km}$. This parameter is determined by Zhang et al. (2015) considering the energy and greenhouse emissions of forest biomass transport in the United States. The log-truck capacity is assumed to be 41 t (Zhang et al. 2015). The timber transport distance is determined by the authors according to the given route maintenance policy. The total distance is measured in kilometers. Table 9 gives the total carbon emissions produced by transporting timber with respect to different route maintenance policies.

The results show that the truck attains minimum carbon emissions in Scenario 3 (rehabilitation maintenance policy). In Scenario 3, routes with current Maintenance Level 1 would be rehabilitated, causing the transportation distance to be 15,160 km (9,420 mi). Therefore, the total carbon emissions resulting from timber transport is 72,720 $\mathrm{kg\,CO_2}$. Changing the route maintenance policy to Scenario 2 (objective maintenance policy) and Scenario 1 (operational maintenance policy) leads to increases in carbon emissions by 52% and 19%, respectively, because the corresponding transportation distance was changed to 23,019.78 and 18,067.42 km (14,298 and 11,222 mi), respectively.

Discussion

This study considered the log-truck routing problem by investigating the effects of current operational and objective maintenance policies of forest roads. The log-truck routing problem was also solved under the proposed (rehabilitation) maintenance policy, resulting in improved timberland harvesting patterns and reduced average log-truck travel time. These results subsequently reduced both user and agency transportation costs and reduced log-truck energy consumption and carbon emissions. Both highway and forest roads were considered for each maintenance policy to complete the network analysis and determine routes between timberlands and wood mills to reach the minimum average travel time. The numerical analysis indicated no significant difference between current operational and objective maintenance policies in terms of the average travel time of log trucks. However, comparison of current operational and objective maintenance policies with the proposed rehabilitation policy revealed a significant difference.

According to the routing solution analysis of the rehabilitation policy (Scenario 3), the proposed maintenance policy reduces travel time by an average of 31.597 min compared to the other maintenance polices (Scenarios 1 and 2). The third scenario also eliminated the loss of forest area service coverage. In Scenarios 1 and 2, 49% and 67% of the timber harvesting areas are inaccessible. This is mainly due to a large number of Maintenance Level 1 (closed) forest roads. These closed forest roads also forced log trucks to use longer routes to reach accessible harvesting areas. However, compared to Scenarios 1 and 2, Table 1 and Fig. 3 indicate that more timber harvesting areas are accessible and connected to serve mills when the maintenance conditions of forest roads are improved. Therefore, the implementation of such a maintenance policy (Scenario 3, Fig. 4) would result in more forestry resources being used from more harvesting areas instead of overconsuming resources from a smaller number of forest harvesting areas. Comparing the three road maintenance policies also shows considerable reductions in log transportation costs (by up to 34%),

