AN ABSTRACT OF THE THESIS OF

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Title: Contemporary Forest Road Management with Economic and Environmental Objectives

Abstract approved:

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One of the basic questions facing transportation planners and road managers is how to provide and maintain a road system that provides efficient access to the forest while limiting adverse effects roads can have on water and soil resources. The purpose of this study is to develop decision support models that will lead to improved economic and environmental efficiency in the management of forest road networks. In particular, I focus on developing techniques to facilitate tradeoff analysis and help landowners identify optimal erosion control policies.

Forest roads contribute to accelerated erosion, which can degrade water quality and aquatic habitat. Federal agencies in the Pacific Northwest are actively seeking to remove and/or improve roads in order to restore watershed condition, and private

landowners face regulatory restrictions under the Clean Water Act and state forest practice acts. Though the treatment that best achieves management objectives for a single road can often be identified, at larger scales the combination of treatments to assign to a suite of roads can become too large for enumeration. In these circumstances decision aids can and have been used. This dissertation is comprised of five manuscripts that pair industrial engineering and forest engineering principles in order to provide relevant decision support tools to facilitate forest road management. The manuscripts address a range of available treatments, including regular maintenance, upgrading, and road removal.

The first chapter describes the challenges associated with erosion control, reviews available road treatments, and summarizes salient applications of decision support for road management, focusing on applications where controlling road-related erosion was an objective. The second chapter introduces a tradeoff analysis framework for controlling road-related erosion. The third chapter presents an algorithm for routing maintenance vehicles (graders) across a forest road network in order to minimize total tour length, a proxy for operating cost. Chapter four extends this work to a multi-objective context, seeking efficient solutions that simultaneously minimize vehicle operating cost plus grading cost and hazard weighted rut depth, a measure of environmental performance. Chapter five develops optimal policies for recycling aggregate from decommissioned forest roads, and demonstrates that recovery and reuse of aggregate can subsidize road removal projects. Chapter six extends this work to a multi-objective context, approximating the efficient frontier for length of road removed and removal cost, and investigating further the potential for aggregate recycling to effectively subsidize decommissioning projects. Chapter seven concludes the dissertation with a review of the preceding chapters.

Contemporary Forest Road Management with Economic and Environmental Objectives

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Matthew P. Thompson

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I understand that my thesis will become part of the permanent collection of Oregon State University libraries. My signature below authorizes release of my thesis to any reader upon request.

Matthew P. Thompson, Author

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CONTRIBUTION OF AUTHORS

Dr. John Sessions was integral to all components of manuscript work, including (but not limited to) identifying research objectives, recommending and synthesizing relevant literature, facilitating analyses, helping with computational difficulties, and editing written work. Dr. Sessions co-authored every manuscript, and was the lone co-author on manuscripts relating to aggregate recycling (Chapters 5-6). Dr. Kevin Boston co-authored manuscripts relating to the routing of maintenance vehicles (Chapters 3-4) and application of technical efficiency for erosion control (Chapter 2). Dr. Boston helped the author with data collection, develop of solution techniques, analysis of results, and framing of issues. Dr. Arne Skaugset co-authored Chapter 2 in an editorial and advisory capacity, and in general contributed to the author's understanding of forest erosion processes. Dr. David Tomberlin co-authored and provided field-collected road segment data for Chapter 2, and introduced the author to computer-based decision support for erosion control. Dr. Jeff Hamann co-authored Chapter 4, assisting with the literature review, development of solution techniques, and simulation of forest and road data. Dr. Hamann is not a member of the author's graduate committee, but rather a recent graduate of Oregon State University and former classmate of the author. Dr. Jeff Arthur, also not a member of the graduate committee, co-authored Chapter 3 by providing support on operations research methodologies. At the time this dissertation was submitted, Chapters 3 and 5 had been published, and Chapters 2, 4, and 6 were undergoing peer review.

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1 Introduction

1.1 Statement of Objectives and Research Contributions

One of the basic questions facing transportation planners and road managers is how to provide and maintain a road system that provides efficient access to the forest while limiting adverse effects roads can have on water and soil resources. The purpose of this study is to develop decision support models that will lead to improved economic and environmental efficiency in the management of forest road networks. In particular, I focus on developing techniques to facilitate tradeoff analysis and help landowners identify optimal erosion control policies.

Weaver and Hagans (1999, p. 236) present a five-step process for forest road erosion prevention and control:

1. Problem identification (through inventory and assessment)
2. Problem quantification (determination of future yield in the absence of treatment)
3. Prescription development (both heavy equipment and labor-intensive)
4. <u>Cost-effectiveness evaluation and prioritization of treatment sites</u>
5. Implementation

This dissertation targets step #4, cost-effective evaluation and prioritization of treatment sites. The intent is to develop computer-based decision support methods that better integrate environmental objectives into forest transportation planning. I consider planning contexts involving the scheduling of regular maintenance (grading), upgrading, and removal. To model environmental performance I consider a range of possibilities, including an assumed benefit from grading, as well as rut depth, sediment production/delivery, and hazard weighted length of roads decommissioned.

As is relevant here, I consider a decision aid to be the paring of appropriate mathematical formulations with solution methods. I employ both exact and heuristic solution methods, depending upon problem size and complexity. For single objective problems, I use traditional mixed integer programming as well as the tabu search metaheuristic. For multiple objective formulations, I employ the epsilon-constraining algorithm paired with mixed-integer programming, as well as multi-objective evolutionary algorithms (MOEA).

This dissertation reflects an interdisciplinary approach, integrating forest engineering principles with a diverse array of other fields, including applied economics, combinatorial optimization, multi-objective optimization, multi-criteria decision making, graph and network theory, computer science, and evolutionary computation. My research contributions include:

- The novel application of the concept of technical efficiency to forest road erosion control
- The identification of techniques to improve the environmental and economic efficiency of forest road management
- The extension of decision support frameworks from single to multiple objective formulations

- The illustration of the role of tradeoff analysis in informing forest road planning, in particular improving understanding of marginal cost/benefit relationships
- The development of vehicle routing algorithms to intelligently deploy forest road maintenance vehicles
- The development of optimal aggregate recycling and road removal policies
- The advancement of the notion that aggregate recycling can effectively subsidize road decommissioning projects

1.2 Literature Review

1.2.1 Forest Roads and Water Quality

Forest roads benefit the landowner by providing access for timber production, research, fire management, recreation, and other activities. However, forest roads are not entirely benign and can lead to negative ecosystem impacts. In particular, forest roads contribute significantly to degradation of water quality and aquatic habitat. They are associated with accelerated erosion and can be a major source of sediment delivery to streams (Jones et al. 2000; Lugo and Gucinski 2000; Forman and Alexander 1998). Elevated levels of in-stream sediment can negatively affect salmonids through mortality, reduced growth rates, disruption of egg and larvae development, and reduction in available food (Newcombe and MacDonald 1991; Hicks et al. 1991). Poorly located or designed stream-crossing culverts on forest roads create barriers to fish passage, which can reduce salmon productivity (Nehlsen et al. 1991). Degradation of aquatic habitat is of special concern in the western United States where endangered salmonid species spawn and rear in watersheds containing potentially erosive forest roads. Maintenance of high quality, unobstructed habitat is crucial to successful conservation efforts (GAO 2001).

The presence of a forest road can substantially and adversely alter natural hillslope hydrologic and geomorphic processes. Forest roads intercept rainfall and subsurface flow, concentrate flow on the surface or adjacent ditches, and divert or reroute water from natural flow paths (Gucinski et al. 2001). They also accelerate chronic and episodic erosion processes, alter channel structure and geometry, alter surface flowpaths, and cause interactions of water, sediment and woody debris at engineered stream crossings (Gucinski et al. 2001). Chronic erosion contributes fine sediment and is generated by surface erosion processes along the road prism (Reid and Dunne, 1984). Episodic erosion occurs in the form of mass-wasting and fluvial erosion due to culvert failures and is often triggered by intense rain events (Reid and Dunne, 1984).

In areas with steep slopes, landslides and other mass movements are responsible for the majority of episodic road-related erosion (Furniss et al. 1991). Chronic inputs from road surface erosion can also be a significant source of sediment related input to streams (Gucinski et al. 2001; Reid and Dunne 1984). Timber hauling during the wet season can be the most significant source of fine sediment associated with forest practices (Oregon Department of Forestry 2003). Fine sediment can originate from the road surface itself due to the breakdown of the aggregate over time from crushing under heavy tire loading and weathering. Sediment production is related to many road design elements, including segment length and gradient (Luce and Black 1999), aggregate quality (Foltz and Truebe 2003), and aggregate depth (Skaugset et al. 1997). Management activities such as maintenance and especially log truck traffic also influence sediment production (Luce and Black 2001; Bilby et al. 1989; Reid and Dunne 1984).

Road drainage systems are designed to move water away from the road surface as quickly as possible, ideally to the forest floor where the water can disperse and infiltrate into the soil. A critical factor affecting surface drainage is the road's surface shape, i.e. the cross-section of the travelling surface. Surface shapes are designed to "encourage shedding of water from the surface before it gains enough concentration and velocity to cause unacceptable surface erosion" (Moll et al. 1997, p.1). Unfortunately, in some circumstances poorly designed and/or maintained drainage systems deposit sediment directly into streams at road-stream crossings.

Improperly designed and/or maintained roads can contribute disproportionately to aquatic habitat impairment. Often forest roads are built with limited effort to control compaction, resulting in variable subgrade strength across road segments (Boston et al. 2008). Those areas with weak subgrades are more susceptible to localized surface failures, such as potholes, washboards (lateral channels), and ruts (longitudinal channels). A rut occurs where the vehicle load exceeds the bearing strength of the surface or subsurface. Rut depth varies with tire operating pressure and traffic levels (Foltz and Elliott 1998), as well as local conditions such as road material and moisture. Excessive rut depth jeopardizes the road structure and can interfere with normal function of the road's designed drainage system. Concentration of water in the wheel rut increases runoff length and water velocity, with the potential to detach and transport additional particles. Sediment production from roads with ruts has been shown to be nearly double that of roads without ruts (Burroughs and King 1989).

Road management issues vary by location and ownership. On federal lands in the Pacific Northwest, the Aquatic Conservation Strategy (ACS) targets forest roads for improvement and removal as an integral component of strategic watershed restoration (Reeves et al. 2006). The aim of watershed restoration is to restore habitat and prevent further degradation across landscapes (Heller 2002), and generally entails restoring isolated habitats and improving or decommissioning roads, among other treatments (Roni et al. 2002). The ACS cites preventing road-related runoff and sediment production as two important components of its watershed restoration program (Reeves et al. 2006; USDA and USDI 1994). Monitoring of ACS implementation indicates that the most improved watersheds had relatively extensive road removal programs (Gallo et al. 2005). These road removal programs generally focused on removing roads from riparian areas and areas with high landslide hazard (Reeves et al. 2006).

The emphasis on removing forest roads in the ACS is, in part, a reflection of the poor state of many of the transportation networks on federally owned lands. Though the USDA Forest Service’s Road Management Policy (USDA 2001) states the goal of reversing adverse ecological impacts associated with roads, the unfortunate reality is that most roads in the national forest system are chronically under-maintained, with a backlog of necessary improvement and removal needs (Sample et al. 2007; USDA 2002). As of 2002, less than 20% of the roads in the national forest system were maintained to the desired standard (USDA 2001). A report by the Pinchot Institute for Conservation recommended that national forests analyze their road systems to identify surplus roads that can be decommissioned (Sample et al. 2007).

Though the ACS emphasizes road removal as a restoration activity, it is important to note that removing roads does not in all circumstances ensure net environmental benefit. Removing an excessive amount of roads could restrict access for fuel reduction activities and fire control. Removing roads also limits future opportunities for biomass recovery for alternative energy generation. Where lands are to be managed for timber production, reducing road density would lead to increased skid trail length, which can degrade soil resources, and could lead to increased utilization of helicopter logging, which significantly increases fuel consumption. Decision makers therefore face tradeoffs when selecting road segments for removal.

On private and state owned lands, where timber production remains more of a dominant management objective, attention is focused less on removing legacy roads and more on minimizing risk while maintaining an economically efficient transportation network. In Oregon, the road systems on state and private lands appear in better shape than the federal lands. A 1998 inventory of forest road drainage systems in western Oregon revealed that 25% of the 285 miles of forest road surveyed delivered sediment directly to streams (Oregon Department of Forestry 1998). Since then, industrial ownerships in Oregon have gone to great lengths to improve their road networks (Chris Jarmer, Director, Water Policy and Forest Regulation, Oregon Forest Industries Council, personal communication, 2009). This improvement reflects funding and a deliberate effort to upgrade road systems, whereas federal land management agencies have faced decreased funding. Nevertheless, opportunities for additional improvement remain.

Beyond general stewardship obligations, the Clean Water Act (CWA) provides a strong motivation to pursue effective erosion control methodologies on state and private lands. Road-related sediment is recognized as a contributing source of pollution for many rivers and streams listed as water quality limited under the CWA (e.g., Environmental Protection Agency, Impaired Waters and Total Maximum Daily Loads: Examples of Approved Sediment TMDLs, http://www.epa.gov/owow/tmdl/examples/sediment.html). Dai et al. (2004), for instance, identified forest roads as the dominant source of controllable erosion in a decision aid designed to support monitoring and assessment for a sediment total maximum daily load (TMDL) in a northern California watershed.

In 1999, the EPA published proposed changes to the TMDL rules that would significantly strengthen the nation's ability to achieve clean water goals by ensuring that the public had more and better information about the health of their watersheds (EPA 1999). The result has been increased interest in sediment production from forest roads. Though the CWA in some circumstances allows for a balancing of economic interests and promotes a progressive approach to pollution control premised on technological innovation over time, it remains a national goal to attain "fishable and swimmable" water quality (CWA §101(a)(2)).

Further, contemporary court precedent relating to the CWA suggests that additional regulations concerning forest practices, especially forest road management, may be forthcoming. A Federal District Court in California recently found that drainage ditches and culverts delivering sediment to streams constitute point sources of pollution, thereby subjecting forest roads to National Pollutant Discharge Elimination System (NPDES) permitting requirements (EPIC v. PALCO, No. C 01-2821 MHP). However, a different outcome was reached on a similar case in Oregon, with the Court ruling effectively that all road-related sediment delivery is more accurately characterized as nonpoint source pollution (NEDC v. Brown, No. 06-1270-K1). NEDC v. Brown was appealed in the US Court of Appeals for the 9th Circuit. If a ruling by the appellate Court aligns with the EPIC decision, it could usher in a new regulatory paradigm, presenting new challenges to landowners seeking to cost-effectively control erosion.

NPDES permits require polluters to adhere to effluent limitation standards. Technology-based standards reward efficiency and innovation, and tighten over time as the state of the art evolves. Standards vary with the nature of the pollutant, but all are premised upon the application of pollution control technology. As sediment is considered a “conventional” pollutant, Best Conventional Pollution Control Technology (BCT) standards would likely apply. As is relevant here, BCT standards “include consideration of the reasonableness of the relationship between the costs of attaining a reduction in effluents and the effluent reduction benefits derived.” (CWA §304(b)(4)(B)) This test for what constitutes “reasonable” is frequently referred to as the “bend of the knee” test, where polluters are required to reduce pollution up to the point where the marginal benefits per dollar spent begin to markedly decline. That is, the CWA presents a statutory requirement to perform a cost/benefit tradeoff analysis in order to establish pollution control standards.

Improving the environmental performance of forest roads therefore remains important to both public and private landowners. Public managers must retain transportation networks sufficient for timber production, fire prevention, public recreation, and other access needs, while at the same time improving and decommissioning roads in accordance with the Aquatic Conservation Strategy. Private managers likewise must ensure their transportation networks meet timber production and other access needs, while complying with state and federal regulatory constraints designed to protect water quality. Contemporary forest road management thus involves identification of a suite of road treatments that best achieve conflicting economic and environmental criteria.

1.2.2 Forest Road Management

Appropriate road management can mitigate the environmental impact of the road system by limiting chronic erosion and reducing the risk of large-scale episodic events (Weaver and Hagans 1999). Management treatments to control road-related erosion include regular maintenance, improvement (upgrading), and removal (closure or decommissioning). Regular road maintenance can limit some of the deleterious effects associated with rough road surfaces (i.e., roads with ruts and/or washboards). Grading is the most common form of maintenance, wherein a bladed vehicle smoothes and re-shapes the road surface. For industrial-sized ownerships grading can be a part of day-to-day operations, and in some circumstances roads may be graded, or serviced, several times in a month. By eliminating ruts and other failures, grading may simultaneously be able to reduce both the environmental impacts and vehicle operating costs. Too frequent grading can unnecessarily increase grading costs, and may in some cases actually lead to environmental degradation by loosening the road surface and making available fine sediment for delivery to streams (Luce and Black 1999). However, compacting, watering, and/or applying chemical additives to the road surface after grading can help reduce sediment production. Too infrequent grading, on the other hand, increases transportation costs and the risk of environmental degradation associated with ruts. The transportation planner therefore faces tradeoffs between economic and environmental objectives when identifying grading maintenance regimes.

Beyond maintenance, there exists a range of available road restoration treatments, from simple upgrading to full decommissioning (USDA and USDA 1994). Upgrading a road may involve removing soil from sites with high landslide risk, installing additional cross-drain culverts, modifying drainage systems to reduce connectivity with the stream network, applying rock to the road surface, changing the road template, and reconstructing stream crossings. Upgrading a road may reduce the rate of surface erosion and likelihood of future road failure, but the road will remain open.

Roads no longer required for transportation can be closed and/or decommissioned. High maintenance needs or high levels of environmental damage are also reasons to decommission a road. Closing a road frequently consists of barricading or gating the road to prevent unauthorized use, particularly during wet seasons, outsloping the surface and installing rolling dips and/or waterbars, and may involve removing some high-risk culverts. A closed road can be re-opened for future use or later decommissioned, and generally requires only periodic inspection. Decommissioning a road may involve removing culverts under significant fills, ripping the roadbed, recontouring hillslopes, and may include planting or seeding the road surface. A decommissioned road is not passable and requires no future maintenance. A common goal of decommissioning is to restore the natural hydrologic processes and prevent future sedimentation; a decommissioned road has lower longer-term environmental impacts than a closed road due to significantly reduced risk of chronic and episodic erosion (Switalski et al. 2004; Kolka et al. 2004; Madej 2001; Trombulak et al. 2000; Weaver and Hagans 1999; Harr and Nichols 1993).

Road decommissioning decisions are complex and influenced by a variety of factors, such as road location, sediment delivery risk, and available resources. Often only a few "problem" roads produce the majority of the sediment, and it therefore may be efficient to direct efforts towards those roads first (Luce and Black 1999). Weaver and Hagans (1999) contend that it is rarely cost-effective to undertake a decommission project without first evaluating its relative importance to overall watershed condition. Similarly, Luce et al. (2001) state that road removal efforts must be prioritized, and argue that management criteria should include economic and social concerns. Lugo and Gucinski (2000) agree that decommissioning decisions should not be made based upon ecological criteria alone, and caution that in some cases the environmental disruption from decommissioning may be less desirable than leaving the road to reach some level of stability. Anderson et al. (2006) point out that decommissioning decisions involve weighing the relative risks of road failure, limited access for fire suppression, and limited access for future market opportunities.

During decommissioning, it is often possible to recover aggregate from the road surface. Recovered aggregate can be delivered to other roads for concurrent maintenance or construction projects, with associated recovery and delivery costs. Alternatively, aggregate required for maintenance or construction can be obtained from either local pits or quarries with associated procurement and delivery costs. Re-use of the recovered aggregate within the forest road network may significantly reduce rock transport distance, especially when quarries are far away. Previous experience (Sessions et al. 2006; Mark Truebe, Assistant Forest Engineer, Willamette National Forest, personal communication, 2007; Jennie Cornell, Washington State Department of Natural Resources, personal communication, 2007) suggests opportunities for significant cost savings, even for small-scale projects. These cost savings can effectively subsidize decommissioning projects, suggesting an economic benefit associated with improving environmental benefit. A major thread of this dissertation is the investigation of the potential for aggregate recycling to lead to improved environmental performance, in addition to the investigation of appropriate decision support tools for road maintenance, upgrading and removal.

1.2.3 Decision Support for Forest Road Management

Controlling road-related erosion to minimize sediment delivery and degradation of aquatic habitat remains an important issue for forest stewardship. Managers are faced with the task to develop efficient road management strategies to achieve conflicting ecological and economic goals. Identification of an appropriate suite of road management treatments can be difficult. Blanket prescription of best management practices can prove ineffective and economically infeasible (Barrett and Conroy 2002); in general it is not an efficient approach to apply treatments to problem areas independently of their impact on overall cost-effectiveness (Weaver and Hagans 1999).

Though it may be possible on a segment by segment basis to identify the optimal treatment, when the decision space extends over broad temporal and spatial scales for entire road networks the pool of possible treatment combinations becomes too large for explicit consideration (Anderson et al. 2006). That is, it is no longer sufficient to evaluate treatment alternatives independently of one another. O'Hanley and Tomberlin (2005), for instance, demonstrate how a simple heuristic to select fish passage barriers for removal according to cost/benefit ratios alone can lead to inefficient and undesirable resource allocations. What is required is some mechanism to facilitate generation and evaluation of alternatives. In these decision-making environments, decision aids can and have been used to facilitate decision-making.

To prioritize treatments, and to assess how well environmental objectives are met as a result of treatment, environmental performance measures for forest roads are required (Mills 2006). Common metrics include estimates of sediment production and/or delivery (e.g., Rackley and Chung 2008; Brooks et al. 2006; Bettinger et al. 1998), road roughness (e.g., Thompson et al. 2007; Provencher 1995), rut depth (e.g., Faiz and Staffini 1979), and length of roads treated (Madej et al. 2006). Another approach is to assign segments a hazard-weight based upon a set of criteria and attributes. Use of a hazard factor enables differentiation between road segments based upon salient characteristics such as proximity to a stream, erosive potential, etc. Similar approaches include Thompson and Sessions (2008), who maximized the hazard-weighted length of roads decommissioned, and Girvetz and Shilling (2003), who assigned environmental impact scores to negatively weight roads for a least cost network path analysis. Boston and Bord (2005) suggest manipulative experiments to improve our understanding between forest road construction practices, material properties, and environmental performance.

A prerequisite for prescribing road treatments is the generation of predictive, or “forward looking,” sediment inventories. Absent estimates of treatment efficacy, it is impossible to prioritize alternative treatments on the basis of cost/benefit. Allison et al. (2004, p. 184) state, “the systematic consideration of each road section together with its alternative restoration treatments reflects an appropriate diligence in generating a ranking of restoration choices.” The California North Coast Regional Water Quality Board has codified this best management practice into their General Waste Discharge Requirement program, requiring forestland owners to develop and implement Erosion Control Plans to “prevent and minimize the discharge of sediment” prior to initiating timber harvest (Robert Klamt, North Coast Regional Water Quality Control Board, personal communication, 2007). Erosion Control Plans must contain an inventory identifying potential discharge sources, their locations, and estimated sediment volume, as well a description and timeline of prevention and minimization measures that will be used.

Despite the apparent presence of conflicting objectives, most applications of decision support for forest road management have considered a decision-making environment with a single objective. A common approach assumes the decision-maker manages to minimize treatment costs or maximize profits, absent environmental considerations. Olsson (2007) compared deterministic and stochastic programming techniques to determine optimal road upgrade treatments. Anderson et al. (2006) used dynamic programming to determine optimal road class and deactivation strategies. Karlsson et al. (2006) paired a mixed integer linear programming model with GIS-based maps to facilitate road upgrading decisions in order to avoid losses associated with blocked roads. Olsson and Lohmander (2005) used mixed-integer formulations to optimize roundwood transport and road investments.

In some applications, environmental benefit as a result of road treatment is implicitly modeled in cost minimization frameworks. Thompson et al. (2007) used a tabu search heuristic to identify low cost tours for a maintenance vehicle to take, implicitly assuming a benefit from grading. Thompson and Tomberlin (2005) similarly assumed an environmental benefit associated with erosion control. They applied stochastic dynamic programming to minimize the cost of erosion control on an unused logging road in the Caspar Creek watershed in northern California (also see Tomberlin et al. 2002), where the decisions included whether to maintain, upgrade, or decommission the road. Rackley and Chung (2008) used NETWORK 2000 (Chung and Sessions 2003) to design road networks with minimal haul and construction costs, incorporating erosion concerns by assigning extra costs to road segments based upon expected erosion.

Transportation planning formulations that explicitly include environmental concerns often model environmental objectives as constraints under an economic objective. Contreras and Chung (2006) used an ant colony heuristic algorithm to identify the set of least cost routes from timber sales to mills, with sediment production constraints. Similarly, Bettinger et al. (1998) used tabu search to schedule harvest and road activities with sediment production constraints to achieve aquatic habitat goals. Akay and Sessions (2005) created a forest road alignment model that used a heuristic procedure to minimize construction, maintenance and construction costs for forest roads, while considering sediment production; this work has been further advanced by Aruga et al. (2007).

Alternatively, the decision-maker can seek to optimize an environmental objective, subject to budgetary constraints and other resource limitations. Thompson and Sessions (2008) presented a mixed integer programming framework for determining optimal levels of aggregate recycling and assigning road removal treatments, using hazard-weighted length of roads decommissioned as an environmental proxy.   Madej et al. (2006) and Eschenbach et al. (2005) applied dynamic programming and genetic algorithms to maximize the sediment saved from entering the stream channel as a result of applying various treatments to roads and stream crossings. Allison et al. (2004) applied a decision analysis framework to generate a ranking of the expected benefits of proposed deactivation strategies for forest roads in steep terrain, where benefits were expressed in terms of avoided damages from road-related slope failures.

As an alternative to modeling objectives as constraints, multiple objectives can be condensed into a single objective function using methods such as goal programming or weighting objectives. Goal programming requires identification of target environmental performance levels. Both techniques require an appropriate mechanism to scale non-commensurate objectives (e.g., $ and kg sediment), as well as a priori elicitation of preferences between objectives. In such cases, multi-criteria decision models (MCDM), which provide for the systematic elicitation of preferences between objectives, can be of use (de Steiguer et al. 2003). Coulter et al. (2006), for example, used the Analytic Hierarchy Process to condense three objectives (minimize impacts to streams, minimize road failures, and minimize Forest Practice Act violations), then solved for the resultant single objective function using a combinatorial heuristic.

1.3 Technical Efficiency: A New Paradigm for Forest Road Erosion Control

Arguably the aforementioned decision support approaches are unsuitable for road erosion control under conflicting economic and environmental objectives. Kennedy et al. (2008) referred to the notion of identifying a singularly "optimal" solution to such problems as a "fallacy of the weighted sum approach," because preferences can change, and because no single answer simultaneously optimizes all objectives. Further, identification of appropriate goals for sediment reduction (or some other metric) is not a trivial task. As with other environmental management contexts, such as managing for wildlife habitat objectives, a priori establishment of target values is a difficult, uncertain exercise. Contreras and Chung (2006) set as an upper bound the estimated sediment delivery associated with the minimal cost solution found absent sediment constraints, then arbitrarily reduced that amount by 17%. Bettinger et al. (1998), to the contrary, established sediment production goals from estimates of impacts from the previous 10 years of harvest activity within the study watershed. Notably, the authors acknowledged the inherent difficulty and ambiguity in establishing such a goal. Rackley and Chung (2008) avoided the difficulties associated with identifying target sediment production levels by instead assigning a dollar value to sediment, but noted the challenge of selecting an appropriate environmental cost factor.

This dissertation instead assumes that the decision-maker explicitly wants to understand the tradeoffs prior to rendering an opinion on how to allocate weights between objectives, on how to scale non-commensurate objectives, or on what environmental targets/goals should be. More specifically, the decision-maker wants to understand the relationship between increasing road treatment costs and increasing environmental performance, and in so doing identify a tradeoff curve comprised of "technically efficient" solutions[1]. A solution is considered efficient when it is impossible to improve one objective (e.g., reduce cost.) without degrading another objective (e.g., increase sediment delivery). Efficient solutions are also referred to as "non-dominated" or "non-inferior." In this context, a multi-objective approach to optimization is required. Employing multi-objective formulations is appropriate for environmental decision-

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[1] In the multi-objective optimization literature, the term "Pareto optimality" is often used to refer to what is defined by economists as technical efficiency, which is a necessary but not sufficient condition for Pareto optimality. Pareto optimality is defined as the allocation of wealth or resources between individuals such that no reallocation can make one individual better without making another individual worse off (Pearce 1992). The multi-objective optimization literature abstracts from notions of individual welfare and utility curves, considering instead objective functions to be optimized.

making, can lead to informed compromise, and should ultimately facilitate tradeoff analysis (Kennedy et al. 2008; Toth et al. 2006).

A general multi-objective problem (MOP) can be formulated as shown below (Jozefowiez et al. 2008):

$$\text{(MOP)} = \begin{cases} \min & F(x) = (f_1(x), f_2(x), \ldots, f_n(x)) \\ s.t. & x \in D \end{cases} \tag{1}$$

where $n \geq 2$ is the number of objective functions, $F(x)$ the objective vector, D the feasible solution space, and $x = (x_1, x_2, \ldots, x_r)$ the vector of decision variables. Consider two decision vectors $a, b \in D$. Using the concept of technical efficiency, a is said to *dominate b* $(a \prec b)$ iff:

$$\forall\, i \in \{1, 2, \ldots, n\} : f_i(a) \leq f_i(b) \quad \cap \quad \exists\, j \in \{1, 2, \ldots, n\} : f_j(a) < f_j(b) \tag{2}$$

The set of efficient solutions is known as the efficient frontier or non-dominated frontier, whose values represent tradeoffs in the objective space. Identifying these solutions facilitates the decision maker's selection of a compromise solution that satisfies the objectives as best as possible (Van Veldhuizen and Lamont 2000). This represents an *a posteriori* optimization approach, wherein the decision-maker selects a solution from the frontier. By contrast, the *a priori* optimization approaches described earlier require that preferences, which can be uncertain and change over time, be identified as inputs to the optimization process.

Where multiple efficient alternatives exist, as is commonly the case, a secondary layer of decision making is necessary in order to select from the set of efficient, or non-dominated, solutions. Kangas and Kangas (2005) identify this as effectively the last step in forest planning, wherein the “best” alternative is identified from among those alternatives deemed efficient with respect to management objectives. Again, MCDM can be used in such situations to elicit preferences, in order to help decision-maker(s) choose from among competing solutions (de Steiguer et al. 2003). MCDM are also helpful in situations where decisions are made by more than one individual, and where there exist multiple stakeholders with differing opinions on how forest management should proceed. Mendoza and Martins (2006) offer an excellent review of previous applications of MCDM, as well as offering insight into new directions for modeling approaches moving forward. The focus in this dissertation is developing techniques to identify the efficient frontier, not to select an alternative from the frontier.

To date in the forest transportation planning literature there are few examples of multi-objective approaches that consider environmental performance. Thompson and Sessions (2008) employed exact methods to schedule road management treatments in order to minimize treatment cost and maximize environmental benefit, but only solved for the boundary solutions (i.e., they did not generate the tradeoff surface). Stückelberger et al. (2006) presented a road network design framework with three objectives: minimize road construction and maintenance costs, minimize deleterious ecological effects, and maximize suitability of cable-yarding landings. They approximated the non-dominated frontier with simulated annealing using an iterative approach, varying weights for a scaled single-objective function. Unfortunately this method is only guaranteed to find all efficient solutions if the frontier is convex. The presence of binary variables assigning particular treatments to particular road segments means in most transportation planning contexts the frontiers will not be convex. Manuscripts presented in this dissertation therefore employ more appropriate multi-objective programming approaches. A notable multi-objective paper that does not explicitly address road-related environmental concerns uses the tabu search heuristic to identify the efficient frontier between lost forest productivity and road construction costs (Richards and Gunn 2000).

To reiterate, transportation managers face a tradeoff between economic and environmental objectives. In some cases the environmental objective is institutional, as with federal agencies and the Aquatic Conservation Strategy, and in others the objective may be imposed, as with private landowners subject to regulations concerning water quality. The challenge therefore becomes to manage in order to achieve a low-cost, environmentally-benign road network.

Identifying the efficient frontier provides valuable information on what is and is not possible with respect to efficient management, and can point out instances where current management practices are inefficient. The efficient frontier also provides valuable information regarding tradeoffs in the objective space. In some circumstances a landowner may opt for marginal increases in expenditure in order to significantly improve the environmental performance of their road network. In others, a landowner may be able to demonstrate that costs associated with additional protective measures are not justified given the marginal benefit. Barrett and Conroy (2002), for instance, relate an experience with the Pacific Lumber Company (PALCO) wherein a systematic analysis of road treatment alternatives resulted in the identification of a road management strategy that was both less expensive and perceived to be more effective at reducing sedimentation than mitigation measures that were imposed as part of a habitat conservation plan.

Employing techniques presented here allows for the identification of the set of possible efficient outcomes, giving the decision-maker more insight into the problem and helping to reach a suitable compromise solution (Toth et al. 2006). Public managers facing reduced road maintenance budgets (due in part to reduced timber sales on national forests) should be able to use methods demonstrated here to improve their treatment efficacy. In particular, approaching aggregate recycling as an effective way to subsidize road removal efforts should result in more roads being removed and ultimately contribute to achieving strategic watershed restoration objectives. Private landowners should also embrace the paradigm shift proposed in this dissertation, in order to evaluate their current practices, identify where improvements can be made, and possibly to demonstrate that additional regulatory restrictions are unnecessary or impractical.

1.4 Dissertation Outline

The subsequent chapters of this dissertation are comprised of five manuscripts relating to various aspects of forest road management, plus a concluding chapter summarizing results. Chapter 2 introduces the notion of using technical efficiency for erosion control, in a scenario where various treatments to upgrade or remove a road can be employed. I use the WEPP:Road sediment prediction model (Elliot et al. 1999) to provide estimates of sediment delivery for each road segment, for each possible treatment. First a very small hypothetical example is constructed to illustrate how identification the set of non-dominated solutions may inform road treatment prioritization. Next I apply the model to a larger network using field-collected road data from the Jackson State Demonstrate Forest in northern California (Ish and Tomberlin 2005). I employ the epsilon-constraint method (Haimes et al. 1971), which iteratively solves for one objective subject to increasing constraint levels representing the other objective, in order to approximate the efficient frontier. Because of the small network sizes I am able to use exact methods (GAMS v 22.7, CPLEX solver) to identify intermediate solutions within the epsilon-constraint algorithm.

Chapters 3-4 instead focus on routing road maintenance vehicles (i.e., a grader) over a road network. In Chapter 3 I model grader routing as the Rural Postman Problem (RPP), the intent of which is to determine a minimal cost closed walk of a subset of some arcs of a graph (Eiselt et al. 1995). The RPP formulation provides a basis for many other industrial applications, including street sweeping, school bus routing, snow plowing, and garbage collection (Corberán et al. 2000, Eiselt et al. 1995). I formulate a single objective model to minimize total operating time, a proxy for grading cost. Reducing grading cost could release resources for other maintenance needs, ideally resulting in a better-maintained road system. Prior to deploying the grader, a subset of road segments requiring grading is identified using a rubric based on road standard and roughness index. A combinatorial optimization method, tabu search, is combined with two local search procedures to generate efficient grading routes. Initially I examine the heuristic's performance on a variety of small cyclical and dendritic networks that vary with respect to graph density, the optimal solutions to which can be found. Then I consider a much larger road network, using a portion of the road network from the McDonald Dunn Forest, a research forest managed by the College of Forestry at Oregon State University.

In Chapter 4 I extend the work of Chapter 3 to simultaneously consider economic and environmental objectives, and to schedule routes over a planning horizon involving multiple periods. This chapter approaches grader scheduling decisions as a multi-objective vehicle routing problem, using a multi-objective evolutionary algorithm (MOEA) as the solution method. The specific algorithm is known as SPEA2, (Strength Pareto Evolutionary Algorithm 2), which maintains an external archive (i.e., secondary population) of non-dominated solutions, and has been demonstrated to perform well in comparative analyses (Zitzler et al. 2001). The economic objectives sums grader operating cost and vehicle operating costs, and the environmental objective sums the hazard weighted rut depth over all segments in the network. Hazard weights are assigned to each segment according to the ratio of segment length over total network length. The importance of segment length is emphasized based upon research by Foltz and Elliott (1998) citing flow path length as an important variable. An empirical model developed by the World Bank (Faiz and Staffini 1979) is used to model both vehicle operating costs and rut depth formulation as a function of cumulative traffic. This problem is similar to solving a sequence of postman problems (as in Chapter 3), but differs in that there is no pre-identified subset of edges that actually require service, and that the costs are dynamic. Portions of the McDonald-Dunn Forest's road network are again modeled for purposes of experimentation.

Chapters 5-6 focus on identifying optimal aggregate recycling policies, and corresponding optimal road removal policies. The chapter presents real-world examples of aggregate recycling and discusses the advantages of doing so. Further, the chapter presents mixed integer formulations to determine optimal levels of aggregate recycling under economic and environmental objectives. The objectives are thought to be representative of management policies common among public managers in the western United States. Here benefit is modeled as the hazard weighted length of roads decommissioned. Two road removal treatments are considered: closure and decommissioning, with the expectation that decommissioning entails significantly greater environmental benefits. It is assumed an experienced professional has identified which road segments require removal, and that the decision variable is whether to close or decommission a particular road segment. If a road is decommissioned, the aggregate can be recovered and used for other scheduled maintenance and construction projects. Again, a portion of the McDonald-Dunn Forest's road network is used for purposes of experimentation (as is the case with Chapter 6). Comparing optimization results with and without the opportunity to recycle provides quantitative information on the degree to which aggregate recovery and reuse may simultaneously provide economic and environmental benefits. Sensitivity analysis is performed with respect to decommissioning cost and aggregate recovery rates.

Chapter 6 extends the work of Chapter 5 to simultaneously consider economic and environmental objectives. That is, I seek to identify the entire frontier of efficient solutions, not just the boundary (minimal cost, maximal benefit) solutions identified in

Chapter 5. The epsilon-constraint method is again employed. Chapter 6 also extends the analysis of the role of aggregate recycling in effectively subsidizing removal projects. I define an accounting variable ES (effective subsidy) as the difference in minimized cost between scenarios with and without the opportunity to recycle aggregate, at a given level of environmental performance. I then examine how ES varies with increasing levels of environmental performance. The expectation is that ES generally increases with increasing environmental performance, because as more roads are decommissioned more low-cost aggregate may become available.

Chapter 6 also extends the work of Chapter 5 to include explicit calculation of a hazard factor. In Chapter 5, the model assumes that all road segments slated for removal are equally detrimental, and therefore the optimal treatment from an environmental perspective is simply a function of length. This assumption is reasonable if it is also assumed an experienced professional has identified appropriate levels of decommissioning such that the expected future impacts per unit length from each segment are nearly identical. With Chapter 6 to the contrary each segment is assigned a score on the scale (0, 1) reflecting the degree to which the segment has potential to cause environmental damage. Scores are assigned according to a model based upon the Ecosystem Management Decision Support (EMDS) system. EMDS employs fuzzy logic and knowledge-based reasoning integrated into a geographic information system (GIS) to provide decision support for ecological assessment (Reynolds 1999). EMDS assesses ecological condition according to a hierarchical, multi-criteria framework. The use of fuzzy, or approximate, logic is thought to extend the ability to reason with the imprecise or qualitative information common to natural resource management (Reynolds et al. 2000). EMDS has been employed for a variety of purposes, including characterization of ecological condition and prioritization of watersheds for restoration on public land in the Pacific Northwest (Reeves et al. 2006), watershed assessment in the Chewaucan Basin (Reynolds and Peets 2001), assessment of habitat and basin-wide health in the Rogue River drainage (Pess et al. 2003), sediment total maximum daily load monitoring in a northern California watershed (Dai et al. 2004), and landscape evaluation of the eastern Washington Cascades (Reynolds and Hessburg 2005). Here I propose adoption of a knowledge base to assign road segments a hazard weight based upon likely negative aquatic impact. I base my specific implementation on a model originally presented by Girvetz and Shilling (2003), who analyzed the Tahoe National Forest road system for potential environmental impacts according to the USDA Forest Service's "Roads Analysis" guidance document (USDA 1999).

Lastly, Chapter 7 summarizes the aggregate results of the manuscripts, and offers suggestions for future work. It is my belief that moving to multi-objective planning frameworks is both appropriate and preferable for contemporary forest road management moving forward. I hope this work will stimulate additional research into tradeoff analysis, and ultimately will lead to improved economic and environmental efficiency in the management of forest transportation networks.

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2 Forest Road Erosion Control using Technical Efficiency

2.1 Abstract

Forest roads are associated with accelerated erosion and can be a major source of sediment delivery to streams, which can degrade aquatic habitat. Controlling road-related erosion therefore remains an important issue for forest stewardship. Managers are faced with the task to develop efficient road management strategies to achieve conflicting environmental and economic goals. This manuscript uses mathematical programming techniques to identify the efficient frontier between sediment reduction and treatment costs. Information on the nature of the tradeoffs between conflicting objectives can give the decision-maker more insight into the problem, and help in reaching a suitable compromise solution. This approach avoids difficulties associated with a priori establishment of targets for sediment reduction, preferences between competing objectives, and mechanisms to scale non-commensurate objectives. Computational results demonstrate the utility of this multi-objective optimization approach, which should facilitate tradeoff analysis and ideally promote efficient erosion control on forest roads.

2.2 Introduction

Forest roads are associated with accelerated erosion and can be a major source of sediment delivery to streams, which can degrade aquatic habitat (Jones et al. 2000; Lugo and Gucinski 2000; Forman and Alexander 1998). Though landslides and other mass movements are responsible for the majority of road-related erosion in areas with steep slopes, surface erosion can be a significant source of road-related sediment input to streams (Gucinski et al. 2001). Timber hauling during the wet season can be the most significant source of fine sediment associated with forest practices (Oregon Department of Forestry 2003). Fine sediment can originate from the road surface itself due to the breakdown of the aggregate over time from crushing under heavy tire loading and weathering. Sediment production is related to many road design elements, including segment length and gradient (Luce and Black 1999), aggregate quality (Foltz and Truebe 2003), and aggregate depth (Skaugset et al. 1997). Management activities such as maintenance and especially log truck traffic also influence sediment production (Luce and Black 2001; Bilby et al. 1989; Reid and Dunne 1984).

The presence of a forest road can substantially alter natural hillslope hydrologic and geomorphic processes. Forest roads intercept rainfall and subsurface flow, concentrate flow on the surface or adjacent ditches, and divert or reroute water from natural flow paths (Gucinski et al. 2001). They also accelerate chronic and episodic erosion processes, alter channel structure and geometry, alter surface flowpaths, and cause interactions of water, sediment and woody debris at engineered stream crossings (Gucinski et al. 2001). Road surface shapes are therefore designed to “encourage shedding of water from the surface before it gains enough concentration and velocity to cause unacceptable surface erosion” (Moll et al. 1997, p.1). Likewise, road drainage systems are designed to move water away from the road surface as quickly as possible, ideally to the forest floor where the water can disperse and infiltrate into the soil.

Unfortunately, in some circumstances poorly designed and/or maintained drainage systems deposit sediment directly into streams at road-stream crossings. Road removal is generally thought the most effective way to reduce long-term environmental impact (Switalski et al. 2004), but comes with the potential opportunity cost of lost access for fire management, commodity production, or other activities (Anderson et al. 2006).

In the U.S., roads in the national forest system are chronically under-maintained, with a backlog of necessary improvement and removal needs (Sample et al. 2007; USDA 2002). The Aquatic Conservation Strategy of the Northwest Forest Plan cites prevention of road-related runoff and sediment production as one of the most important components of a watershed restoration program (Reeves et al. 2006; USDA and USDI 1994). Watersheds that have seen the most improvement to date had relatively extensive road removal programs (Gallo et al. 2005), and a majority of the funding to date has been allocated for road-related treatments (Heller 2002). Roni et al. (2002) recommended managers focus on road decommissioning and maintenance, among other treatments, to restore hydrologic and geologic processes. Thus erosion control on forest roads is crucial to an effective watershed restoration strategy.

Beyond efforts to improve aquatic habitat on federally owned land, the Clean Water Act (CWA) provides a strong motivation to pursue effective erosion control methodologies. Road-related sediment is recognized as a contributing source of pollution for many rivers and streams listed as water quality limited under the CWA (e.g., Environmental Protection Agency, Impaired Waters and Total Maximum Daily Loads: Examples of Approved Sediment TMDLs, http://www.epa.gov/owow/tmdl/examples/sediment.html). Dai et al. (2004), for instance, identified forest roads as the dominant source of controllable erosion in a decision aid designed to support monitoring and assessment for a sediment total maximum daily load (TMDL) in a northern California watershed. The CWA also calls for development of regional water quality management programs, which can include limitations on forest and road impacts. For example, the General Waste Discharge Requirement program administered by the California North Coast Regional Water Quality Board requires that forestland owners develop and implement Erosion Control Plans to "prevent and minimize the discharge of sediment" prior to initiating timber harvest (Robert Klamt, North Coast Regional Water Quality Control Board, personal communication, 2007).

Contemporary court precedent relating to the CWA suggests that additional regulations concerning forest practices, especially forest road management, may be forthcoming. A Federal District Court in California recently found that drainage ditches and culverts delivering sediment to streams constitute point sources of pollution, thereby subjecting forest roads to National Pollutant Discharge Elimination System (NPDES) permitting requirements (EPIC v. PALCO, No. C 01-2821 MHP*)*. However, a different outcome was reached on a similar case in Oregon, with the Court ruling effectively that all road-related sediment delivery is more accurately characterized as nonpoint source pollution (NEDC v. Brown, No. 06-1270-K1). NEDC v. Brown was appealed in the US Court of Appeals for the 9th Circuit. If a ruling by the appellate Court aligns with the EPIC decision, it could usher in a new regulatory paradigm, presenting new challenges to landowners seeking to cost-effectively control erosion.