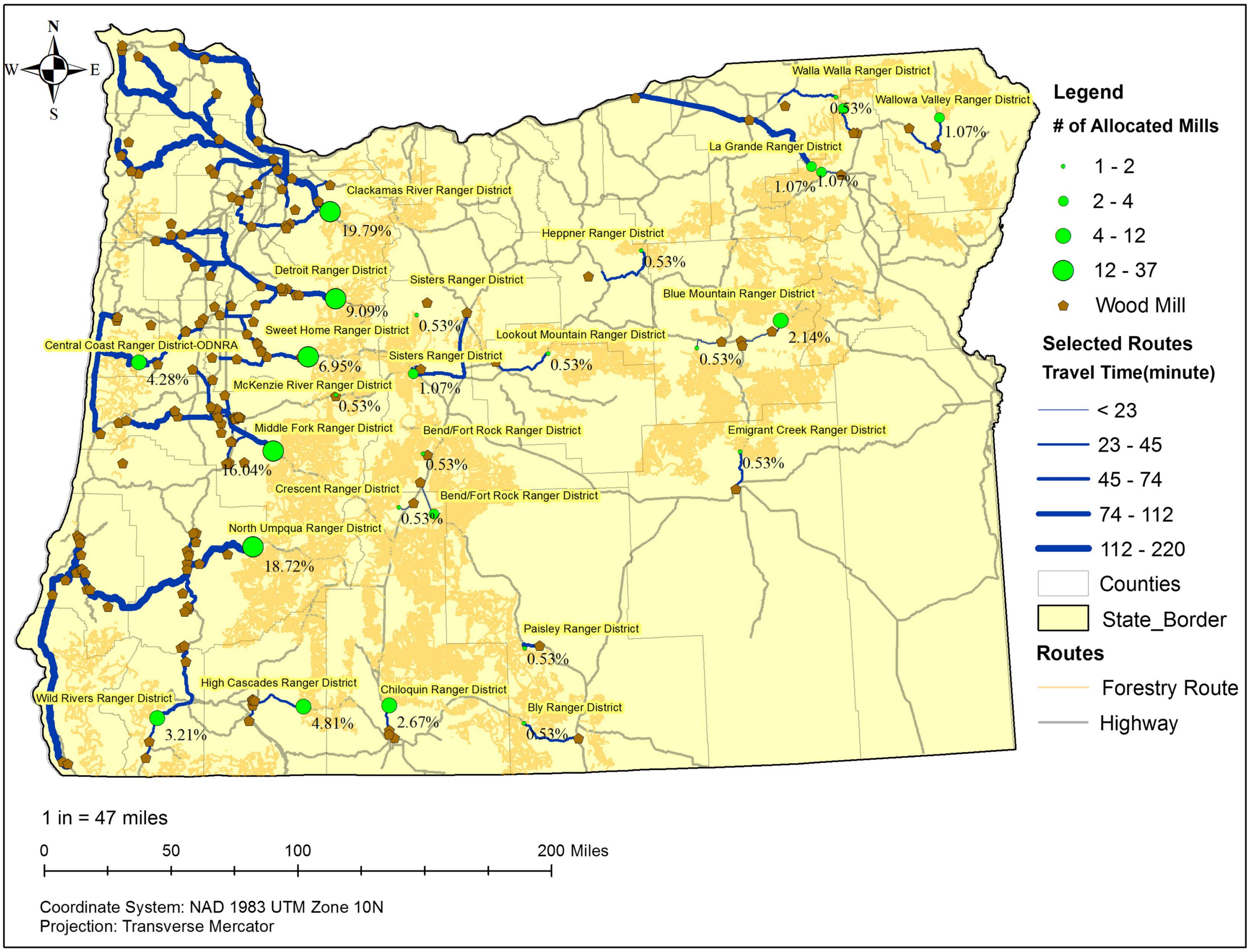

Fig. 4. Routing solution of rehabilitation policy (Scenario III). Map generated using ArcGIS software.

energy consumption, and carbon emissions (by up to 52%) when forest road maintenance conditions are improved in Scenario 3.

Ultimately, this study concludes that ignoring route maintenance conditions as one of the main transportation factors in connecting wood mills to harvesting area results in more costly routing solutions with higher energy consumption and carbon emission levels for log trucks. These financial and environmental consequences will be directly improved by enhancing forest road maintenance conditions.

Conclusions

This study argues for the growing need to reorient and link log-truck route selection and transportation maintenance policies in Oregon forest areas to achieve optimal log-truck routing and harvest area accessibility to serve more wood mills. This information may have an impact on the National Environmental Policy Act (NEPA) process, decision making by the Oregon Department of Transportation, and future actions and decisions by both single and multiple log-truck companies. Important decisions and choices regarding future road maintenance policies, as well as transportation mobility and accessibility, must be based on research and analysis that reflect real-world conditions. Agencies could maintain existing road maintenance policies with low accessibility to timber harvest areas, resulting in fewer accessible supplies in forest areas and increased log-truck operation costs, road maintenance costs, energy consumption, and carbon emissions. A better choice would be to formulate a new vision based on a proposed rehabilitation policy that promotes improved log-truck routing, increases forest service coverage, and reduces log-truck transportation costs, energy consumption, and air pollution. A proposed maintenance policy can be formulated if defined forest road segments with OML 1 are improved to Maintenance Level 3 through additional capital improvement expenditures. In terms of a cost-benefit evaluation, this extra cost is substantially lower than the maintenance cost savings achieved after improving road maintenance conditions (Table 4). To improve road maintenance conditions, an agency would pay \$151,467. In comparison, with the current maintenance policy applied to forest and highway roads, the improvement in road maintenance conditions reduces the total maintenance cost by 16% (from \$304,150,170 to \$255,546,510). Recommendations are made by the authors for future research and include, but are not limited to, (1) carrying out validation studies in different states, (2) conducting further in-depth cost-benefit relationship analysis, (3) investigating complete maintenance and rehabilitation policies rather than just three fixed ones, and (4) conducting complete safety and environmental benefit analysis using available data. Several studies' results, along with these research findings, can support such future study by considering trade-offs between carbon dioxide emissions and logistics costs, environmental assessment of freight transportation, and estimation of greenhouse gas emissions for highway construction operations, for example (Bai et al. 2015, 2012; Kim et al. 2009; Reger et al. 2014; France-Mensah and O'Brien 2019; Cass and Mukherjee 2011).

Data Availability Statement

Some or all data, models, or code generated or used during the study are available from the corresponding author by request:

- Selected optimal routes under three scenarios including road type, speed limits, and distance, for example;
- Allocated mills under three scenarios including their corresponding service timber area.

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