NPDES permits require polluters to adhere to effluent limitation standards. Technology-based standards reward efficiency and innovation, and tighten over time as the state of the art evolves. Standards vary with the nature of the pollutant, but all are premised upon the application of pollution control technology. As sediment is considered a "conventional" pollutant, Best Conventional Pollution Control Technology (BCT) standards would likely apply. As is relevant here, BCT standards "include consideration of the reasonableness of the relationship between the costs of attaining a reduction in effluents and the effluent reduction benefits derived." (CWA §304(b)(4)(B)) This test for what constitutes "reasonable" is frequently referred to as the "bend of the knee" test, where polluters are required to reduce pollution up to the point where the marginal benefits per dollar spent begin to markedly decline. That is, the CWA presents a statutory requirement to perform a cost/benefit *tradeoff analysis* in order to establish pollution control standards.

In this manuscript we advocate adoption of tradeoff analysis for facilitating forest road erosion control planning. Irrespective of whether forest roads are subject to CWA NPDES requirements, tradeoff analysis is attractive because it can help decision-makers achieve desired environmental and economic results in the most efficient manner. Specifically, we propose multi-objective optimization techniques based on the concept of technical efficiency. This paradigm is suitable for environmental decision-making contexts, facilitates tradeoff analysis, and can lead to informed compromise (Kennedy et al. 2008). In the following sections we will review existing techniques for erosion control, present the multi-objective erosion control model formulation, briefly discuss available solution techniques, then demonstrate the utility of approaching erosion control through the lens of technical efficiency with results from an example, and lastly offer concluding thoughts.

2.3 Forest Road Erosion Control

Controlling road-related erosion to minimize sediment delivery and degradation of aquatic habitat remains an important issue for forest stewardship. Managers are faced with the task to develop efficient road management strategies to achieve conflicting ecological and economic goals. Identification of an appropriate suite of road management treatments can be difficult. Blanket prescription of best management practices can prove ineffective and economically infeasible (Barrett and Conroy 2002); in general it is not an efficient approach to apply treatments to problem areas independently of their impact on overall cost-effectiveness (Weaver and Hagans 1999). At the watershed scale the pool of possible road treatment combinations is frequently too large for explicit consideration, necessitating some mechanism to facilitate generation and evaluation of alternatives. Appropriate decision support tools can and have been used to help managers plan cost-effective erosion control treatments.

Despite the presence of conflicting objectives, most applications of decision support for erosion control have considered a decision-making environment with a single objective. A common approach assumes the decision-maker manages to minimize treatment costs. Rackley and Chung (2008) used NETWORK 2000 (Chung and Sessions 2003) to solve transportation problems, incorporating erosion concerns by assigning extra costs to road segments based upon expected erosion. Thompson and Tomberlin (2005) applied stochastic dynamic programming to minimize the cost of erosion control on an unused logging road in northern California.

In some applications additional environmental objectives are modeled as side constraints under an economic objective. Contreras and Chung (2006) used an ant colony heuristic algorithm to identify the set of least cost routes from timber sales to mills, with sediment production constraints. Similarly, Bettinger et al. (1998) used tabu search to schedule harvest and road activities with sediment production constraints to achieve aquatic habitat goals. Akay and Sessions (2005) created a forest road alignment model that used a heuristic procedure to minimize construction, maintenance and construction costs for forest roads, while considering sediment production; this work has been further advanced by Aruga et al. (2007).

Alternatively, the decision-maker can seek to optimize an environmental objective, subject to budgetary constraints and other resource limitations. Madej et al. (2006) and Eschenbach et al. (2005), for instance, applied dynamic programming and genetic algorithms to maximize the sediment saved from entering the stream channel as a result of applying various treatments to roads and stream crossings. Thompson and Sessions (2008) presented a mixed integer programming framework for determining optimal levels of aggregate recycling and assigning road removal treatments, using hazard-weighted length of roads decommissioned as an environmental proxy.

As an alternative to modeling objectives as constraints, multiple objectives can be condensed into a single objective function using methods such as goal programming or weighting objectives. Goal programming requires identification of target environmental performance levels. Both techniques require an appropriate mechanism to scale non-commensurate objectives (e.g., $ and kg sediment), as well as a priori elicitation of preferences between objectives. In such cases, multi-criteria decision models, which provide for the systematic elicitation of preferences between objectives, can be of use (de Steiguer et al. 2003). Coulter et al. (2006), for example, used the Analytic Hierarchy Process to condense three objectives (minimize impacts to streams, minimize road failures, and minimize Forest Practice Act violations), then solved for the resultant single objective function using a combinatorial heuristic.

Arguably the aforementioned decision support approaches are unsuitable for road erosion control under conflicting economic and environmental objectives. Kennedy et al. (2008) referred to the notion of identifying a singularly “optimal” solution to such problems as a “fallacy of the weighted sum approach,” because preferences can change, and because no single answer simultaneously optimizes all objectives. Further, identification of appropriate sediment reduction goals is not a trivial task. As with other environmental management contexts, such as managing for wildlife habitat objectives, a priori establishment of target values is a difficult, uncertain exercise. Contreras and Chung (2006) set as an upper bound the estimated sediment delivery associated with the minimal cost solution found absent sediment constraints, then arbitrarily reduced that amount by 17%. Bettinger et al. (1998), to the contrary, established sediment production goals from estimates of impacts from the previous 10 years of harvest activity within the study watershed. Notably, the authors acknowledged the inherent difficulty and ambiguity in establishing such a goal. Rackley and Chung (2008) avoided the difficulties associated with identifying target sediment production levels by instead assigning a dollar value to sediment, but noted the challenge of selecting an appropriate environmental cost factor.

Here we assume instead the decision-maker explicitly wants to understand the tradeoffs prior to rendering an opinion on how to allocate weights between objectives, on how to scale non-commensurate objectives, or on what environmental targets/goals should be. More specifically, we want to understand the relationship between increasing road treatment costs and decreasing sediment delivery to streams, and in so doing identify a tradeoff curve comprised of technically efficient solutions. A solution is considered efficient when it is impossible to improve one objective (e.g., reduce cost.) without degrading another objective (e.g., increase sediment delivery). Efficient solutions are also referred to as “non-dominated” or “non-inferior.” The set of all efficient solutions is called the efficient frontier.[2]

Consider for the purposes of illustration a forest landowner with 3 roads requiring treatment. Four treatments are available per road, amounting to $4^3 = 64$ total treatment combinations. The landowner has a predictive inventory for road-related sediment production with and without treatment. Benefit is calculated as the sediment saved from

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[2] In the multi-objective optimization literature, the term “Pareto optimality” is often used to refer to what is defined by economists as technical efficiency, which is a necessary but not sufficient condition for Pareto optimality. Pareto optimality is defined as the allocation of wealth or resources between individuals such that no reallocation can make one individual better without making another individual worse off (Pearce 1992). The multi-objective optimization literature abstracts from notions of individual welfare and utility curves, considering instead objective functions to be optimized.

entering the stream compared to the baseline, no-treatment scenario. Cost and efficacy of treatment vary by road segment, as can be seen in Table 1.

Figure 1 displays the efficient frontier for this example scenario. In total 12 efficient solutions were identified, with the other 52 solutions in some way dominated. There are three noteworthy aspects to Figure 1. First, the efficient frontier curve is not convex. Second, beyond a certain point additional expenditures on erosion control clearly have only marginal sediment reduction benefit. Third, in a single objective, cost minimization framework, the selection of a target constraint level for sediment production could bias the ultimate decision, possibly resulting in an undesirable allocation of resources. For instance, it may be that bolstering sediment reduction from 100 kg to 500 kg is worth the marginal expenditure, a possibility that would not have been explored absent a tradeoff analysis.

Information on the nature of the tradeoffs between conflicting objectives can give the decision-maker more insight into the problem, and help in reaching a suitable compromise solution (Toth et al. 2006). This process represents *a posteriori* preference articulation, where the decision-maker selects from a set of non-dominated solutions (Hwang and Masud 1979). Ultimately the final solution results from both optimization, used to identify the efficient frontier, and some decision process, used to select a preferred alternative (Van Veldhuizen and Lamont 2000). Readers wishing for more information regarding the latter step are referred to excellent reviews: Mendoza and Martins (2006) and Kangas and Kangas (2005). Our focus in this paper is on the optimization component.

2.4 Problem Formulation

Below we present the mathematical formulation of our multi-objective erosion control planning problem.

$$\min \quad Z_c = \sum_i \sum_j C(i,j) * X(i,j) \tag{1}$$

$$\max \quad Z_s = \sum_i \sum_j S(i,j) * X(i,j) \tag{2}$$

Subject to:

$$\sum_j X(i,j) = 1 \tag{3}$$

$$X(i,j) \in \{0,1\} \tag{4}$$

where Z_c = cost minimization objective; Z_s = sediment reduction maximization objective; i = set of road segments; j = set of road treatments; $C(i,j)$ = cost of implementing treatment j on road segment i; $S(i,j)$ = sediment reduction achievable by implementing treatment j on road segment i; and $X(i,j)$ = binary variable indicating which treatment road segment i receives.

Equation (1) presents the cost minimization objective and Equation (2) the sediment reduction maximization objective. Equation (3) ensures that each road segment is assigned exactly one treatment (including “do nothing”), and Equation (4) requires the decision variables remain binary.

2.5 Solution Techniques

Approaches to identify the efficient frontier within the forest planning literature vary. One common approach is to assign a weight to each objective in order to create a singular objective function, as described above, and then iterate over all possible combinations of weights. Stückelberger et al. (2006) employed this technique to design a road network to minimize road construction and maintenance costs, minimize negative ecological effects to wildlife habitat, and maximize the suitability of cable-yarding landings. Unfortunately this method is only guaranteed to find all efficient solutions if the frontier is convex. In this planning context the frontier is not necessarily convex due to the presence of binary decision variables, as we demonstrated in the example above.

Another common approach is the epsilon-constraint method (Haimes et al. 1971), wherein an algorithm iteratively optimizes for a single objective while updating constraint levels, ε, representing other objectives. Connaughton and Fight (1984) employed this method to analyze tradeoffs for national forest planning. Nalle et al. (2004) and Calkin et al. (2002) also used this approach, to examine the tradeoffs between timber production and wildlife metrics. One drawback to this approach is the need to identify a suitable increment, δ, for updating ε levels (Laumanns et al. 2006). Choosing too small a value of δ could result in unnecessary redundant runs, and too large a value could miss solutions within the interval defined by δ.

Another possible drawback to the epsilon-constraint method is that a solution optimizing objective A subject to a constraint on objective B (Solution #1) is not necessarily an efficient solution. However, the algorithm can be modified slightly to rectify this situation. Specifically, insert a step to solve the problem optimizing objective B subject to achievement of the value just identified for objective A (Solution #2). Either Solution #2 is an improvement (i.e., it dominates Solution #1), or Solution #1 represents what is achievable, and is therefore efficient (Sadagopan and Ravindran 1982). Toth et al. (2006) employed this modified version of the epsilon-constraint method and reported satisfactory computational results for a two objective harvest scheduling problem.

Figure 2 outlines the major steps in this modified epsilon-constraint algorithm. For the purposes of this manuscript we also employ this modified algorithm (see Example Application). Initially two boundary solutions are obtained, corresponding to solutions optimizing each objective (treatment cost and sediment reduction) absent side objectives on the competing objective. The algorithm then progressively proceeds from one end of the frontier to the other.

Whether the specific algorithm iterates over objective weights or constraint levels, a solution technique is required to generate solutions to the single-objective problems. Depending upon problem size and complexity, exact methods can be used (e.g., Toth and McDill 2008; Toth et al. 2006), but use of heuristics is probably more common (e.g., Stückelberger et al. 2006; Nalle et al. 2004; Calkin et al. 2002). In fact, with some heuristic implementations it is unnecessary to iteratively solve for a single objective. Population-based methods, by generating a suite of possible solutions, allow for the approximation of the efficient frontier in a single run of the algorithm. In particular, multi-objective evolutionary algorithms (MOEA) have become a popular tool for solving multi-objective forest planning problems (e.g., Kennedy et al. 2008; Ducheyne et al. 2006; Ducheyne et al. 2004).

Solution techniques necessarily become more complex for planning contexts involving more than two objectives. For the three-objective case, the decision-maker analyzes tradeoffs along a surface rather than along a curve; for higher-dimension problems visualization of tradeoffs becomes more difficult. Toth et al. (2009) extended three traditional bi-objective approaches (epsilon-constraint method, decomposition method based on the Tchebycheff metric, and a novel alpha-delta method) for a spatially constrained harvest schedule with three objectives, and generated solutions using exact integer programming techniques. Generalization to the n-objective case with the epsilon-constraint method was considered fairly straightforward, but very computationally expensive. In fact, the authors stated that all of the exact approaches are suitable only for pilot studies given current computing capacities. Again, here heuristics become attractive, in particular population-based evolutionary algorithms. Kennedy et al. (2008), for instance, used MOEA to apply forest fuel treatments in order to achieve three objectives: minimize the total area treated, maximize habitat protection for the northern spotted owl, and maximize protection for late successional forest reserves. Hamann (2008) employed MOEA to develop operational harvest plans under five objectives, including minimization of soil disturbance.

2.6 Example Application

We now present a hypothetical example of moderate complexity to demonstrate identification of the efficient frontier. We use road data collected from the Jackson State Demonstration Forest in northern California (Ish and Tomberlin 2007). For the purposes of this illustration we opted to use the WEPP:Road web interface to estimate sediment delivery (FS WEPP Interfaces; http://forest.moscowfsl.wsu.edu/fswepp/). Previous applications of WEPP to predict erosion from forest roads include Rackley and Chung (2008), Ish and Tomberlin (2007), Contreras and Chung (2006), Thompson and Tomberlin (2005), and Elliot and Tysdal (1999).

WEPP:Road is an extension of the WEPP model to predict erosion for forest road settings. WEPP simulates the daily climactic conditions using a stochastic climate simulator, and ultimately calculates erosion and deposition rates for a representative hillslope. Annual sediment yields are calculated from these daily estimates (Elliot et al. 1999). We selected the Fort Bragg, CA climate data for the WEPP weather simulator. Erosion processes are modeled to occur along a hillslope that is defined by a series of overland flow elements (OFE). An OFE is a unique combination of soil, slope, and vegetation. In WEPP:Road, three OFEs are used: the road, fillslope and forest buffer. Four soil textures are available: clay loam; silt loam; sandy loam; and loam. Four road designs are available: in-sloped rocked or vegetated ditch; in-sloped bare ditch; out-sloped un-rutted; and out-sloped rutted. The user is responsible for specifying road segment length, road width, and steepness of road and buffer.

We consider three treatments that reflect a directed effort to control primary factors thought to influence sediment generation and delivery. Treatment 1 is to install additional cross-drain culverts in order to reduce effective road segment length. Effective lengths after culvert installation vary by segment, with length reductions ranging from 30-70% of the initial segment length. Treatment 2 upgrades the road surface from native soil to aggregate. We assume the manager has access to sources of both marginal and high quality aggregate for use in improving native-surfaced roads. Higher quality aggregate, though significantly more expensive, can also significantly reduce sediment production. Foltz and Truebe (2003) reported that marginal aggregate produced ~3 times the sediment produced by high quality aggregate. Here we conservatively estimate that higher quality aggregate produces 50% less sediment. Simulations from WEPP:Road with gravel (aggregate) were assumed to represent the marginal quality scenario. Lastly, the third treatment is decommissioning. Only those segments servicing low levels of traffic may be decommissioned, and the expectation is that all chronic sedimentation and delivery will cease. Combinations of treatments are also possible, bringing the total suite of possible treatments to seven: no treatment, install cross drain, apply marginal aggregate, apply high quality aggregate, install cross drain and apply marginal aggregate, install cross drain and apply high quality aggregate, and decommission.

Using the road data from Ish and Tomberlin (2007), we model a road network with a total of 47 road segments. Of the 47 road segments, 21 are modeled as having a sandy loam surface and 26 as having an aggregate (marginal quality) surface; all segments have a vegetated ditch. Five of the native-surfaced segments service low traffic and are therefore eligible for decommissioning in addition to the other available treatments. The rest of the native-surfaced segments are expected to service high levels of timber haul traffic in the next planning period - these segments are not eligible for decommissioning, but can have cross drains installed and rock applied. For the aggregate-surfaced segments the only available improvement is to install cross-drain culverts. Table 2 summarizes the road segment information by gradient, length, surfacing, traffic, and available treatments.

Cost estimates for the treatments were obtained from Weaver and Hagans (Road upgrading, decommissioning and maintenance, estimating costs on small and large scales, available at http://www.st.nmfs.gov/st5/Salmon_Workshop/10_Weaver_and_Hagans.pdf). Installing ditch relief culverts cost $600 each. Purchase and application of marginal quality aggregate was estimated to be $9.84 per linear meter ($3 / ft), with costs rising to $13.94 per linear meter ($4.25 / ft) for higher quality aggregate. Decommissioning costs were estimated as $13.12 per linear meter ($4 / ft).

Unlike the earlier simple example, here the cardinality of the solution space is far too large for enumeration. However, with only 136 binary decision variables, the problem is not too large as to be prohibitive for mixed integer programming. We therefore opted to employ the modified epsilon-constraining method, with δ set to 0.05 kg of sediment. Arguably this value could have been set much higher to a more reasonable unit of management for sediment control, but since our problem was sufficiently small we opted to pursue an accurate approximation of the frontier. The algorithm was coded using GAMS v22.7, and used the CPLEX linear program solver.

The mixed-integer algorithm identified a total of 635 non-dominated efficient solutions. The last non-dominated solution was identified after just under 5 minutes of computing time. For larger or more constrained problems however solution times may be much greater. Compared to the time and effort spent inventorying roads and modeling sediment delivery, the time spent identifying the efficient frontier may actually be quite small. If the decision-maker wishes to perform a great deal of sensitivity analysis, however, having a technique capable of generating solutions more quickly might be preferred. Thus for much larger planning problems heuristics may be more suitable. At a minimum, the exact approaches used here could be used to validate a combinatorial heuristic approach.

Figure 3 displays the calculated efficient frontier for erosion control on Road 630. Note the decreasing marginal benefit (in terms of sediment reduction) associated with increased treatment costs. To illustrate the cost/benefit tradeoffs we consider Efficient Solutions (EFS) 176 and 635, with with objective function values of (Z_c = \$14,560, Z_s = 26,086 kg) and (Z_c = \$45,000, Z_s = 32,591 kg), respectively. By opting for EFS 176 a landowner could achieve 80% of the estimated total sediment reduction possible at only 32% of the cost. The former solution is clearly preferable outcome to a blanket prescription of treatments resulting in significantly greater costs with only marginal benefits.

2.7 Discussion

Our results demonstrate that identification of the efficient frontier is an important tool for selecting appropriate environmental performance measures for forest road management. This type of tradeoff analysis facilitates cost-effective erosion control, helping decision-makers identify a reasonable relationship between treatment cost and sediment reduction. We propose an a posteriori approach, wherein optimization techniques are used to demonstrate to decision-makers the realm of possible efficient solutions. Decision-makers then, based upon their preferences, select from this set of non-inferior solutions.

The intent of this manuscript is to demonstrate the utility of multi-objective programming and tradeoff analysis for erosion control planning. For the purposes of illustration we therefore made several simplifying assumptions. In particular we limited our choice of management treatments and used an off-the-shelf erosion model with little site-specific information. Generation of predictive inventories that estimate erosion levels under alternate treatments, necessary for the type of analysis promoted here, has many challenges. Various approaches include, like ours, the use of existing predictive models (e.g., Rackley and Chung 2008), or proprietary erosion models (e.g., Bolstad and Peterson 2005), field-based estimates (e.g., Madej et al. 2006), risk assessments (e.g., Rice and Lewis 1991), and environmental rating scores used as a proxy (e.g., Dai et al. 2004).

One problem with existing erosion prediction models such as WEPP is that much of the variation is explained by contributing drainage area and road gradient, and not the hillslope hydrology. Surfleet (2008) demonstrated however that pairing field data with road erosion models improved watershed scale estimates of road sediment delivery. Further, he demonstrated that road runoff observations could be used to accurately estimate road sediment production at the catchment and road scale.

To prioritize spending, having information on the hydrology and likely efficacy of treatment at the segment scale is therefore very important. Chronic sediment often comes from a minority of road segments, which cannot be identified a priori (Skaugset et al. 2007). Inspection and monitoring can therefore be useful by allowing managers to “buy” information today in order to cost-effectively avoid sediment in the future. Here forest engineers can play an important role through careful design of monitoring programs to link data collection, analysis and reporting to management objectives, and to incorporate new knowledge into future design (Pyles 2005). Monitoring and evaluation allow for improvements in understanding and planning, and learning should therefore be an active component of resource management (Olson and Orr 1999).

The transportation manager therefore faces the challenges of how to allocate scarce resources between erosion monitoring and control efforts and how to amend management strategies given new information. With new information on expected erosion from segments before and after treatment(s), a new efficient frontier can be generated and a new suite of road management actions identified. Innovative decision support tools may be necessary to help managers evaluate these difficult decisions. Partially observable Markov decision processes are one proposed tool for identifying conditions under which immediate expenditures on erosion control are less costly than the cost of monitoring and follow-up (Tomberlin and Ish 2007). Bayesian inference and decision theory may be another promising approach for updating our beliefs as monitoring generates new information (e.g., Dorazio and Johnson 2003).

Of course, controlling road-related erosion to protect water quality is a universal problem, and forest managers across the globe could benefit from more efficient and effective erosion control measures. The authors are most familiar with the legal and regulatory situation in the U.S., and therefore used this context to motivate additional research into efficient erosion control planning.

2.8 Conclusion

We presented an application of decision support applied to forest road management, wherein we used the principles of forest and industrial engineering to identify efficient road management alternatives. Specifically we proposed the use of multi-objective programming techniques to identify the efficient frontier between sediment reduction and management costs. In natural resources management, road management in particular, incorporation of competing objectives is common and therefore having a tool to facilitate tradeoff analysis should prove useful. Ultimately, the tradeoff-analysis techniques promoted here should facilitate improved and efficient forest road management.

Future research could seek to apply the methods presented here across a larger ownership, or to include a broader scope of possible treatments. For instance, researchers could include as decision variables maintenance regimes, traffic levels, seasonal road closure, and reduced tire inflation. Also important to include in the tradeoff analysis are the opportunity costs of such management actions. Toman et al. (2007) for example demonstrated that the opportunity costs associated with restricting wet weather timber haul and harvest could be up to 18% of total net revenue. Work pairing tradeoff analysis with adaptive management paradigms would also be a promising direction. For instance, it may be possible to incorporate model uncertainty into our multi-objective programming approach, perhaps through robust optimization or other techniques. Alternatively, it may be possible to develop approaches that identify not only optimal allocations of resources between monitoring and treatment, but what types of monitoring and treatment to apply.

Advancements in computing capacity and in algorithmic development increasingly make solving more complex problems, such as those with multiple objectives, possible. We therefore expect that techniques to identify efficient frontiers will become preferable to traditional methods that seek to condense multiple objectives into a single objective function. It is our hope that this manuscript demonstrating the utility of technical efficiency for erosion control will spur future research into efficient multi-objective road management.

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Figure 2.1: Efficient Frontier, 3 Segment Example

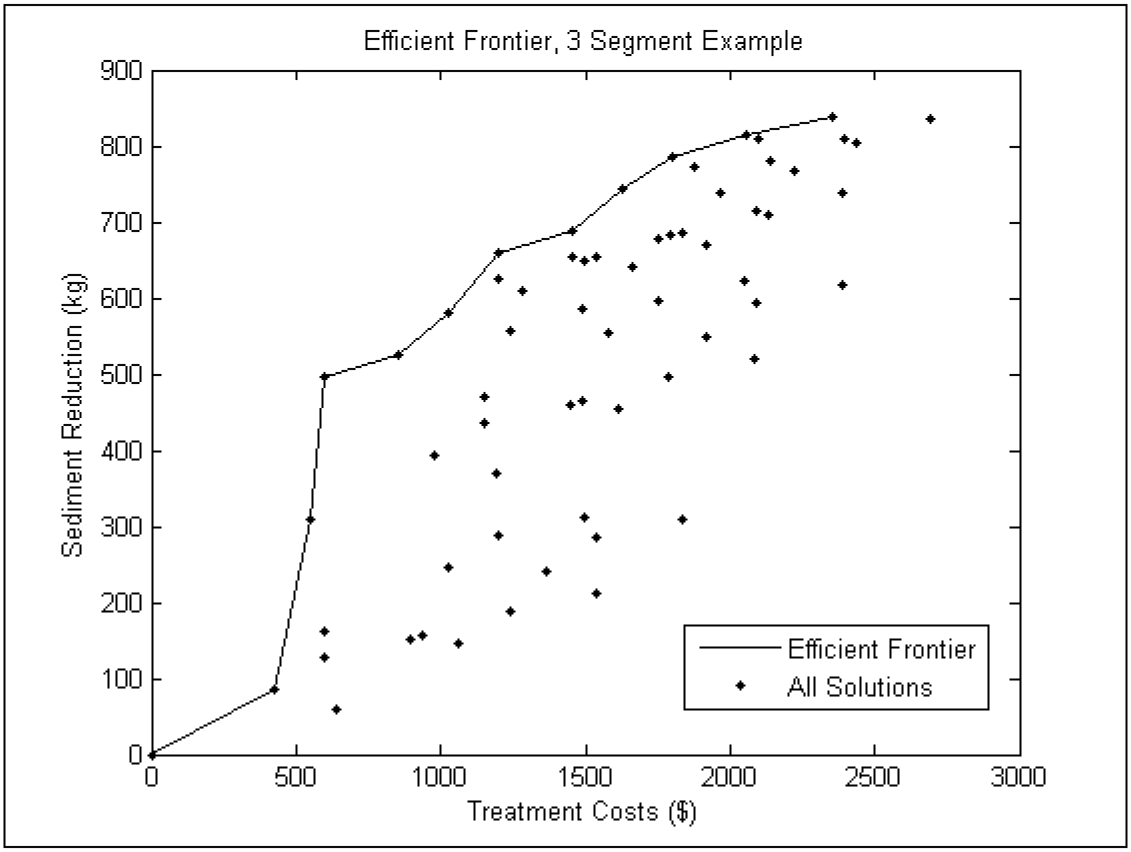

Figure 2.2: Modified Epsilon-Constraint Algorithm

```
Step 1
Solve each objective individually.
Define ideal solutions ( $Z_c^0$, $Z_s^0$ )

Step 2
$\min \quad Z_c \quad s.t.\ SED \geq Z_s^0$
Define efficient solution, EFS(1) = ( $Z_c^{SED}$, $Z_s^0$ )

Step 3
$\max \quad Z_s \quad s.t.\ COST \leq Z_c^0$
Define efficient solution, EFS(2) = ( $Z_c^0$, $Z_s^{COST}$ )
Set $\overline{SED} = Z_s^{COST}$
Set n = 3

Step 4
$\min \quad Z_c \quad s.t.\ SED \geq \overline{SED} + \varepsilon$
Define solution, $COST_{SED}$

Step 5
$\max \quad Z_s \quad s.t.\ COST \leq COST_{SED}$
Define solution, $SED_{SED}$
Define efficient solution, EFS(n) = ( $COST_{SED}$, $SED_{SED}$ )

Step 6
If $\overline{SED} = Z_s^0$ Then Stop
Else Goto Step 7

Step 7
$\overline{SED} = SED_{SED}$
n = n + 1
Goto Step 4
```

Figure 2.3: Efficient Frontier, 47 Segment Example

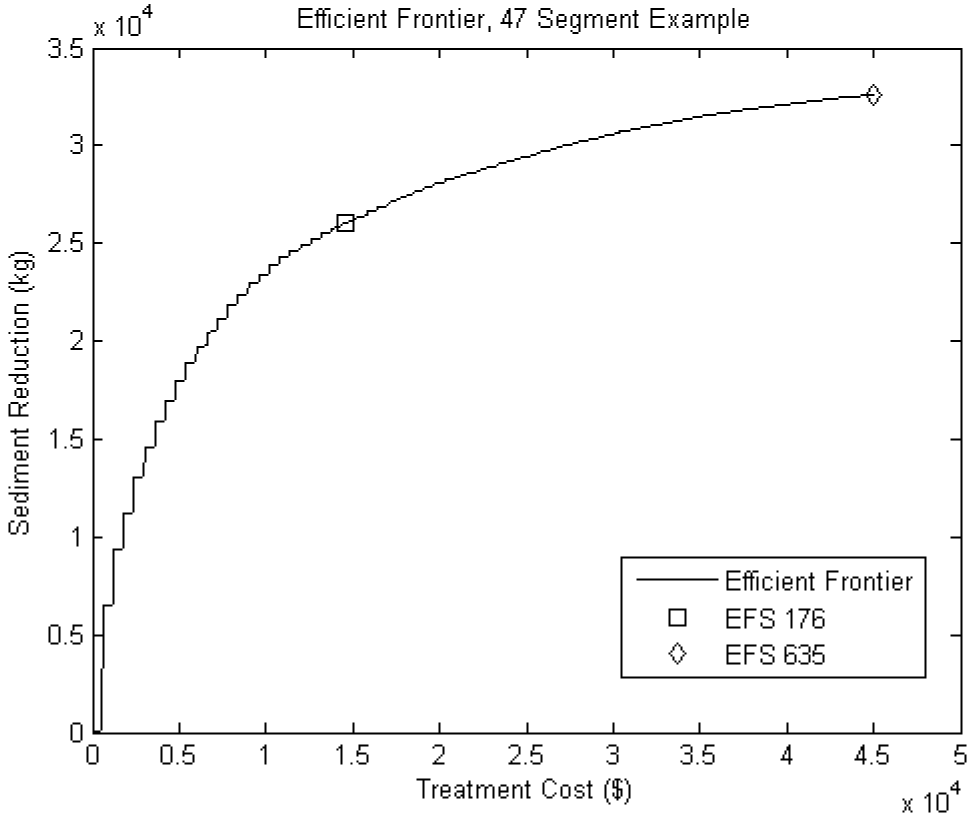

Table 2.1: Example Inventory of Sediment Reduction and Treatment Cost

Treatment	**Sediment Reduction (kg) / Cost of Treatment ($)**		
	Road 1	**Road 2**	**Road 2**
A (no treatment)	0 kg / $0	0 kg / $0	0 kg / $0
B	161 kg / $600	127 kg / $600	497 kg / $600
C	60 kg / $638	84 kg / $425	308 kg / $552
D	157 kg / $940	151 kg / $898	526 kg / $855

Table 2.2: Road Segment Information, Case Study. Available treatments are: no treatment (N), install cross drain (C), apply marginal quality aggregate (MA), apply high quality aggregate (HA), install drain and apply marginal aggregate (CMA), install drain and apply high quality aggregate (CHA), and decommission (D).

Segment	Gradient (%)	Length (m)	Effective Length (m)	Surface	Traffic Level	Available Treatments
1	2	100	65	Native	Low	All
2	2	44	15	Native	Low	All
3	4	72	35	Native	Low	All
4	8	138	84	Native	Low	All
5	0	23	9	Native	Low	All
6	6	115	52	Native	High	N, C, MA, HA, CMA, CHA
7	2	28	13	Native	High	N, C, MA, HA, CMA, CHA
8	4	65	34	Native	High	N, C, MA, HA, CMA, CHA
9	3	69	29	Native	High	N, C, MA, HA, CMA, CHA
10	3	79	42	Native	High	N, C, MA, HA, CMA, CHA
11	2	171	66	Native	High	N, C, MA, HA, CMA, CHA
12	2	147	49	Native	High	N, C, MA, HA, CMA, CHA
13	4	70	47	Native	High	N, C, MA, HA, CMA, CHA
14	1	50	17	Native	High	N, C, MA, HA, CMA, CHA
15	7	145	83	Native	High	N, C, MA,

						HA, CMA, CHA
16	6	96	64	Native	High	N, C, MA, HA, CMA, CHA
17	0	16	6	Native	High	N, C, MA, HA, CMA, CHA
18	7	214	148	Native	High	N, C, MA, HA, CMA, CHA
19	4	187	121	Native	High	N, C, MA, HA, CMA, CHA
20	4	75	36	Native	High	N, C, MA, HA, CMA, CHA
21	2	91	46	Native	High	N, C, MA, HA, CMA, CHA
22	3	169	104	Aggregate	High	N, C
23	5	119	77	Aggregate	High	N, C
24	1	58	26	Aggregate	High	N, C
25	2	47	18	Aggregate	High	N, C
26	5	140	61	Aggregate	High	N, C
27	4	145	68	Aggregate	High	N, C
28	2	112	41	Aggregate	High	N, C
29	4	105	58	Aggregate	High	N, C
30	3	112	38	Aggregate	High	N, C
31	4	146	56	Aggregate	High	N, C
32	1	147	86	Aggregate	High	N, C
33	0	79	40	Aggregate	High	N, C
34	3	89	33	Aggregate	High	N, C
35	3	90	63	Aggregate	High	N, C
36	4	220	109	Aggregate	High	N, C
37	2	120	36	Aggregate	High	N, C
38	1	39	19	Aggregate	High	N, C
39	4	147	62	Aggregate	High	N, C
40	2	159	97	Aggregate	High	N, C
41	1	70	47	Aggregate	High	N, C
42	2	68	43	Aggregate	High	N, C
43	3	84	31	Aggregate	High	N, C
44	6	68	23	Aggregate	High	N, C

45	6	105	32	Aggregate	High	N, C
46	2	32	12	Aggregate	High	N, C
47	7	109	50	Aggregate	High	N, C

INTELLIGENT DEPLOYMENT OF FOREST ROAD GRADERS

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3 Intelligent Deployment of Forest Road Graders

3.1 Abstract

Road grading is the most common maintenance activity performed on forest roads. Reducing grading cost could release resources for other maintenance needs, ideally resulting in a better-maintained road system. A combinatorial optimization method, tabu search, is combined with two local search procedures to generate efficient grading routes. Determining the optimal grading route is modeled as an extension of the Mixed Rural Postman Problem (MRPP), adapted to include a daily operating time limit, a requirement to originate and return to the same location, and different traversal/service times. The objective is to minimize total operating time, a proxy for grading cost. The heuristic is tested on both artificial and real forest road networks, and computational results are presented. The heuristic demonstrates the ability to generate efficient and feasible grader routes.

3.2 Introduction

3.2.1 Road Maintenance & Grading

Road grading is the most common maintenance activity performed on forest roads. A grader operates by traversing the road with a lowered blade, which smoothes the surface of the road eliminating potholes, ruts and washboards. As with other forms of road maintenance, grading has both economical and environmental benefits. A well-graded road reduces haul costs by allowing vehicles to travel at design speeds, and reduces vehicle ownership and operating costs by reducing the amount of wear and tear incurred while traveling. Insurance costs could potentially be reduced due to enhanced driver safety. Proper grading also serves to maintain the road's designed drainage system, which reduces environmental degradation associated with erosion and sedimentation.

The transportation manager is often responsible for ensuring that the road network meets some minimum acceptable levels for driver safety, vehicle traffic and drainage. Budgetary constraints limit the amount of maintenance a planner can implement in a given period. Identifying cost-saving measures, therefore, could release these resources for other maintenance projects, ideally resulting in a better-maintained road network. As grading cost is driven largely by total operating time (Dave Young, pers. comm.), emphasis should be placed on minimizing grader operating time. Additionally, careful selection of road segments that are actually in need of maintenance can reduce overall costs by reducing the number of road segments treated. In a study performed in eastern Canada, for example, it was found that identifying segments in poor condition and scheduling grading accordingly could reduce grading costs by thirty percent over a policy of grading at fixed time intervals (Provencher 1995). Limiting unnecessary grading can also limit potential environmental degradation from grading, which is associated with increased sediment yields due to disruption of the road surface (Luce and Black 1999).

In this paper, we propose a novel method for assisting grader deployment decisions, the goal of which is to determine minimal cost tours that visit all road segments requiring grading. We hope to demonstrate that use of computerized decision aids could result in increased efficiency when determining routes for graders to take over a road network. We also hope to demonstrate that a "monitor and manage" approach to road grading scheduling is more appropriate than adhering to ad hoc or uniform pre-determined grading schedules.

3.2.2 Grading Decisions

First, the manager must decide which road segments require grading. Typically the decision to grade is made based upon weather and traffic patterns, as well as observations and complaints from drivers. Rarely are these decisions based upon quantifiable information regarding road roughness or water content. Recent technological developments, however, provide for improved data collection and analysis, which could inform and improve the grading decision making process. A good example of progress in this field is the Opti-Grade© package, developed by the Forest Engineering Research Institute of Canada (FERIC 2007). Opti-Grade includes a device to be installed on a vehicle that can measure and record road roughness values as the vehicle traverses a road network. The roughness data is paired with GPS time and location data to provide an objective, quantitative measure of the road network's roughness levels, which is then analyzed by the package's software to determine which segments require grading. Opti-Grade determines grading requirements according to roughness thresholds identified by managers, but similar technology could implement additional decision criteria such as road category, season of use, and volume of traffic.

3.2.3 Grader Routing

After the subset of road segments that require grading has been established, the transportation manager must then determine the route the grader will take over the road network. This route, or tour, must visit all road segments that the manager has identified as requiring grading. In practice knowledge about local conditions, experience, and a roadmap are the primary drivers of this decision process, which is often ad-hoc (Dave Young, pers. comm.). As mentioned above, the manager seeks to minimize total project cost, or as a proxy, total grader operating time. There exist numerous possible routes that traverse all segments requiring grading, and the manager must select an efficient tour from among them. For networks of substantial size, the pool of possible solutions is far too vast to be evaluated by hand and the manager must decide upon the route according to some heuristic process.

In mathematical terms, the generic problem facing the transportation manager is known as the Rural Postman Problem (**RPP**), part of a broader class of Arc Routing Problems (**ARP**s). The aim of the **RPP**, and **ARP**s in general, is to determine a minimal cost closed walk of a subset of some arcs of a graph (Eiselt et al. 1995a, 1995b). A closed walk is a sequence of arc traversal over a network, with the sequence beginning and ending at the same point. The rural postman, for instance, leaves the post office in the morning, visits some subset of county roads to deliver mail, and returns to the post office at the end of the day. The **RPP** formulation provides a basis for many other industrial applications, including street sweeping, school bus routing, snow plowing, and garbage collection (Corberán et al. 2000, Eiselt et al. 1995b). In this context, road segments represent arcs and road intersections represent vertices on a graph. To accurately reflect most real forest road networks the underlying graphs are considered mixed, meaning they contain both arcs (one-way) and edges (two-way). The manager's problem is therefore an instance of the Mixed Rural Postman Problem (**MRPP**), defined as below (Eiselt et al. 1995b):

> Let G = (V, E, A) be a connected mixed graph, where V is the vertex set, A is the arc set, E is the edge set, and a nonnegative cost is associated with all arcs and edges. Define $A_R \subseteq A$ and $E_R \subseteq E$ to be the subsets of arcs and edges, respectively, that require grading. The aim of the **MRPP** is to find a minimal cost closed walk that traverses each required arc and edge at least once.

The **RPP** and **MRPP** are proven to be NP-Hard, and generally require a heuristic method to generate near optimal solutions (Corberán et al. 2000, Eiselt et al. 1995b). In a survey of **ARP**s, Eiselt et al. (1995b) conclude that arc routing theory could benefit from additional research, and identify tabu search as a direction for future research. The success of tabu search applied to Vehicle Routing Problems (**VRP**s) is cited as an example of the promise of the heuristic. Gendreau et al. (1994) developed TABUROUTE, a tabu search heuristic for the **VRP** with capacity and route length restrictions, which upon testing outperformed the best existing heuristics. Tabu search was later applied to the Capacitated Arc Routing Problem (**CARP**) with similar success (Hertz et al. 2000). Most relevant, a tabu search heuristic was implemented in concert with a construction heuristic for the **MRPP**, and the authors (Corberán et al. 2000) considered tabu search to have performed “remarkably well.”

Tabu search is a commonly used and effective combinatorial heuristic algorithm. Developed by Glover (1989, 1990), tabu search uses memory structures to characterize and prioritize candidate solutions. It is essentially an improvement method in which successive solutions, which are perturbations of previous solutions, are examined and the best is selected. Ideally, an improving solution will be found, but where none of the perturbations would result in an improvement the best solution is still selected. Thus, in a given iteration the objective function may worsen, but it is hoped that doing so will allow the heuristic to escape local optima. In addition, a tabu list is used that identifies forbidden moves; this prevents cycling and ideally prevents the heuristic from keying in on local optima. Essentially, tabu search can be viewed as a metaheuristic that can guide any local search procedure towards a global optimum. Utilization of heuristics like tabu search provide the opportunity to evaluate increasingly large pools of data and alternative scenarios, and to seek optimal solutions to complex problems.

Tabu search has been successfully implemented in various vehicle routing and arc routing problems (Amberg et al. 2000, Corberán et al. 2000, Hertz et al. 2000, Gendreau et al. 1994). Additionally, tabu search has been widely implemented in the field of forest management (Richards and Gunn 2003). Examples include harvest scheduling (Boston and Bettinger 2002, Bettinger et al. 1999, Bettinger et al. 1997), wildlife planning (Bettinger et al. 2002), landscape planning with environmental goals (Bettinger et al. 1998), road optimization (Aruga 2005), and logging crew assignment (Murphy 1998).

Like most applications, the transportation manager's problem includes additional characteristics that require modifications from the original **MRPP** formulation. We include a daily maximum operable time limit, which has the potential to greatly increase the complexity of the problem. In excessively steep terrain the grader may be limited to unidirectional travel, or may be forced to reduce speeds due to safety and sliding concerns (Caterpillar Inc. 2002). We incorporate this into our model by assuming the extreme case of different grading speeds for uphill and downhill travel. This assumption introduces elements of the Windy Postman Problem (**WPP**), in which the cost of traversal depends on the direction of travel; the **WPP** is also proven to be NP-Hard (Eiselt et al. 1995a). Where not appropriate the formulation can easily be amended to include uniform grading speeds, which in fact reduces the complexity of the problem by reducing the size of the solution space. Traversal over road segments without grading (deadheading) is assumed at a constant speed.

Thus, the solution methodology can draw from **MRPP** theory but will necessarily require a tailored approach. We propose a tabu search metaheuristic algorithm, combined with two improvement procedures, that seeks efficient grader routes across the road network while incorporating the operational constraints discussed above. Upon obtaining an acceptable solution, the manager can deploy the grader to begin operation.

In practice grading time depends on the number of passes required to service the road segment, a function largely of road width and standard. For this paper we assume all road segments require a single pass, but variable pass requirements for different road segments can easily be included - grading time is a model parameter that can be updated appropriately. Where an even number of passes is required, the algorithm would need to be updated to continue traversal from the beginning of the recently graded road segment rather than the end. Including number of passes, however, would not fundamentally change problem complexity or our solution approach, and thus we omitted its consideration from our example application presented below. Rather, we chose to include considerations such as an operating time limit and directional-dependent speeds to increase problem complexity and challenge our solution method.

3.2.4 Notation & Definitions

Edges henceforth generically refer to both arcs and edges, and are defined by a vertex pair (*i, j*). Here *i* is the "from" vertex, and *j* is the "to" vertex defining the edge. If an edge is undirected, the edge defined by *(j, i)* also exists. Edges that require grading are said to require *service*, are denoted as *service edges*, and are represented as [i, j]. A *tour* is the order in which service edges are visited. A given tour may be comprised of multiple *sub-tours*, which are necessary when the overall tour exceeds the daily time capacity. All tours (including sub-tours) originate and end at the *depot* vertex, where the grader is stored when not in use. A grader traversing an edge without grading is said to be *deadheading.* A *spur* is an edge only connected to the network via one vertex, i.e. the edge comes to a dead-end.

3.3 Tabu Search

Our tabu search heuristic iteratively generates alternative solutions (tours) by re-ordering the traversal of service edges. Total tour time is calculated as the sum of all grading times plus the time to traverse between service edges. Note this calculation includes time to return to the depot at the end of each sub-tour, if required due to operating time constraints. When traveling between edges requiring service, the grader is assumed to follow the shortest path between service edges. Specifically, this shortest path originates at the “to” vertex of the service edge graded prior and ends at the “from” vertex of the next service edge where grading will begin. When traversing between two service edges the grader may deadhead over a third service edge, and failing to grade that service edge along the way may result in an inefficient solution. The Shortest Path Service Edge Insertion (**SPSEI**) heuristic, described below, addresses this concern. When a tour length extends beyond the maximum allowable time, it must be divided into sub-tours that are feasible. We developed the Tour Partition Heuristic to address this concern, and describe it below. The tabu search seeks an efficient ordering of service edges that results in an overall minimal closed-walk time.

3.3.1 Neighborhood Definition

Each instance of traversal re-ordering is considered a “swap.” The neighborhood of the search procedure includes both 1-edge and 2-edge swaps. 1-edge swaps are only applicable for undirected service edges; the direction in which it is graded is simply reversed. A 2-edge swap switches the location of two service edges in the tour. Service edges that are undirected can be inserted into their new locations in either possible traversal direction; the procedure evaluates both possibilities. All possible combinations of service edge swaps are considered per iteration of the tabu search, to provide as broad a scope as possible.

To illustrate the allowable swaps, consider the example network in Figure 1. The network contains 5 vertices (depot, A, B, C, D) and 7 undirected edges. The black dot represents the depot. Two edges require service: [A, B] and [C, D]. Table 1 displays the average deadhead and grading times for these edges. Note that deadhead times are the same for either direction, whereas grading times vary with direction. In this example, moving from B to A and D to C is in the downhill direction.

Assume the current solution is to traverse the service edges in the order [A, B] → [C, D]. Figure 2 displays the resulting tour the grader would traverse over the network for this solution. Bold lines represent service edges; arrowheads indicate direction of traversal. Figures 3-5 display tours for modified tours described below.

<u>Current Solution: [A, B] → [C, D]</u>

Total Tour: (DEP, A) → [A, B] → (B, A) → (A, C) → [C, D] → (D, B) → (B, DEP)

Total Time: 21.5

Table 2 lists all possible 1- and 2-edge swaps for this original candidate solution.

Presented below is a subset of these eligible swaps, including the resulting tours generated and associated total times. Because pre-determined shortest paths are traversed between grading service edges, the tour can substantially change when swaps are performed.

<u>1-edge swap: [B, A] → [C, D]</u>

Total Tour: (DEP, B) → [B, A] → (A, C) → [C, D] → (D, B) → (B, DEP)

Total Time: 18.1

<u>2-edge swap: [C, D] → [A, B]</u>

Total Tour: (DEP, A) → (A, C) → [C, D] → (D, A) → [A, B] → (B, DEP)

Total Time: 20.6

<u>2-edge swap: [D, C] → [A, B]</u>

Total Tour: (DEP, B) → (B, D) → [D, C] → (C, A) → [A, B] → (B, DEP)

Total Time: 16.8

3.3.2 Tabu Search Implementation Details

Initial solutions are generated as a random permutation of service edge ordering. The tabu search procedure is then invoked to improve upon the random initial solution. The maximum number of iterations was set at 10,000, where per iteration a neighborhood search is performed to select a new solution. The neighborhood search consists of an exhaustive investigation into all possible 1-and 2-edge swaps, as detailed above. The SPSEI heuristic is invoked for each candidate move to investigate the potential to reduce tour redundancy. A redundancy, as defined here, would be to deadhead over a service edge while traversing the shortest path between two other service edges. If necessary, the Tour Partition heuristic is also invoked to divide the candidate tour into feasible sub-tours. The inclusion of the two sub-heuristics makes calculations of the change in solution quality rather difficult, so we opted to recalculate total tour time for each candidate move after invoking the two sub-heuristics.

Diversification criteria included both recency and frequency memory structures. The recency memory structure is a tabu list of fixed length, which varied depending on problem size. We used values of 15-25, which were arrived at through initial experimentation and analysis of solution quality. The frequency memory structure maintained the number of times moves, or swaps, were selected, the idea being to penalize moves that are selected more frequently to avoid returning to previously visited local optima too quickly. The aspiration criterion stipulated that moves considered tabu can only be selected if their solution time is the best time achieved yet.

Per iteration the swap providing the greatest improvement in solution is selected, provided it is not currently on the tabu list. Pursuant to the aspiration criteria, a tabu move must yield the best solution to be permissible. The selected move is then entered into the tabu list (if not already there), replacing the least recently added move. The selected swap's frequency count is also updated. In situations where no improving moves exist, all solutions are penalized according to their frequency and the move with the best penalty-adjusted time is accepted. The penalty function multiplies the grading time by a factor of 0.5 and adds this to the total solution time.

3.3.3 Shortest Path Service Edge Insertion (SPSEI) Heuristic

This heuristic seeks to rearrange the order of service edge traversal in order to improve overall tour efficiency. When evaluating candidate solutions, the heuristic investigates the shortest paths that would be inserted into the tour as a result of the swap under consideration. Specifically the routine is searching for instances where these shortest paths create redundancies in service edge traversal. If such an instance is found, the solution is re-ordered so that any service edge located along a shortest path between two other service edges is graded along the way.

Consider the solution as depicted in Figure 5, and additionally assume the edge connecting vertices B and D also requires service. When traversing between service edges [A, B] and [D, C] the grader will take the shortest path between vertices B and D, which is the edge (B, D). Clearly it makes no sense to traverse this edge (B, D), grade [D, C] and then return later to grade [B, D]. A more economical option would be to grade the service edge [B, D] en route to [D, C], which would result in the candidate solution [A, B] → [B, D] → [D, C].

3.3.4 Tour Partition Heuristic

If a tour's total time exceeds the allowable limit, it must be partitioned into some subset of feasible sub-tours. This heuristic attempts to partition the tour into sub-tours in such a way as to minimize total operating time. A simple rule is to continue grading for as long as possible and stop with enough time to return to the depot. There could exist cases, however, where it would be more efficient to return early. For example consider the case where elapsed time is near the limit, and the remaining service edges are clustered in some area far away from the depot. Rather than travel the far distance with only enough time to service one or two edges, it might be more economical to return to the depot early and finish all of the remaining service edges in the next day's sub-tour. This heuristic considers multiple partition locations to seek the best location to partition the overall tour into sub-tours. The tour is initially partitioned at the last possible location, and then a neighborhood around that initial partition is evaluated by reducing the current sub-tour by one service edge at a time.

3.4 Computational Results

All procedures were programmed in C and compiled in Microsoft Visual C++ 6.0. We tested a variety of road networks. These include networks with cycles and directed networks that are more commonly found in steep terrain. Initially we tested the tabu search heuristic model on four artificially generated networks, purposefully created small enough so the optimum solutions could be found through complete enumeration. Then we applied the model to a real data set from a research forest owned by Oregon State University. The following parameters are used to generically define an instance of a road network: the number of vertices (|V|) and the number of edges (|E|). Density, d, is computed as $|E| / |V|^2$. Typically forest road networks have a very sparse density, and the generated data sets reflect that. Additionally, |SE| represents the number of edges requiring service in a particular network.

We tested each generated network with nine problem instances, where a problem instance consists of an |SE| value and a randomly generated combination of that many service edges. A total of thirty-six instances were therefore solved on artificial networks, and for each instance the heuristic algorithm generated 100 results. Appendix 1 contains a listing of the service edges associated with each problem instance for the artificial networks. Appendices 2-5 contain segment-level input data for artificial networks 1-4. For the Oregon State Research Forest we tested a total of six problem instances and for each instance the heuristic algorithm generated 50 results. Appendix 6 contains a listing of all input data for the larger network.

Initially the tests were run absent the maximum operating time constraint in order to evaluate the baseline performance of the model. After it was determined the model could provide satisfactory results the time constraint was incorporated, but only for one |SE| value per network, due in part to the increased computational difficulty of determining the optimal solution when incorporating such a constraint. The values used for “Max Time” were chosen based upon the obtained unconstrained solutions, and should not be construed to have any real world meaning. Because the optimal solution was found through enumeration, for Networks 1-4 the values in the “Num Best” column represent the number of times the model determined the actual optimal solution. A value of 75, for example, in this column means that the optimum solution was reached by the tabu search heuristic in 75 out of 100 runs. This will not be the case for the Oregon State research forest network, for which the optimal solution is unknown. The “Avg Dev” column represents the average percent deviation from the best solution found.

The results obtained and reported here were performed on a machine equipped with Optiplex GX280 3.3 GHz with 1 GB RAM. CPU time was not recorded, although observationally solutions were generated in less than a second for all but the real forest network. CPU times for that network ranged from seconds to over 2 minutes, depending on the value of |SE|.

Network 1, |V| = 10, |E| = 10, d = 10%

The model was first tested on Network 1, displayed in Figure 6. The thicker lines represent directed edges, or arcs. In Network 1 there is only one directed edge, (4, 2), and five spurs. Vertex 0 represents the depot. A tabu list size of 15 was used for this network.

Table 3presents the results of the model tested on Network 1. Instances 1.7, 1.8 and 1.9 are comprised of the same service edges as instances 1.1, 1.2, and 1.3, respectively, but with the inclusion of operational time constraints.

Network 2, |V| = 10, |E| = 20, d = 20%

Network 2, displayed in Figure 7, is an extension of Network 1. (Similarly, Network 4 is an extension of Network 3.) A total of 10 edges have been added; two of which are one-way: (7,9) and (8,5). Network 2 contains no spurs. A tabu list size of 15 was used for this network.

Table 4 presents the results for Network 2. Instances 2.7, 2.8 and 2.9 are comprised of the same service edges as instances 2.1, 2.2, and 2.3, respectively, but with the inclusion of operational time constraints.

Network 3, |V| = 20, |E| = 20, d = 5%

Network 3 is displayed in Figure 8. Two edges are one-way: (15, 16) and (16, 10). Twelve spurs are contained in Network 3. A tabu list size of 15 was used for this network.

Table 5 presents the results for Network 3. Instances 3.7, 3.8 and 3.9 are comprised of the same service edges as instances 3.1, 3.2, and 3.3, respectively, but with the inclusion of operational time constraints.

Network 4, |V| = 20, |E| = 40, d = 10%

Network 4 is displayed in Figure 9. Twenty edges were added to Network 3 to create this network, including four one-way edges: (4, 7), (7, 8), (8, 13) and (18, 16). This network, like Network 2, contains no spurs. A tabu list size of 20 was used.

Table 6 presents the results for Network 4. Instances 4.7, 4.8 and 4.9 are comprised of the same service edges as instances 4.1, 4.2, and 4.3, respectively, but with the inclusion of operational time constraints.

Oregon State Research Forest, |V| = 127, |E| = 141, d = 0.9%

Road segment data for this network was obtained from GIS data published by Oregon State University. Specifically, a portion of the roads in the northwest corner of the Dunn Forest was selected. Of the 141 edges, 123 were undirected and 18 were directed. The network contained a total of 38 spurs.

Data on segment roughness and maintenance need were unavailable and were therefore artificially generated. Arbitrary roughness index levels (1-5, 5 highest level of roughness) and road categories (1-3, 3 least-trafficked road) were randomly assigned to various road segments. Road segment classifications were done according to assigned probabilities that mimic the distribution of roads on the network in the OSU forest, whereas roughness levels were assigned in such a way as to have approximately 10% of the segments requiring service. As a proxy for managerial decisions, a framework was established in which road segments of a certain category require grading if the roughness level is above a threshold. The following rubric was imposed to create a quantitative framework for determining when to grade a road segment.

Grading Rules

Category 1: Grade if RI > 2

Category 2: Grade if RI > 3

Category 3: Grade if RI > 4

A tabu list size of 25 was used. Note that only 50 runs were performed over this larger network. Table 7 presents the results for the research forest network.

3.5 Discussion

For the smaller networks the heuristic performs quite well, even when operational time constraints are included. In aggregate over the artificial networks, the optimal solution was reached in 2107 of 2400 runs (87.79%) for problem instances with no operating constraints, and in 1037 of 1200 runs (86.42%) for instances with operational time constraints. Aggregate percent deviation was 0.52% and 0.71%, for the constraint-free scenario and operating time limit scenario, respectively.

In instances where the optimal solution was achieved a relatively small proportion of the time, the heuristic selected the known second or third best solution a high proportion of the time. Instance 3.6 of Network 3 (see Table 5), for example, only locates the optimal solution 44 times. However, the tabu search procedure located the known second-best solution an additional 38 times, meaning that at least 82% of the obtained solutions are of extremely high quality.

For the much larger forest road network the low average deviation suggests that the heuristic consistently obtains good results, although there is no optimal solution as a basis for comparison. One possible method to estimate the quality of our solutions would be to compare against solutions from relaxations of integer linear programs, although Eiselt et al. (1995b) state that in practice this method has not been very successful for **ARP**s. Alternatively a global optimum may be estimated using extreme value theory, although Boston and Bettinger (1999) demonstrated that estimates of optima were unreliable, and Bettinger et al. (2002) found the technique of limited usefulness.

Since it is difficult to compare our solution against a known or estimated optimal value, it might be informative to learn if the heuristic would yield improvements over current practices. To validate our model we developed a greedy heuristic, which might mimic how a grader operator would traverse the network to grade the segments. Starting from the depot, the grader first travels to the closest segment requiring grading and services that segment. From there, the grader travels to the next nearest segment requiring grading, and so on until all segments requiring grading have been serviced. We tested the greedy heuristic on RF.1. Our tabu search heuristic achieved a 12.5% reduction in total grading time as compared to the greedy heuristic. Given that in practice an operator may not know with certainty which is the nearest segment requiring service, it is possible savings could be even higher. Further, given that in practice many grading decisions are assigned not based on road condition but on time since the last grading, the overall decision framework presented here may yield substantial reductions in overall maintenance cost.

As the road density increases so does the complexity of the problem, but it is important to note that in forest road networks density is usually very small, and thus this solution framework may prove quite acceptable. Additionally, maintenance needs rarely constitute a large proportion of the road network, suggesting the instances generated above may be quite representative of the real-world problems faced by industry. Certainly the results demonstrate the gains possible from using computational methods to evaluate complex decisions, especially in light of the current management practices, which cannot or do not account for the combinatorial nature of the networks.

Solution quality appears to be associated with two factors: number of directed service edges and to a lesser degree, number of service edges that are spurs. On average, as the number of directed service edges or spur service edges increases, solution quality decreases. Additional work with this data set could include testing a variety of service edge requirements to determine what impact, if any, the number of directed and spur service edges have upon solution quality for larger networks.

Future research should focus on both the solution methodology and the problem definition. Improvements might be achievable by increasing the complexity of the tabu search heuristic, such as utilizing a dynamic tabu list size or implementing harmonic oscillation. The tour partition heuristic could also be expanded and possibly implemented as a combinatorial heuristic such as tabu search or simulated annealing. This method would be of great benefit in cases where the initial tour’s length is so great as to require multiple partitions; the world of possible partitions increases exponentially with respect to a unit increase in the number of partitions required. Incorporation of time-windows would create a more realistic model, applicable perhaps to a high volume network experiencing simultaneous haul and maintenance traffic. Some industrial applications might involve a fleet of graders, operating from different depots or perhaps without an assigned depot. Operational time constraints may not be quite so limiting, allowing for a small exceedance in order to gain overall tour efficiency.

Future work could also be devoted to creating a broader decision framework for determining which segments to grade. Rather than utilize a binary decision rule, priorities could be established for segments requiring service. Thus the heuristic would ensure that some segments of the highest priority are graded, but in addition would seek opportunities to grade other high priority segments. If successfully implemented this framework could free up future resources for other maintenance activities, hopefully preventing future drainage and transportation problems. Perhaps this method would best be employed in scenarios where the manager's goal is to achieve the highest level of maintenance possible, rather than a goal of cost minimization.

It is the intention of this paper to demonstrate the potential for cost savings in grader scheduling and deployment. Our heuristic performed well on both cyclical and dendritic networks, the latter being more common in mountainous terrain. The tabu search heuristic presented here can provide for improved decision making with regard to routing graders, and could improve overall road maintenance.

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Figure 3.1: Example network to illustrate allowable "swaps." The network contains 5 vertices (depot, A, B, C, and D) and 7 undirected edges. The black dot represents the depot. Two edges require service: [A, B] and [C, D].

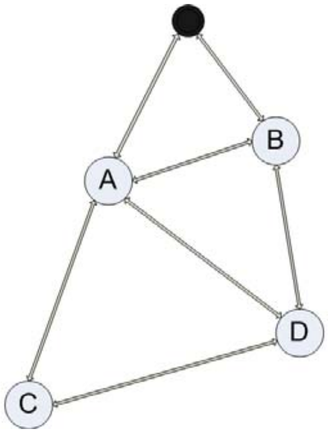

Figure 3.2: Current Solution: [A, B] → [C, D]. This figure illustrates the resulting tour the grader would take over the network. Bold lines represent service edges; arrowheads indicate direction of traversal. The total tour would be: (DEP, A) → [A, B] → (B, A) → (A, C) → [C, D] → (D, B) → (B, DEP).

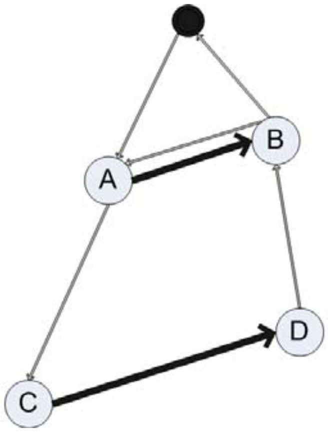

Figure 3.3: 1-edge swap: [B, A] → [C, D]. Because pre-determined shortest paths are traversed between grading service edges, the tour can substantially change when swaps are performed. For this solution, the total tour would be: (DEP, B) → [B, A] → (A, C) → [C, D] → (D, B) → (B, DEP)

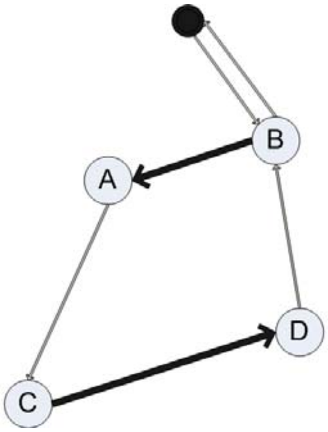

Figure 3.4: 2-edge swap: [C, D] → [A, B]. Total tour is: (DEP, A) → (A, C) → [C, D] → (D, A) → [A, B] → (B, DEP).

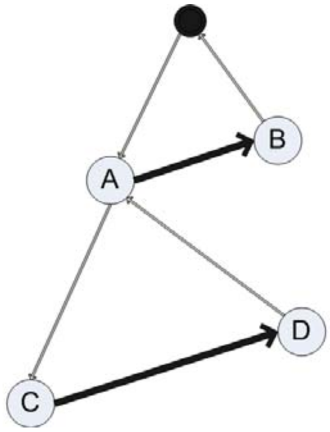

Figure 3.5: 2-edge swap: [D, C] → [A, B]. Total tour is: (DEP, B) → (B, D) → [D, C] → (C, A) → [A, B] → (B, DEP)

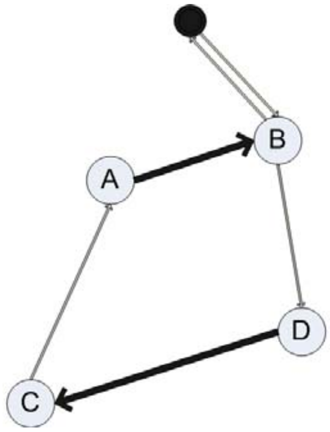

Figure 3.6: Network 1. This network has 10 vertices and 10 edges. Vertex 0 represents the depot. There is one directed edge (4, 2) and 5 spurs.

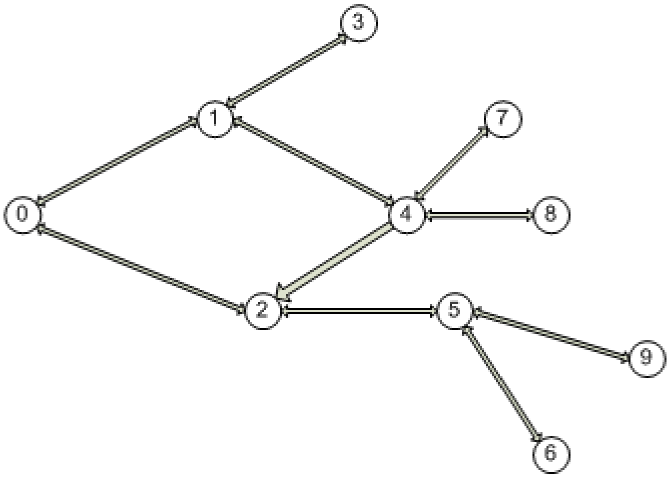

Figure 3.7: Network 2. This network is an extension of Network 1. A total of 10 edges have been added; two of which are one-way: (7,9) and (8,5). Network 2 contains no spurs.

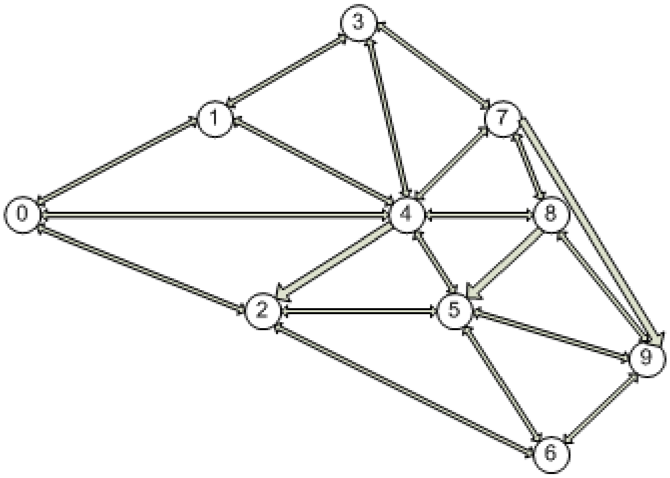

Figure 3.8: Network 3. This network contains 20 edges, 20 vertices, 2 one-way edges, (15, 16) and (16, 10), and 12 spurs.

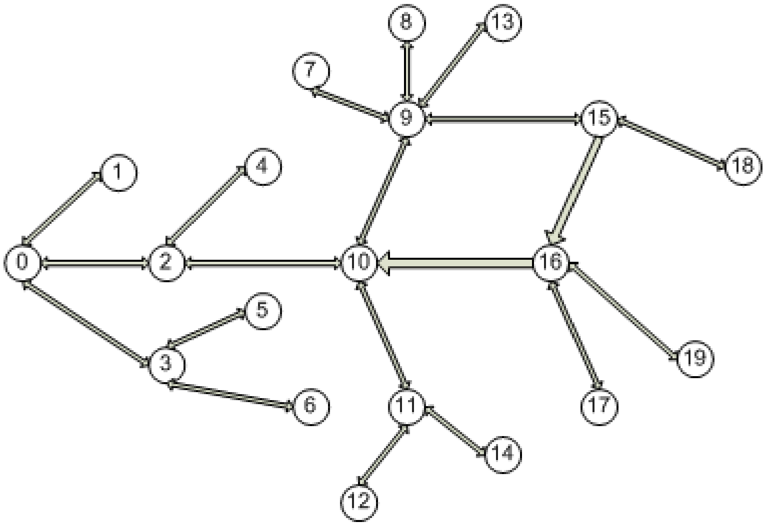

Figure 3.9: Network 4. This network extends Network 3 by adding 20 edges, including 4 one-way edges: (4, 7), (7, 8), (8, 13) and (18, 16). This network, like Network 2, contains no spurs.

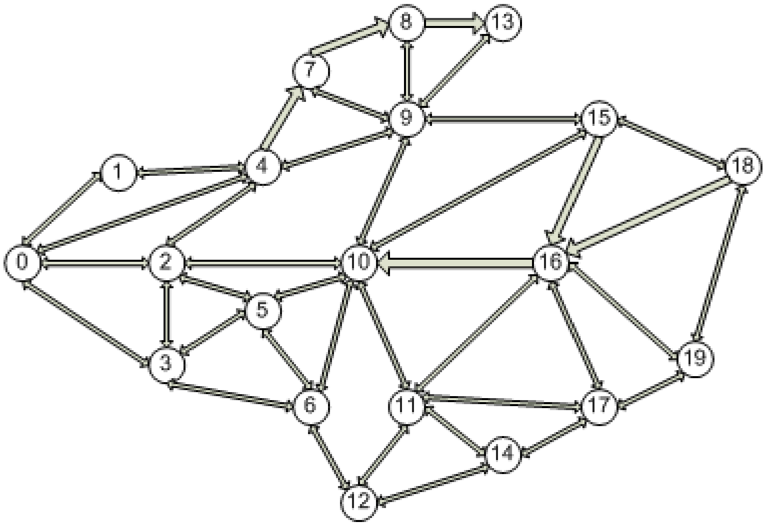

Table 3.1: Example deadhead and grading times, for the example network presented in figures 1-5.

DEADHEAD		**GRADE**	
Edge(s)	**Time**	**Edge**	**Time**
(DEP, A) & (A, DEP)	1.7	[A, B]	4.5
(DEP, B) & (B, DEP)	1.3	[B, A]	3
(A, B) & (B, A)	1.5	[C, D]	8.4
(A, C) & (C, A)	2.3	[D, C]	5.6
(A, D) & (D, A)	2.4		
(B, D) & (D, B)	1.8		
(C, D) & (D, C)	2.8		

Table 3.2: Possible candidate solutions from swaps, for the example network presented in Figures 1-5.

1-edge swaps	2-edge swaps
[B, A] → [C, D]	[C, D] → [A, B]
[A, B] → [D, C]	[C, D] → [B, A]
	[D, C] → [A, B]
	[D, C] → [B, A]

Table 3.3: Computational results for Network 1. The tabu search heuristic was able to identify the known optimal solution for every problem instance.

Instance	|SE|	Max Time	Num Best	Avg Dev
1.1	2	-	100	0.00%
1.2	2	-	100	0.00%
1.3	2	-	100	0.00%
1.4	4	-	100	0.00%
1.5	4	-	100	0.00%
1.6	4	-	100	0.00%
1.7	2	1.5	100	0.00%
1.8	2	1.5	100	0.00%
1.9	2	1.5	100	0.00%

Table 3.4: Computational results for Network 2. Solution quality remains high although the heuristic does not always identify the known optimal.

Instance	|SE|	Max Time	Num Best	Avg Dev
2.1	4	-	100	0.00%
2.2	4	-	100	0.00%
2.3	4	-	98	0.06%
2.4	8	-	100	0.00%
2.5	8	-	99	0.09%
2.6	8	-	79	0.35%
2.7	4	1.5	100	0.00%
2.8	4	1.5	100	0.00%
2.9	4	1.5	38	3.44%

Table 3.5: Computational results for Network 3. In instances where the optimal solution was achieved a relatively small proportion of the time, the heuristic selected the known second or third best solution a high proportion of the time. Instance 3.6 of Network 3, for example, only locates the optimal solution 44 times. However, the tabu search procedure located the known second-best solution an additional 38 times, meaning that at least 82% of the obtained solutions are of extremely high quality.

Instance	|SE|	Max Time	Num Best	Avg Dev
3.1	6	-	100	0.00%
3.2	6	-	87	0.67%
3.3	6	-	78	1.12%
3.4	8	-	79	0.97%
3.5	8	-	72	1.17%
3.6	8	-	44	2.40%
3.7	6	2	100	0.00%
3.8	6	2	90	1.11%
3.9	6	2	68	1.48%

Table 3.6: Computational results for Network 4. Values presented here have a similar interpretation to that from Table 2.5.

Instance	|SE|	Max Time	Num Best	Avg Dev
4.1	8	-	96	0.17%
4.2	8	-	88	0.29%
4.3	8	-	55	3.84%
4.4	9	-	100	0.00%
4.5	9	-	81	0.71%
4.6	9	-	51	0.74%
4.7	8	2	93	0.46%
4.8	8	2	84	0.36%
4.9	8	2	64	1.62%

Table 3.7: Results for Oregon State Research Forest network. For the much larger forest road network the low average deviation suggests that the heuristic consistently obtains good results, although there is no optimal solution as a basis for comparison. When compared to a greedy heuristic thought to be representative of actual grader operation, the tabu search heuristic achieved a 12.5% reduction in total grading time.

Instance	|SE|	Max Time	Num Best	Avg Dev
RF.1	14	-	19	1.45%
RF.2	15	-	4	2.28%
RF.3	15	-	1	3.71%
RF.4	14	3	10	2.63%
RF.5	13	3	8	2.29%
RF.6	15	3	2	5.18%

Appendix 3.1: Listing of randomly generated service edges for Networks 1-4. Generating service edges consisted of randomly assigning roughness indices to each road segment, and then identifying segments requiring service. Segment-level input data, including roughness index, presented below in Appendices 2-5 therefore correspond to a particular instance (e.g. Network 1.1).

Network 1:
1.1: [1,3], [4,7]
1.2: [2,5], [5,6]
1.3: [0,2], [4,2]
1.4: [4,2], [4,7], [4,8], [5,9]
1.5: [0,1], [1,3], [4,2], [5,6]
1.6: [0,2], [1,3], [1,4], [4,7]

Network 2:
2.1: [0,1], [2,5], [5,9], [4,5]
2.2: [1,4], [5,6], [4,5], [8,9]
2.3: [4,2], [4,7], [3,4], [7,9]
2.4: [0,2], [1,4], [4,2], [4,7], [0,4], [3,4], [7,9], [8,9]
2.5: [0,1], [1,3], [4,2], [4,8], [0,4], [2,6], [3,4], [6,9]
2.6: [1,4], [2,5], [4,8], [5,9], [3,4], [4,5], [6,9], [8,5]

Network 3:
3.1: [0,2], [0,3], [3,6], [7,9], [10,11], [11,12]
3.2: [2,4], [7,9], [9,10], [10,11], [15,16], [16,17]
3.3: [2,10], [8,9], [9,13], [11,14], [15,16], [16,10]
3.4: [0,2], [2,4], [2,10], [8,9], [11,12], [11,14], [15,18], [16,10]
3.5: [0,1], [0,3], [3,5], [7,9], [9,13], [11,12], [15,16], [16,17]
3.6: [2,4], [3,5], [8,9], [9,15], [10,11], [11,14], [15,18], [16,19]

Network 4:
4.1: [0,1], [9,10], [9,13], [9,15], [10,11], [11,17], [12,14], [14,17]
4.2: [1,4], [2,5], [3,5], [3,6], [5,10], [6,12], [7,8], [16,17]
4.3: [0,3], [0,4], [4,7], [7,8], [9,13], [11,12], [15,18], [16,17]
4.4: [0,1], [0,2], [0,3], [0,4], [1,4], [2,3], [2,4], [2,5], [2,10]
4.5: [0,4], [5,6], [6,12], [8,9], [8,13], [10,15], [12,14], [16,19], [18,19]
4.6: [2,4], [5,10], [6,10], [7,9], [8,13], [9,13], [10,15], [11,16], [16,10]

Appendix 3.2: Input segment-level data for Artificial Network 1. Columnar data presents, from left to right: node 1, node 2, distance, uphill indicator (0-1), one-way indicator (0-1), and road standard (1-3). For simplicity all roads in artificial networks were assigned identical standards. Roughness values were generated randomly to identify service edges, and varied by problem instance (see Appendix 1).

0	1	4.472135955	0	0	1
0	2	5.385164807	0	0	1
1	3	3.605551275	0	0	1
1	4	4.472135955	0	0	1
2	5	4.000000000	0	0	1
4	2	3.605551275	0	1	1
4	7	2.828427125	0	0	1
4	8	3.000000000	0	0	1
5	6	3.605551275	0	0	1
5	9	4.123105626	0	0	1

Appendix 3.3: Input segment-level data for Artificial Network 2. Columnar data presents, from left to right: node 1, node 2, distance, uphill indicator (0-1), one-way indicator (0-1), and road standard (1-3). For simplicity all roads in artificial networks were assigned identical standards. Roughness values were generated randomly to identify service edges, and varied by problem instance (see Appendix 1).

0	1	4.472135955	0	0	1
0	2	5.385164807	0	0	1
1	3	3.605551275	0	0	1
1	4	4.472135955	0	0	1
2	5	4.000000000	0	0	1
4	2	3.605551275	0	1	1
4	7	2.828427125	0	0	1
4	8	3.000000000	0	0	1
5	6	3.605551275	0	0	1
5	9	4.123105626	0	0	1
0	4	8.000000000	0	0	1
2	6	6.708203932	0	0	1
3	4	4.123105626	0	0	1
3	7	3.605551275	0	0	1
4	5	2.236067977	0	0	1
6	9	2.828427125	0	0	1
7	8	2.236067977	0	0	1
7	9	5.830951895	0	1	1
8	5	2.828427125	0	1	1
8	9	3.605551275	0	0	1

Appendix 3.4: Input segment-level data for Artificial Network 3. Columnar data presents, from left to right: node 1, node 2, distance, uphill indicator (0-1), one-way indicator (0-1), and road standard (1-3). For simplicity all roads in artificial networks were assigned identical standards. Roughness values were generated randomly to identify service edges, and varied by problem instance (see Appendix 1).

0	1	2.828427125	0	0	1
0	2	3.000000000	0	0	1
0	3	3.605551275	0	0	1
2	4	2.828427125	0	0	1
2	10	4.000000000	0	0	1
3	5	2.236067977	0	0	1
3	6	3.16227766	0	0	1
7	9	2.236067977	0	0	1
8	9	2.000000000	0	0	1
9	10	3.16227766	0	0	1
9	13	2.828427125	0	0	1
9	15	4.000000000	0	0	1
10	11	3.16227766	0	0	1
11	12	2.236067977	0	0	1
11	14	2.236067977	0	0	1
15	16	3.16227766	0	1	1
15	18	3.16227766	0	0	1
16	10	4.000000000	0	1	1
16	17	3.16227766	0	0	1
16	19	3.605551275	0	0	1

Appendix 3.5: Input segment-level data for Artificial Network 4. Columnar data presents, from left to right: node 1, node 2, distance, uphill indicator (0-1), one-way indicator (0-1), and road standard (1-3). For simplicity all roads in artificial networks were assigned identical standards. Roughness values were generated randomly to identify service edges, and varied by problem instance (see Appendix 1).

0	1	2.828427125	0	0	1
0	2	3.000000000	0	0	1
0	3	3.605551275	0	0	1
0	4	5.385164807	0	0	1
1	4	3.000000000	0	0	1
2	3	2.000000000	0	0	1
2	4	2.828427125	0	0	1
2	5	2.236067977	0	0	1
2	10	4.000000000	0	0	1
3	5	2.236067977	0	0	1
3	6	3.16227766	0	0	1
4	7	2.236067977	0	1	1
4	9	3.16227766	0	0	1
5	6	2.236067977	0	0	1
5	10	2.236067977	0	0	1
6	10	3.16227766	0	0	1
6	12	2.236067977	0	0	1
7	8	2.236067977	0	1	1
7	9	2.236067977	0	0	1
8	9	2.000000000	0	0	1
8	13	2.000000000	0	1	1
9	10	3.16227766	0	0	1
9	13	2.828427125	0	0	1
9	15	4.000000000	0	0	1
10	11	3.16227766	0	0	1
10	15	5.830951895	0	0	1
11	12	2.236067977	0	0	1
11	14	2.236067977	0	0	1
11	16	4.242640687	0	0	1
11	17	4.000000000	0	0	1
12	14	3.16227766	0	0	1
14	17	2.236067977	0	0	1

15	16	3.16227766	0	1	1
15	18	3.16227766	0	0	1
16	10	4.000000000	0	1	1
16	17	3.16227766	0	0	1
16	19	3.605551275	0	0	1
17	19	2.236067977	0	0	1
18	16	4.472135955	0	1	1
18	19	4.123105626	0	0	1

Appendix 3.6: Input segment-level data for the Oregon State Research Forest Network. Columnar data presents, from left to right: node 1, node 2, distance, uphill indicator (0-1), one-way indicator (0-1), road standard (1-3), and roughness index (1-5). Roughness values were generated randomly to identify service edges, and varied by problem instance. Presented below are randomly generated roughness indices for a particular instance.

0	1	1536.16713	0	0	2	1
1	2	1094.55235	0	0	2	2
1	3	224.89367	0	0	3	3
2	6	157.18054	0	0	2	3
3	4	2469.21762	1	0	3	2
3	5	668.45786	1	0	2	4
5	39	291.70943	1	0	2	3
6	17	330.51659	1	0	1	1
7	8	1889.44167	1	0	1	2
7	11	215.31377	1	0	1	2
8	9	869.35764	1	0	3	5
9	10	3778.69869	0	0	3	3
10	34	3002.55391	0	0	2	4
11	12	327.92963	0	0	2	4
11	22	855.92767	1	0	3	1
12	13	585.52057	1	0	3	4
13	14	51.47532	1	0	2	2
14	15	1171.74226	0	0	3	3
14	26	401.63586	0	0	2	3
15	16	770.91617	0	0	1	3
16	1	6218.41279	0	1	3	5
17	11	1010.21833	1	0	2	1
17	18	334.30609	1	0	3	2
17	21	2543.23318	0	0	2	2
18	19	579.97512	0	0	2	5
19	20	487.53772	0	0	3	5
20	16	1088.78552	1	1	2	1
20	21	524.99749	1	0	1	3
21	16	541.20898	0	1	1	2
22	23	705.55718	0	0	3	5
23	24	806.20944	0	0	3	5
23	25	1108.13402	1	0	1	1

24	25	318.84395	0	0	3	2
26	27	249.34469	1	0	2	2
27	28	610.49002	1	0	3	1
28	29	308.58908	1	0	3	5
29	22	193.98729	1	1	1	4
29	30	793.54848	0	0	2	3
30	26	202.96872	0	1	3	3
30	28	313.26692	0	1	1	5
31	6	744.346	0	0	3	5
32	33	903.26212	1	0	2	4
35	71	1557.58417	1	0	2	1
35	73	207.20167	0	0	1	1
36	33	49.97247	1	0	1	3
37	112	2288.80415	1	0	3	4
37	119	291.60221	0	0	3	1
38	4	410.2114	0	0	1	1
39	40	2119.78581	0	0	2	3
39	41	290.18548	1	0	3	3
43	44	73.63756	0	0	1	1
44	45	38.28541	1	0	2	1
45	46	1417.03203	0	0	2	3
46	47	2664.23705	1	0	3	1
47	48	7.8559	1	0	1	1
48	49	245.11226	1	0	3	1
48	51	210.49096	0	0	2	1
49	50	2381.49334	0	0	1	3
51	49	227.474	1	1	1	5
52	50	3563.82083	0	0	3	1
53	52	240.60937	0	1	2	1
54	52	189.47472	1	0	3	3
54	53	172.20318	0	1	1	1
55	53	2450.04623	0	0	1	4
56	57	3910.71873	0	0	3	3
57	54	3362.33972	1	0	1	2
58	51	5522.03476	0	1	3	1
58	59	6.1628	0	0	2	3
60	57	2540.10546	0	0	1	1
61	60	440.70247	0	1	1	1
61	63	209.04659	1	0	3	1
62	60	438.9034	1	0	3	2
62	61	410.37684	1	1	1	3
63	58	3747.51272	0	1	2	1
63	67	1444.96175	0	0	3	4
64	67	1490.4683	0	0	3	2

65	66	352.80896	1	0	2	3
66	68	1348.03481	0	0	2	2
67	72	5130.89214	1	0	1	2
68	69	165.68467	0	0	3	5
69	62	2697.1344	1	1	1	1
70	68	204.77576	1	1	1	2
70	69	101.63879	0	1	1	5
71	70	2338.26735	1	1	2	4
72	73	243.18422	1	0	2	1
72	76	5820.27941	0	0	2	3
73	75	2310.62351	0	0	3	5
75	74	1497.717	1	0	3	2
75	77	767.64464	0	0	1	1
76	82	975.74585	1	0	1	1
77	78	375.61719	1	0	1	4
78	80	561.65708	1	0	1	2
79	78	136.29895	1	0	3	5
80	8	2333.61589	0	0	1	2
81	79	1163.23691	0	0	2	4
82	85	1385.74306	1	0	3	4
82	88	1859.30558	0	0	1	1
83	79	783.67796	0	0	1	2
84	85	750.63307	1	0	3	1
85	86	8.9413	1	0	3	2
85	92	688.56029	1	0	2	5
87	36	31.12595	0	0	1	3
87	83	1319.08812	1	0	2	5
88	89	804.03699	0	0	1	2
89	90	794.04776	1	0	1	2
90	91	330.55983	1	0	3	2
92	93	685.80742	0	0	3	5
92	97	841.88716	0	0	2	4
94	95	1112.28295	1	0	2	4
95	96	812.02102	1	0	1	4
95	100	2327.02151	1	0	1	2
98	6	8.97443	0	1	1	1
98	7	1164.84609	0	0	3	5
99	31	1254.8144	1	0	1	4
100	97	1355.97638	0	0	3	2
100	101	16.40361	1	0	1	3
102	103	213.76723	1	0	3	1
102	104	1010.34702	0	0	1	1
103	100	1959.79864	0	0	3	2
103	108	2133.174	1	0	1	1

105	104	1172.89201	1	0	2	2
106	105	1148.15668	1	0	2	3
107	105	2201.59935	0	0	3	1
108	109	10.9556	1	0	2	2
108	123	6396.79386	0	0	3	1
110	108	568.20243	0	0	3	5
111	38	913.74513	1	0	1	4
112	111	286.77853	1	0	2	4
113	114	1422.42731	0	0	2	4
114	122	774.11789	1	0	3	5
115	118	1479.97713	0	0	2	4
116	115	283.80169	1	0	3	5
116	117	752.55686	1	0	1	1
117	120	212.33068	1	0	3	2
118	114	1022.51992	1	0	3	3
119	117	962.93952	0	0	3	3
120	42	670.10725	1	0	2	4
121	116	45.71968	0	0	3	3
122	125	187.7666	1	0	3	1
124	118	17.87732	0	0	1	1
125	126	8.67252	0	0	3	5

4 Identifying Optimal Forest Road Grading Policies Using a Multi-Objective Evolutionary Algorithm

4.1 Abstract

Timber haul and related traffic contribute to the deterioration of forest road surfaces, which can lead to increased vehicle operating costs as well as to negative ecosystem impacts, especially degradation of water quality due to increased sedimentation rates. Regular maintenance, in particular grading, can mitigate some of the economic and environmental costs associated with road surface roughness. This manuscript approaches grader scheduling decisions as a multi-objective vehicle routing problem, using a multi-objective evolutionary algorithm (MOEA) as the solution method. Identifying the non-dominated frontier facilitates tradeoff analysis and the identification of efficient grading policies. An economic objective function aggregates vehicle operating and maintenance costs, and an environmental objective function measures as a proxy hazard-weighted rut depth. Experimental results from two example applications using real-world road networks demonstrate the utility of this multi-objective approach. Solutions output by the MOEA are shown to dominate simulated management policies representative of current practice. Ultimately this manuscript demonstrates that use of computerized decision aids could lead to increased efficiency when determining routes for graders to take over a road network. The multi-objective programming techniques employed here should help landowners to "jointly produce" environmentally benign, low-cost road networks.

4.2 Introduction

Forest roads benefit the landowner by providing access for timber production, fire management, recreation, and other activities. However, forest roads are not entirely benign and can lead to negative ecosystem impacts, in particular degradation of water quality due to increased sedimentation beyond natural levels. Poor quality aquatic habitat is a special concern in western timber-producing regions of the United States that are home to threatened and endangered salmonid species. Erosion from the road surface can be a significant source of sediment associated with forest practices (Gucinski et al. 2001). On actively managed landscapes, forest roads service heavy vehicle traffic (e.g., log trucks), which is associated with increased sediment production (Reid and Dunne 1984; Bilby et al. 1989; Luce and Black 2001). Management treatments to control road-related erosion include regular maintenance, road improvement (upgrading), relocation, and removal (which can vary from closure to decommissioning). Our focus in this paper is development of optimal road maintenance policies.

Improperly maintained roads can contribute disproportionately to aquatic habitat impairment. Often forest roads are built with limited effort to control compaction, resulting in variable subgrade strength across road segments (Boston et al. 2008). Those areas with weak subgrades are more susceptible to localized surface failures, such as potholes, washboards (lateral channels), and ruts (longitudinal channels). A rut occurs where the vehicle load exceeds the bearing strength of the surface or subsurface. Rut depth varies with tire operating pressure and traffic levels (Foltz and Elliott 1998), as well as local conditions such as road material and moisture. Excessive rut depth jeopardizes the road structure and can interfere with normal function of the road's designed drainage system. Concentration of water in the wheel rut increases runoff length and water velocity, with the potential to detach and transport additional particles. Sediment production from roads with ruts has been shown to be nearly double that of roads without ruts (Burroughs and King 1989).

Road-related sediment is recognized as a contributing source of pollution for many rivers and streams listed as water quality limited under the Clean Water Act (CWA). For example, Dai et al. (2004) identified forest roads as the dominant source of controllable erosion in a decision aid designed to support monitoring and assessment for a sediment total maximum daily load (TMDL) in a northern California watershed. In 1999, EPA published proposed changes to the TMDL rules that would significantly strengthen the nation's ability to achieve clean water goals by ensuring that the public had more and better information about the status of their watersheds (EPA 1999). The result has been increased interest in sediment production from forest roads. Though the CWA in some circumstances allows for a balancing of economic interests and promotes a progressive approach to pollution control premised on technological innovation over time, it remains a national goal to attain "fishable and swimmable" water quality (CWA §101(a)(2)). Improving the environmental performance of forest roads therefore remains an important research topic within the forestry community.

Driving on forest roads with potholes and other surface failures can result in economic costs in addition to environmental impacts. Conceptually, a rough road results in slower travel speeds and increased vehicle wear. Vehicle operating costs (VOC) have been shown to increase as surface roughness increases (Hide 1975; Faiz and Staffini 1979). Vibration damages also increase with surface roughness, and include accelerated damage to cab and suspension components that may result in cracks in frames and other components. Tire wear has been shown to increase and driver comfort is also impacted. Driving speeds are reduced, increasing travel time and cost per trip.

Regular road maintenance can limit some of the deleterious effects associated with rough road surfaces. Grading is the most common form of maintenance, wherein a vehicle with a finely controlled blade (grader) smoothes and re-shapes the road surface. For industrial-sized ownerships grading can be a part of day-to-day operations, and in some circumstances roads may be graded, or serviced, several times in a month. By eliminating ruts and other failures, grading may simultaneously be able to reduce both the environmental impacts and vehicle operating costs. Too frequent grading can unnecessarily increase grading costs, and may in some cases actually lead to environmental degradation by loosening the road surface and making fine sediment available for delivery to streams (Luce and Black 1999). However, compacting, watering, and/or applying chemical additives to the road surface after grading can help reduce sediment production. Too infrequent grading, on the other hand, increases transportation costs and the risk of environmental degradation associated with ruts and pot holes. The transportation planner therefore faces tradeoffs between economic and environmental objectives.

The unit of management for maintenance decisions is the road segment, typically delineated by lateral drainage structures, changes in grade, and road junctions. In practice segments are scheduled for grading either at fixed intervals or in response to traffic levels. The latter approach results in cyclical patterns of VOC and road deterioration, and is generally more effective as it targets the primary cause of surface deterioration. Alternatively the actual road surface condition (as measured by rut depth, road roughness, or some other metric) can be used to guide grading decisions. Provencher (1995) presented a scheduling method based upon segment-level estimates of International Roughness Index values (Sayers et al. 1981), which vary with segment slope and traffic levels. Once any given segment's index exceeded a threshold value, all segments whose index was within some tolerance of that value were graded. When compared to a fixed policy of grading after a pre-determined number of vehicle trips, grading costs were shown to be reduced by 35%.

At the segment level, the economically optimal grading frequency can be found by setting the marginal vehicle operating costs equal to the marginal grading costs. In general, however, the management context is a road network comprised of numerous road segments, with varying characteristics, varying traffic levels, and with a limited grader resource. The optimal schedule considering individual roads may not be optimal for the road network when considering system-wide constraints and moving costs. In this context, the transportation planner's problem becomes one of finding a tour or set of tours (ordered sequences of road segments to grade) taken by the grader to best achieve management objectives. Often routes are established according to an ad-hoc process, driven primarily by knowledge about local conditions, experience, and a roadmap (Dave

Young, College Forest Roads and Trails Specialist, Oregon State University, personal communication, 2006).

Thompson et al. (2007) modeled the grader routing problem as a rural postman problem, the goal of which is to identify a minimal cost closed walk of a subset of edges on a network (Eiselt et al. 1995). The authors considered a planning scenario with a single maintenance vehicle and daily operating time limits, where the manager sought to minimize total grading cost. Grading requirements were established according to a rule-based framework that incorporated road class and roughness index values, and solutions were generated using the tabu seach heuristic. Though there is an assumed level of benefit associated with grading, the authors made no attempt to quantify said benefit.

Inclusion of environmental performance as an explicit management objective necessitates identification of an appropriate metric. As a proxy, we consider the hazard-weighted rut depth of each road segment. Use of a hazard factor enables differentiation between road segments based upon salient characteristics such as proximity to a stream, erosive potential, etc. Similar approaches include Thompson and Sessions (2008), who maximized the hazard-weighted length of roads decommissioned, and Girvetz and Shilling (2003), who assigned environmental impact scores to negatively weight roads for a least cost network path analysis. Another common performance measure is sediment production and/or delivery, often estimated from road erosion models (e.g., Rackley and Chung 2008). Common transportation planning formulations either optimize an economic objective subject to constraints on environmental performance (e.g., Aruga et al. 2007; Bettinger et al. 1998), or optimize an environmental objective subject to budgetary constraints (e.g., Thompson and Sessions 2008; Madej et al. 2006).

Frequently in natural resource management it is difficult to identify acceptable or target levels of environmental performance with certainty (Kennedy et al. 2008). Here, we assume the transportation planner is not able to with certainty identify acceptable levels of road surface deterioration associated with timber haul traffic. This assumption precludes use of a single objective approach, wherein total cost is minimized subject to environmental constraints. It also precludes a dual objective aggregation approach, due to the planner's inability to appropriately weigh and scale the non-commensurate objectives. In this context, identification of the efficient tradeoff surface is required. That is, the planner seeks Pareto optimal (non-dominated) solutions, which requires a multi-objective approach.

A general multi-objective problem (MOP) can be formulated as shown below (Jozefowiez et al. 2008):

$$(\text{MOP}) = \begin{cases} \min \quad F(x) = (f_1(x), f_2(x), \ldots, f_n(x)) \\ s.t. \quad x \in D \end{cases} \tag{1}$$

where $n \geq 2$ is the number of objective functions, $F(x)$ the objective vector, D the feasible solution space, and $x = (x_1, x_2, \ldots, x_r)$ the vector of decision variables. Consider two decision vectors $a, b \in D$. Using the concept of Pareto optimality, a is said to *dominate b* $(a \prec b)$ iff:

$$\forall\, i \in \{1, 2, \ldots, n\} : f_i(a) \leq f_i(b) \quad \cap \quad \exists\, j \in \{1, 2, \ldots, n\} : f_j(a) < f_j(b) \tag{2}$$

The set of Pareto optimal solutions is known as the Pareto frontier (PF), whose values represent tradeoffs in the objective space. Identifying these solutions facilitates the decision maker's selection of a compromise solution that satisfies the objectives as best as possible (Van Veldhuizen and Lamont 2000). This represents an *a posteriori* optimization approach, wherein the decision-maker selects a solution from the PF. Employing Pareto optimal formulations is appropriate for environmental decision-making, can lead to informed compromise, and should ultimately facilitate tradeoff analysis (Kennedy et al. 2008; Toth et al. 2006).

To date in the forest transportation planning literature there are few examples of multi-objective approaches that consider environmental performance. Thompson et al. (2008) employed exact methods to schedule road management treatments in order to minimize treatment cost and maximize environmental benefit, as measured by reduction in sediment delivery to streams. Stückelberger et al. (2006) presented a road network design framework with three objectives: minimize road construction and maintenance costs, minimize deleterious ecological effects, and maximize suitability of cable-yarding landings. They approximated the frontier with simulated annealing using an iterative approach, varying weights for a scaled single-objective function. Coulter et al. (2006) scheduled road maintenance treatments in order to minimize stream impacts, minimize road failures, and minimize regulatory violations, but aggregated objectives using the Analytic Hierarchy Process to identify a singularly "optimal" solution.

In this paper, we develop a model that identifies the optimal forest policy for maintaining a network of gravel roads under heavy truck traffic, with conflicting economic and environmental objectives. We formulate the problem as a multi-objective vehicle routing problem (MOVRP) with daily operating limits, and generate a series of daily tours over a planning horizon involving multiple scheduled timber harvests. MOVRP's can be defined by a network and sets of demands, vehicles, costs and objectives (Jozefowiez et al. 2008). Our planning problem is unique in that each edge (road segment) has zero demand. That is, there is no extant requirement to grade any particular road segment. Instead, the algorithm identifies grading frequencies for each road segment as part of an overall tour, so that the grader may visit some segments multiple times and others never.

In the subsequent sections, we present the mathematical formulation of the multi-objective problem facing the transportation planner, discuss our chosen solution method, apply our model to two forest road networks of increasing size, contrast multi-objective results with policies representative of industry norms, and offer suggestions for future research.

4.3 Problem Statement

Consider a forested landscape that will be subject to a series of timber harvests over the planning horizon. We assume that harvest volumes and associated log truck requirements are known, that the log trucks' routes across the road network are predetermined, and that the road network is undirected. There exists a single maintenance vehicle (grader) that is deployed on a daily basis. Daily tour lengths can vary, but they are limited to a maximum operating time. The grader must begin and end each day’s tour at the same location, hereafter referred to as the depot. We assume constant, known speeds for grading and deadheading (traveling with the blade raised). Grading and deadheading costs are directly proportional to service/travel time, a function of segment length, width, and design standard.

We begin by presenting the formulation for a policy that schedules segments for grading based on traffic levels. That is, segments are serviced so that there is a constant level of traffic (not time) over each segment in between gradings. In this circumstance the problem is to determine the optimal number of times to grade each road segment during the planning horizon, and the daily tours to take in order to do so. The economic objective (Equation 3) seeks to minimize the sum of vehicle operating costs (Equation 5) and maintenance costs (Equation 6). The environmental objective (Equation 4) seeks to minimize the hazard-weighted rut depth across all segments in the road network. Again, the hazard factor is used to differentiate segments based upon criteria and attributes thought to increase sedimentation risk. A road with high rut depth but very low risk may be considered less degrading than a road with more shallow rut depth but significant potential to deliver sediment to streams. The integration function reflects our expectation that deleterious impacts are cumulative; a road segment with ruts has a continued likelihood of causing harm to aquatic resources so long as the road remains rutted, and that risk increases as rut depth deepens. Maintenance costs include the grading activities themselves, plus the cost of traversing between segments (deadheading) as part of a daily tour. The deadhead tour length is calculated exclusive of grading times, includes travel time to/from the depot, and assumes travel routes along shortest paths between segments.

Minimize:

$$Z_{econ} = VOC + MC \tag{3}$$

$$Z_{env} = \sum_i \alpha_i \int_0^{T_i / N_i} r(t)dt \tag{4}$$

Subject to:

$$VOC = \sum_i \left(N_i \int_0^{T_i / N_i} f(t)dt \right) \tag{5}$$

$$MC = \sum_i C_{gi} N_i + \sum_t C_d DL_t \tag{6}$$

$$N_i = \sum_t X_{it}, \quad \forall\, i \tag{7}$$

$$DL_t = f(X_{it}, SP_{ij}), \quad \forall\, t \tag{8}$$

$$DL_t + \sum_i H_i X_{it} \le TL, \quad \forall\, t \tag{9}$$

$$X_{it} \in \{0, 1\}, \quad \forall\, i, t \tag{10}$$

Where:

X_{it}	binary variable indicating whether segment *i* is scheduled to be graded in period *t*
N_i	number of times road segment *i* is graded over the analysis period
DL_t	deadhead tour length in period *t* (hr)
T_i	cumulative traffic over road segment *i* during the analysis period, in both directions (thousands of vehicles)
C_{gi}	cost to grade road segment *i* ($)

C_d	deadhead travel cost (\$/hr)
H_i	time required to grade road segment i (hr)
α_i	hazard rating for road segment i (dimensionless)
$f(t)$	vehicle operating cost as a function of traffic (\$/1000-km)
$r(t)$	rut depth as a function of traffic (mm)
SP_{ij}	shortest path between road segments i and j, inclusive of the depot (hr)
TL	daily operating time limit (hr)

Equation 7 defines as an accounting variable the total number of times over the planning horizon each edge will be serviced. Equation 8 defines the daily deadhead tour length as a function of the segments scheduled for service and the shortest paths between said segments. Equation 9 stipulates that the total daily tour length (deadheading + grading) does not exceed a daily operating time limit. Lastly, Equation 10 requires the grading decision variables to remain binary.

A more flexible approach would not limit service schedules to occur in a cyclical pattern based on threshold traffic levels. Allowing variation in scheduling decisions provides additional degrees of freedom and could lead to objective function improvements. For instance, it may be the case that a particular tour traverses some segments that under a traffic-based policy would be scheduled for later service. Adding these segments to the current tour could eliminate redundancy and free up grader resources for future tours. This approach also enables clustering of proximal segments, possibly leading to more efficient daily routes.

Introducing this scheduling flexibility increases the complexity of the problem. Effectively, the search now identifies a sequence of threshold traffic levels $\{T_{i1}, T_{i2}, \ldots, T_{in}\}$ for each segment i, where $n = N_i$. To accommodate this framework, the equations for vehicle operating cost (Equation 11) and environmental performance (Equation 12) must be adapted. Equation 13 ensures that inter-grading traffic levels sum to the cumulative traffic.

$$VOC' = \sum_i \sum_{k=1}^{N_i} \left(\int_0^{T_{ik}} f(t)dt \right) \tag{11}$$

$$Z_{env}{}' = \sum_i \sum_{k=1}^{N_i} \alpha_i \int_0^{T_{ik}} r(t)dt \tag{12}$$

$$\sum_k T_{ik} = T_i, \quad \forall\, i \tag{13}$$

To model vehicle operating cost and rut depth formation we rely on empirical results from a study conducted by the World Bank in Kenya on lateritic gravel roads (Faiz and Staffini 1979). Vehicle operating costs varied according to the vehicle type, and were found to rise with the square of the cumulative traffic, t, since grading. Equations 14 and 15 present VOC for light vehicles and heavy truck-trailers, respectively. An average VOC equation was calculated by weighting the VOC equations for different vehicles by their respective share of the cumulative traffic stream (Faiz and Staffini 1979). Given log truck traffic, we estimate an additional 5% of heavy vehicle traffic due to rock haul, plus 47 support (light) vehicles per million board feet (BLM 2003). Assuming 4 mbf (thousand board feet) per log truck load, this amounts to 0.188 light vehicles per loaded log truck (one-way traffic). Equation 16 presents our average

VOC equation. A road deterioration relationship predicts rut depth to increase with traffic (Equation 17).

$$f_{light}(t) = 213.32 + 0.0094t^2 \tag{14}$$

$$f_{heavy}(t) = 861.93 + 0.0557t^2 \tag{15}$$

$$f_{average}(t) = 763.43 + 0.0164t^2 \tag{16}$$

$$r(t) = 11 + 0.23t - 0.0037t^2 + 0.000073t^3 \tag{17}$$

The problem is nonlinear, both in terms of the integer requirements for grading as well as the nonlinearity of the cost and rut depth functions. It is similar to solving a sequence of postman problems, but differs in that there is no pre-identified subset of edges that actually require service, and that the costs are dynamic. Having no set of pre-identified edges requiring service increases the complexity of the problem relative to the traditional postman problem. Let *n_pd* be the number of periods in the planning horizon, *n_seg* be the number of segments, and assume an undirected road network, so that all segments can be traversed in either direction. The cardinality of the decision space can be calculated as $\left(\sum_{i=0}^{n\_seg} i!\,2^i\right)^{n\_pd}$, where $\sum_{i=0}^{n\_seg} i!\,2^i$ is the number of possible tours in a given period. Clearly the solution space grows dramatically as the number of segments and planning periods increase. This problem can be approached using multi-objective meta-heuristic techniques. A meta-heuristic is a solution method that orchestrates an interaction between local improvement procedures and higher level strategies to create a process capable of escaping from local optima and performing a robust search of a solution space (Glover and Kochenberger 2003).

4.4 Solution Method

We employed a multi-objective evolutionary algorithm (MOEA) to generate solutions to this problem. MOEA's are a popular tool for solving multi-objective routing problems (Jozefowiez et al. 2008) and, more generally, multi-objective combinatorial optimization problems (Ehrgott and Gandibleux 2000). In a survey of multi-objective metaheuristic use, Jones et al. (2002) found that 94% of practitioners used some form of an evolutionary algorithm. According to Zitzler et al. (2000, p. 173), evolutionary algorithms "have become established as the method at hand for exploring the Pareto-optimal front in multi-objective optimization problems that are too complex to be solved by exact methods."

Evolutionary algorithms mimic natural processes of biological evolution, in particular the concept of natural selection. From a population of solutions, high quality solutions are preferentially selected to mate, and these solutions are then stochastically perturbed to create a new generation of solutions. Maintaining a population of solutions is advantageous for multi-objective programming, as a single run of the algorithm can generate multiple solutions along the efficient frontier. Retaining multiple solutions also promotes diversity in the solution space.

There exist numerous MOEA approaches, though generally speaking there is no algorithm that is superior for all problem types (Wolpert and Macready 1997), or across all possible performance measures (Tan et al. 2002). That said, there are certain design elements that have been shown to facilitate convergence and diversity, notably elitism and fitness sharing (Van Veldhuizen and Lamont 2000). Elitism in particular is important, as it is required to guarantee convergence of MOEA's (Rudolph and Agapie 2000).

We opted to employ the Strength Pareto Evolutionary Algorithm (SPEA), which employs both fitness sharing and elitism (Zitzler and Thiele 1999). In fact, SPEA is considered a landmark in MOEA development because it formally introduced the elitist notion of retaining an external population of non-dominated solutions (Coello Coello 2006). Fitness assignment proceeds according to two phases. In the first phase, individuals in the external set are assigned a strength value that is proportional to the number of individuals in the current population they dominate. Next, individuals in the current population are assigned fitness values as the sum of the strengths of all external solutions. Clustering is used to reduce the size of the number of non-dominated solutions while preserving the essential characteristics of the tradeoff frontier, and a novel Pareto-based niching method is employed to preserve diversity.

Comparative analyses have demonstrated that SPEA can produce high quality solutions to multi-objective test problems. SPEA was found to efficiently guide the search towards the Pareto-optimal front, and outperformed four other MOEA's on 0/1 knapsack problems (Zitzler and Thiele 1999). Zitzler et al. (2000) evaluated eight solution methods and identified SPEA as the best algorithm in terms of producing solutions closest to the true Pareto front, citing elitism as an important factor in its success. Tan et al. (2002) also reported good performance from SPEA, referring to elitism and fitness sharing as important algorithm design features.

Zitzler et al. (2001) proposed an improved version, SPEA2, which was shown to provide improved results over SPEA. Major differences in SPEA2 include a modified fitness assignment scheme based on dominance relations between the population and the archive, a new density estimation technique to facilitate clustering, and a new method for truncating the elitist archive to preserve boundary solutions. Steps in the algorithm are presented below (Zitzler et al. 2001, p. 5):

1. <u>Initialization</u>**:** Generate an initial population P_0 and create the empty archive (external set) $\overline{P_0} = \varnothing$. Set $t = 0$.
2. <u>Fitness assignment</u>: Calculate fitness values of individuals in P_t and $\overline{P_t}$.
3. <u>Environmental selection:</u> Copy all non-dominated individuals in P_t and $\overline{P_t}$ to $\overline{P_{t+1}}$. If size of $\overline{P_{t+1}}$ exceeds $\overline{N}$ then reduce $\overline{P_{t+1}}$ by means of the truncation operator, otherwise if size of $\overline{P_{t+1}}$ is less than $\overline{N}$ then fill $\overline{P_{t+1}}$ with non-dominated individuals in P_t and $\overline{P_t}$.
4. <u>Termination:</u> If $t \geq T$ or another stopping criterion is satisfied then set A to the set of non-dominated individuals in $\overline{P_{t+1}}$. Stop.
5. <u>Mating selection:</u> Perform binary tournament selection with replacement on $\overline{P_{t+1}}$ in order to fill the mating pool.

6. Variation: Apply recombination and mutation operators to the mating pool and set P_{t+1} to the resulting population. Increment generation counter ($t = t + 1$) and go to Step 2.

4.5 Algorithm Design

We represent solutions as chromosomes of length *n*, where *n* corresponds to the number of periods in the planning horizon. Each gene in the chromosome in turn represents a daily tour for the maintenance vehicle to take. As stated above, tours define the order in which certain road segments are to be graded, and can vary in total number of road segments serviced. Between solutions therefore, chromosome length but not gene length are constant. In terms of data structures, this can easily be represented by an array of pointers, with each pointer referencing a dynamically-sized array or linked list corresponding to each tour.

With recombination solutions mate and exchange genetic information through a process called crossover. Recombination is a stochastic procedure that promotes diversity in the search process. Various implementations exist; based upon the initial algorithm in Zitzler et al. (2001) we opted for a 1-point crossover, wherein a point in the chromosome is randomly selected to act as a dividing point for the offspring. The first offspring receives all the genes up through that point from one parent, and from the other parent beyond that point. The second offspring similarly receives contiguous genetic blocks, but from the opposite parents. In our implementation, sequences of daily tours are swapped between offspring, but the tours themselves are not altered. We opted for a recombination rate of 80% based upon previous implementations of SPEA (Zitzler et al. 2000; Zitzler and Thiele 1999).

Mutation is another diversity preserving mechanism, and serves to change the genetic composition of solutions to that which could not be achieved through inheritance alone. As we implemented it, mutation stochastically alters the tours themselves. Four tour-changing operators are defined: add, remove, replace, and swap. Per mutation an operator is randomly assigned, with each operator assigned an equal probability. The "add" and "remove" operators increase/decrease the number of edges serviced on the tour. "Replace" and "swap" instead rearrange a given tour, wherein either a new service edge is inserted or the order of two existing edges rearranged.

We hypothesized that for our implementation it would be necessary to emphasize the role of mutation, in order to facilitate exploration of individual tours. Mutation rates for MOEAs typically range from 1% to $1/k$, where k is the number of genes in a chromosome (Tan et al. 2002; Knowles and Corne 2000; Zitzler et al. 2000; Zitzler and Thiele 1999). Too low of a rate of mutation however may result in few additions, removals, or permutations of service edges for individual tours beyond that generated initially. We therefore experimented with mutation rates of 1%, 5%, 10%, 20%, 40%, 60%, and 80%. The concern that too high a mutation rate can effectively lead to pure random search may be tempered in this context because of retention of the elitist archive to populate subsequent generations. That is, the trajectory of the search isn't determined by the current population to which the mutation operator was just applied, but rather by the archive.

The sizes of the population and in particular the archive can significantly impact algorithm performance, and are therefore important design choices. Too small an archive may not sufficiently span the objective space, but too large an archive increases computational effort, which is of special concern here due to the complexity of the SPEA2 archive truncation operator (Zitzler et al. 2001). In some studies the archive size has been set to roughly a quarter of the population size (e.g., Tan et al. 2002; Zitzler et al. 2000; Zitzler and Thiele 1999), whereas others have used identical population and archive sizes (e.g., Zitzler et al. 2001; Knowles and Corne 2000). Ultimately any size chosen will reflect a compromise between solution quality (i.e., how closely the results approximate the true Pareto frontier) and computational effort. After experimentation we arrived at an archive size of 40% of the population size, where the population size changes with the size of the problem being solved. Both the population and archive were stored in a linear list per the recommendation of Mostaghim et al. (2002).

Prior to invoking the SPEA2 algorithm, the population is initialized according to a semi-random procedure. First, solutions to the simulated policy scenarios are input. These policies correspond to the practice of grading at fixed traffic intervals, and are described in more detail in the following section. The rationale for doing so is that these solutions may already lie near or along the Pareto frontier, and thus may be good starting points for further exploration. For all subsequent solutions in the population, both the number of service edges per period and the specific edges to be serviced in that period are generated randomly. After initializing the population, we ran the algorithm for a total of 20,000 generations, a value arrived at after initial experimentation.

4.6 Example Applications

To demonstrate the utility of a planning approach based upon Pareto optimality, we present results from two example applications. For both examples we use road segment information obtained from the GIS database for the McDonald-Dunn Forest, a research forest managed by the College of Forestry at Oregon State University. The first case study, Example #1, is of moderate size (though the cardinality of the solution space, as described above, is quite large), which we describe in detail for the benefit of the interested reader. Example #1 extracts timber sale information from 3 planned sales (Dave Lysne, College Forests Director, Oregon State University, personal communication, August 2008), the traffic for which is routed across 9 road segments, over a planning horizon of 22 periods. The second case study considers a larger 141-edge network, using road data originally presented in Thompson et al. (2007), and considers six hypothetical timber sales scheduled over a 20 period planning horizon.

Parameters relating to operation of the grader were estimated using data from Provencher (1995). We assume an operating cost of $50/hr, and that the grader can deadhead at 40 km/hr and grade at 5km/hr. Daily tour lengths are limited to 8 operating hours. Feasibility is retained through the search by requiring feasibility as a precondition for selection into the archive. In addition, the population initialization procedure only adds segments to tours if doing so won't result in an infeasible tour length.

Loaded log truck traffic was estimated assuming daily production levels of ~20mbf per timber sale. Each loaded log truck carries ~4mbf per load, and each pickup/delivery requires two one-way trips. Associated light vehicle and rock haul traffic were calculated using methods outlined above. Based on these regimes we calculated the total number of loaded log trucks entering each segment for each period, as well as the cumulative traffic volume (support vehicle, rock haul, timber haul) across each segment.

For simplicity we model grading to evenly split segment-level traffic. That is, half of the traffic occurs before the segment is graded, and the remainder of traffic after grading. Consider a single segment over the course of two periods, with 20 vehicles per period, and assume the segment will be graded in both periods. The sequence of threshold traffic levels in this scenario would be $T = \{10, 20, 10\}$. Because traffic levels are consistent irrespective of tour ordering, rut depth calculations will not change in response to a re-ordering of a given period's tour. Rather, the total number of times each segment is serviced and the associated inter-grading traffic levels influence rut depth levels.

For purposes of comparison we simulate four alternative grading policies representative of practices that are common within the forest industry (Provencher 1995). Individual segments are assigned to be graded based upon cumulative timber volume haul since the previous grading. Infrequent grading will lead to lower total costs at the expense of higher hazard-weighted rut depth scores. We identified traffic thresholds based upon cumulative timber volume levels of 0.5 MMBF, 1 MMBF, 1.5 MMBF, and 2 MMBF, which henceforth are referred to as Policy Solutions #1, #2, #3, and #4, respectively. Service periods could then be calculated by overlaying the grading policy on the cumulative traffic for each segment.

We used the MOEA to find efficient tours for each simulated grading policy, given a fixed grading schedule as an initial solution. Because the traffic levels between grading were fixed, and therefore rut depth fixed as well, the MOEA sought only to rearrange daily tours so as to minimize total cost. To accomplish this we modified the mutation procedure to only perform “replace” and “swap” operations. Any lower cost solution by definition dominates in this context, and would therefore be updated into the archive. We set the archive size to one, effectively rendering our MOEA a single-objective evolutionary algorithm. Alternatively we could have opted to use tabu search, which has demonstrated success for single objective routing problems (Thompson et al. 2007; Corberán et al. 2000; Hertz et al. 2000; Gendreau et al. 1994), but retained the MOEA approach for consistency.

To compare algorithm performance across mutation rates we employ two complementary metrics: size of the space covered (*S*) and coverage of two sets (*C*). Returning to the formulations of Equations 1 and 2, let $X' = (x_1, x_2, ..., x_r) \subseteq D$ be a set of *r* decision vectors. In our two-dimensional case, the function $S(X')$ calculates the union of all rectangles defined by the points (0, 0) and $(f_1(x_i), f_2(x_i))$. Larger values of *S* indicate broader coverage of the objective space, which is desirable. As an independent measure of performance *S* is limited however, because it does not distinguish between concave and convex regions in the objective space.

The second metric, *C,* indicates the degree to which the outcomes of one algorithm dominate another algorithm, thereby overcoming the shortcoming of *S*. Consider $X', X'' \subseteq D$. The function $C(X', X'')$ maps the order pair (X', X'') to the interval [0, 1], where a value of 1 indicates that all points in X'' are dominated by or are equal to (i.e., covered by) points in X'. A value of 0 indicates that none of the points in X'' are covered by points in X'. In a pair-wise comparison of output from algorithms (or, in our case, various mutation rates), we would clearly prefer solution X' to X'' when $S(X') \geq S(X'') \quad \cap \quad C(X', X'') \geq C(X'', X')$. Readers are referred to Zitzler and Thiele (1999) for more detailed information on these metrics.

We developed our SPEA2 code in Microsoft Visual C++ 6.0. *S* values were calculated using the *polyarea()* functionality of MATLAB, and *C* values were calculated using a simple Visual Basic for Applications macro within Microsoft Excel. All results presented below were generated on a HP Pavilion dv6000 laptop, which has a dual-core 2.2 GHz processor and 2GB DDR2 SDRAM.

Example #1

Figure 1 displays the road network and timber sales for Example #1. Estimated timber volumes were 715 mbf, 1700 mbf, and 1300 mbf for the Bean, Berry, and Racetrack sales, respectively. Traffic associated with these sales is routed over five roads (R100, R140, R142, R190, and R1010), divided into a total of nine segments (R100.1, R100.2, R100.3, R140.1, R140.2, R142.1, R190.1, R190.2, and R1010.1). The network comprises a total of 11.00 km. Traffic regimes associated with each timber sale are presented in Table 1. For each timber sale the log trucks' routes over the network, as identified by segment order, are presented. Each timber sale is modeled as having three landings, and subsequently three different input segments.

Table 2 presents total traffic over each segment (in both directions), which includes light support vehicles, rock haul, and log truck traffic. Road 100 is the mainline, and thus aggregates the most traffic. The depot, the point to which the grader must return, is assigned to the beginning of Road 100. Segment-level grading frequencies for each simulated policy are presented in Table 3.

Table 4 presents *S* and *C* values for the various mutation rates we tested on Example #1. Values used in S and C calculations represent the aggregated non-dominated solutions from multiple runs of each mutation rate. We felt 30 runs were sufficient to account for inherent stochastic variability (Zitzler and Thiele 1999). The area of the objective space spanned (*S*) generally increases with the mutation rate, although *S* for the 1% mutation rate is slightly larger than for rates of 5% and 10%. Based on *S* alone, a mutation rate of 80% appears superior because its frontier spans the largest area of objective space. This could suggest that higher mutation rates facilitate additional exploration of individual (daily) tours, thereby exploring more of the objective space to reach efficient boundary solutions. Alternatively, it could suggest that with higher mutation rates the algorithm identifies a frontier with convex regions, which in this dual-minimization case is undesirable. Figure 2, which displays the frontiers for mutation rates of 1% and 80%, indicates in this instance that the latter is occurring. Solutions generated using the higher mutation rate span more of the objective space, especially the low rut-depth, high-cost region, but at the same time are dominated across nearly the entire objective space.

Moving next to examine C values, our results indicate that lower mutation rates outperform higher rates. The diagonal of the C matrix corresponds to the identity matrix, because a solution (set of decision vectors) by definition covers itself. Above this diagonal, coverage values range from 46-100%, demonstrating the better performance of lower mutation rates. Below the diagonal coverage values are much lower. The non-dominated frontier generated using a mutation rate of 5% covered (dominated or was equal to) all other rates (i.e., $C(5\%, X'') = 1.00 \quad \forall \; X'' \subseteq D$). Thus there is a benefit to expanding the search via higher mutation rates (relative to the more standard rate of 1%), but only to a point. With significantly higher mutation rates the search does not converge towards the Pareto frontier. Though this result is not unexpected, it would be premature to conclude that higher mutation rates are always undesirable, as this is a relatively small example where perhaps expansive exploration of each tour was unnecessary. Based upon our results from Example #1, we opted to experiment with rates of 1%, 5%, 10%, 20%, and 40% for the larger problem in Example #2.

Hazard weighted rut depth values ranged from 8.47 to 8.58 mm, where the latter value corresponds to no grading at all. Note this metric is an integral of the aggregated hazard weighted rut depth across all road segments; it does not reflect actual rut depth values on any particular segment. Absent grading, we would expect a rut depth of ~11.5 mm for road segment 100.1 at the end of the planning horizon (see Equation 17). We integrate over all days in the planning horizon to reflect our assumption of cumulative environmental degradation associated with rutted road surfaces. Values for total cost ranged from \$6458 to \$7842. Vehicle operating costs were relatively insensitive to grading because of the small network and low traffic levels, and so most of the range in cost variation stems from grader utilization.

Figure 3 presents the non-dominated frontier in relation to the four policy solutions, represented as discrete points in the objective space. In total our MOEA identified 111 non-dominated solutions. The policy corresponding to grading after 2 MMBF (Policy Solution #4) is the upper left policy solution in Figure 3. Progressing along the frontier towards higher cost solutions leads to policies with progressively smaller intervals between grading. Policy Solution #1 (0.5 MMBF) results in the best environmental performance of the policy solutions. Beyond Policy Solution #1 there appears to be decreasing marginal returns, suggesting monetary resources slated for grading could be better utilized performing other maintenance operations.

Policy Solutions #1, #2, and #4 were each dominated by 1, 4, and 1 individual(s), respectively. Policy Solution 3 was non-dominated. This suggests that, with this network and traffic regime, the simulated management policies are efficient.

Example #2

Figure 5 displays the road network for the Dunn Forest managed by the College of Forestry at Oregon State University, a portion of which is modeled for Example #2. The network contains 127 nodes, 141 edges, and comprises a total of 72.27 km. Six timber sales were simulated using values bounded by the range of the sales in Example #1, and were scheduled to occur over a planning horizon of 20 periods. Table 5 presents traffic regimes associated with each timber sale. Truck routing from timber sales results in traffic across 67 segments, effectively reducing the size of the decision space (i.e., roads servicing no traffic were assumed to require no grading). Information on all road segments needs to be retained however, as the algorithm routes the grader over shortest paths between segments when deadheading. Appendix 1 presents segment-level information for those segments over which traffic will flow.

Figure 6 compares the non-dominated frontier output by SPEA to simulated policy solutions. A total of 152 non-dominated solutions were identified. All policy simulations were dominated, indicating that the same level of environmental performance (as measured by hazard weighted rut depth) can be achieved at lower overall total cost, thereby freeing up resources for other road management activities. Alternatively, for the same level of expenditure the environmental performance of the road network could be improved.

Table 6 presents *S* and *C* values for various mutation rates tested in Example #2. Here a mutation rate of 10% is clearly dominant, as it spans the largest region of the objective space (*S*), and completely covers frontiers generated using other mutation rates (*C*). Higher mutation rates performed better in Example #2 than in Example #1, suggesting a positive association between mutation rate, problem size, and algorithm performance. Our results also suggest a positive association between problem size and coverage of policy solutions by the MOEA's approximated Pareto frontier, though this question is best answered by further experimentation.

Solution time increased dramatically from Example #1 to Example #2. This is due to a combination of the larger road network and the larger respective archive and population sizes. We used sizes of 100 and 40 for the population and archive, respectively, for Example #1. For Example #2 we increased these values to 150 and 60, respectively. Thus per generation the MOEA performed either 140 (Example #1) or 210 (Example #2) fitness evaluations. With Example #1 the MOEA iterated over an average of 22.22 generations per second. With Example #2 algorithm speed dropped to 2.584 generations per second, nearly an order of magnitude lower. For much larger road networks or much longer planning horizons, practitioners might want to consider implementing the evolutionary algorithm in parallel to improve computational performance (specifically, to speed up fitness evaluation). Of course reducing population size and generation counts are also options, but generally come with the expectation of worse solution quality.

4.7 Discussion

Forest road maintenance vehicle routing using the Pareto optimality approach provides landowners with the opportunity to evaluate the economic and environmental performance of their grading routing policies. Identifying more efficient grading routes ideally results in a better-maintained road system. Cost-savings measures could release resources for other road management activities, including those directed at reducing the occurrence of ruts and other surface imperfections. This could entail reducing tire pressure, changing traffic regimes, or strengthening the subgrade (Sessions et al. 2007). Landowners may also wish to move along the non-dominated frontier towards grading policies with better environmental performance, perhaps to achieve certification or comply with regulatory requirements relating to water quality.

Efficient frontiers generated using the strength Pareto algorithm could be a starting point for regulatory discussions regarding forest road management. Regulatory frameworks, such as the Clean Water Act, often involve a balancing act between the cost and benefit of any particular pollution control measure. The type of tradeoff analysis we propose here informs landowners and regulators not only of what is possible, but of where current management policies lie. If current policies comprise interior solutions (i.e., they are dominated), there is clearly room for improvement. Alternatively, landowners may demonstrate that their current practices are already efficient.

In our two examples we found that four simulated management policies based upon cumulative timber-haul-related traffic were on or near the non-dominated frontier. A primary benefit of identifying the frontier in this context is an improved understanding of the environmental tradeoffs associated with scheduling grading according to various traffic frequencies. Our results suggest that the marginal cost of achieving increasing environmental performance beyond Policy Solution #1 (grade every 0.5 MMBF) can be quite significant.

Certainly our results are in no small way artifacts of the particular cost and environmental performance models used. The Faiz and Staffini (1979) study provided published models for both vehicle operating cost *and* rut depth formation on low-volume unpaved roads, which is scarce in the literature, and the Provencher (1995) study provided a source for important parameters relating the operation of forest road maintenance vehicles. The Faiz and Staffini (1979) study was particularly attractive for our purposes because their work condensed the VOC equation to a function of a single variable, cumulative traffic. In general, VOC is a function of multiple parameters including climate, road geometry, road surfacing, and road surface deterioration. The World Bank's "Roads Software Tools" knowledge base is another source for VOC models (http://www.worldbank.org/transport/roads/tools.htm), as is the National Transportation Library (http://ntl.bts.gov/).

Forest landowners employing methods presented here may have alternate cost models, different assumptions regarding grader operation, or may be more interested in different measures of environmental performance. Another common metric to represent road surface condition is roughness, often measured by the International Roughness Index, a method employed by both Thompson et al. (2007) and Provencher (1995). Alternatively other forms for measuring rut depth may be used. A model developed by the U.S. Army Corps of Engineers (Barber et al. 1978) considers traffic, load, and road surfacing parameters. Hazard factor calculations could be modified include additional explanatory variables. We emphasized the importance of segment length, based upon research by Foltz and Elliott (1998) citing flow path length as an important variable. Rut length can interfere with the normal function of road shape and substantially increase flow length. Slope along the flow path, water velocity, flow depth, and the detachability of the road bed particles are known to affect sediment transport from the sediment transport mechanics literature (Morris 1963). A stronger link is likely needed between sediment, traffic, and road condition. We have bridged that gap using road deterioration models predicting rut depth as a proxy.

4.8 Conclusion

Substantial sums are expended on gravel road maintenance throughout the world, but there has been limited research directed towards systematically managing gravel roads. Road maintenance and transport activities have been linked to sediment production, but again, there has been limited research directed toward systematically managing roads for sediment production. In the U.S., roads are receiving increasing attention for their negative impacts on water quality, particularly relating to impacts on fish. Although this attention has primarily been focused on forest lands, increasing attention is being directed toward aggregate surfaced roads on non-forested lands as well. We have brought together the ideas for managing roads to simultaneously minimize user costs and environmental degradation associated with formation of ruts and other road surface failures. Our examples have drawn coefficients from empirical results from the literature. They are not intended to be handbook ready formulas, but are drawn from specific studies and are intended to illustrate a conceptual system for approaching aggregate road management.

We limited our discussion of road maintenance costs to grading. Surface rock replacement is a function of traffic and could be considered a road maintenance activity. We have assumed that rock replacement is a fixed cost and have not included it in the objective function. If rock replacement is not directly proportional to total traffic, but is a function of both grading schedule and traffic, then we could expand our maintenance cost function to include it.

Future work in this area could focus on improving development of both the solution algorithm and the operational model. Though solutions did appear to span large regions of the objective space, it may be fruitful to consider using the notion entropy to promote diversity along the non-dominated front (Farhang-Mehr and Azarm 2002). One option mentioned earlier is to move to a parallel processing setup to speed up fitness evaluations, and possibly to include much larger populations to offer a wider look into the decision space. As we emphasized the role of mutation, considering other MOEAs that focus on mutation could also be interesting. The Pareto Archived Evolution Strategy of Knowles and Corne (2000), for instance, abandons recombination and only uses mutation to introduce diversity into the solution space.

On the operational model side, there exists the possibility to employ alternate models forms for both economic and environmental objectives. Perhaps most promising would be the adoption of alternate equations to model rut depth formation. An equation developed by the Army Corps of Engineers (Barber et al. 1978) and used by the U.S. Forest Service for aggregate surface depth considers as input variables subgrade strength, surface strength, tire pressure, and traffic. Using this equation would allow for rut depth calculations more in line with what is expected for forest roads in the western U.S. The model might also be expanded to incorporate log truck routing, or time windows during which grading operations should not occur. Multiple maintenance vehicles and multiple depots would be appropriate for larger networks.

Our results demonstrate the utility of using a multi-objective approach; using the Strength Pareto Evolutionary Algorithm we were able to identify efficient solutions that dominated simulated management policies in terms of economic and environmental performance. Adoption of an *a posteriori* optimization approach should facilitate tradeoff analysis and lead to informed compromise. Ultimately this manuscript demonstrates that use of computerized decision aids could lead to increased efficiency when determining routes for graders to take over a road network. The multi-objective programming techniques we employed here could help landowners to “jointly produce” environmentally benign, low-cost road networks. We hope this discussion will stimulate additional research in road management of aggregate surfaced roads.

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Figure 4.1: Road network for Example #1. Shaded areas represent the various timber sales scheduled for the 2009 season. The light gray stands represent the Bean sale, cross-hatched stands represent the Berry sale, and shaded stands the Racetrack sale.

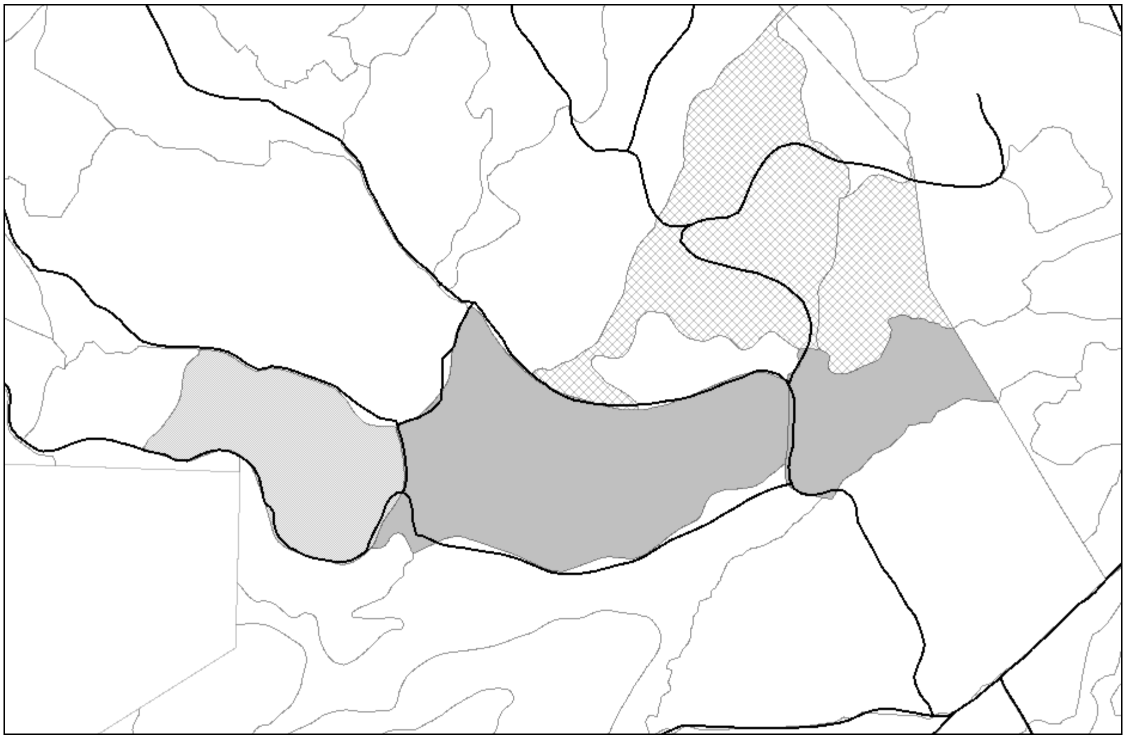

Figure 4.2: Non-Dominated Frontier, Mutation Rates = 1% and 80%, Example #1. This figure provides a comparison of non-dominated frontiers generated using mutation rates of 1% and 80%. Total cost is defined as the sum of vehicle operating cost and maintenance (grading) costs. The non-dominated frontier generated using a mutation rate of 1% covered (dominated or was equal to) 98% of solutions generated with a mutation rate of 80%. This figure demonstrates that spanning a larger region of the objective space (as measured by *S*) it is not necessarily preferable.

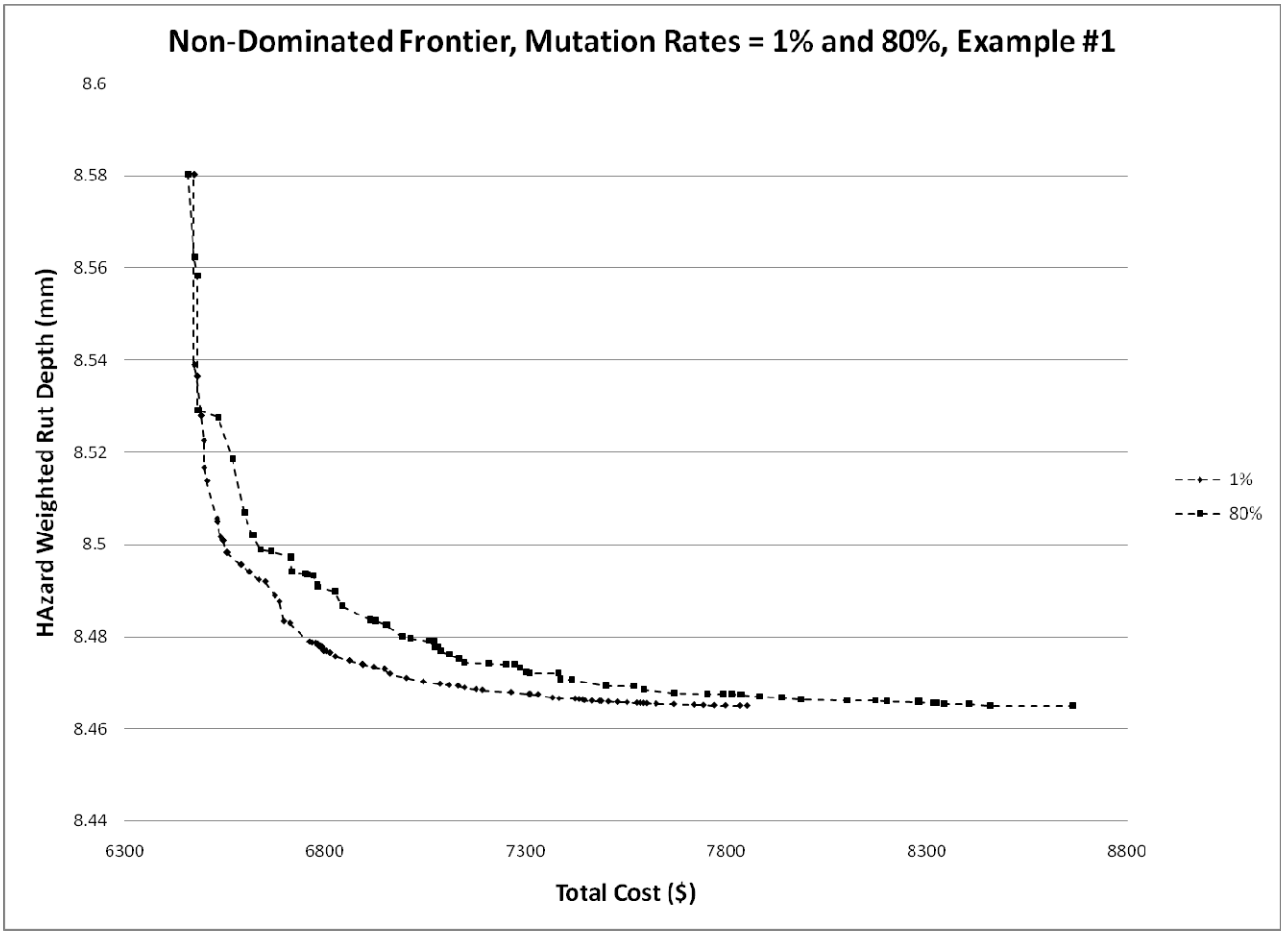

Figure 4.3: Non-Dominated Frontier (NDF) vs. Simulated Policy Solutions, Example #1. This figure provides a comparison of non-dominated frontier against simulated policy solutions, Example #1. Policy Solution #4 (grade every 2 MMBF) is the upper left solution. Infrequent grading leads to lower total costs at the expense of higher hazard-weighted rut depth scores. Progressing along the frontier towards higher cost solutions leads to policy solutions associated with more frequent grading. As expected, Policy Solution #1 (0.5 MMBF) results in the highest overall cost and the best environmental performance of the policy scenarios. These results suggest that the marginal cost of improving environmental performance beyond Policy Solution #1 can be quite significant.

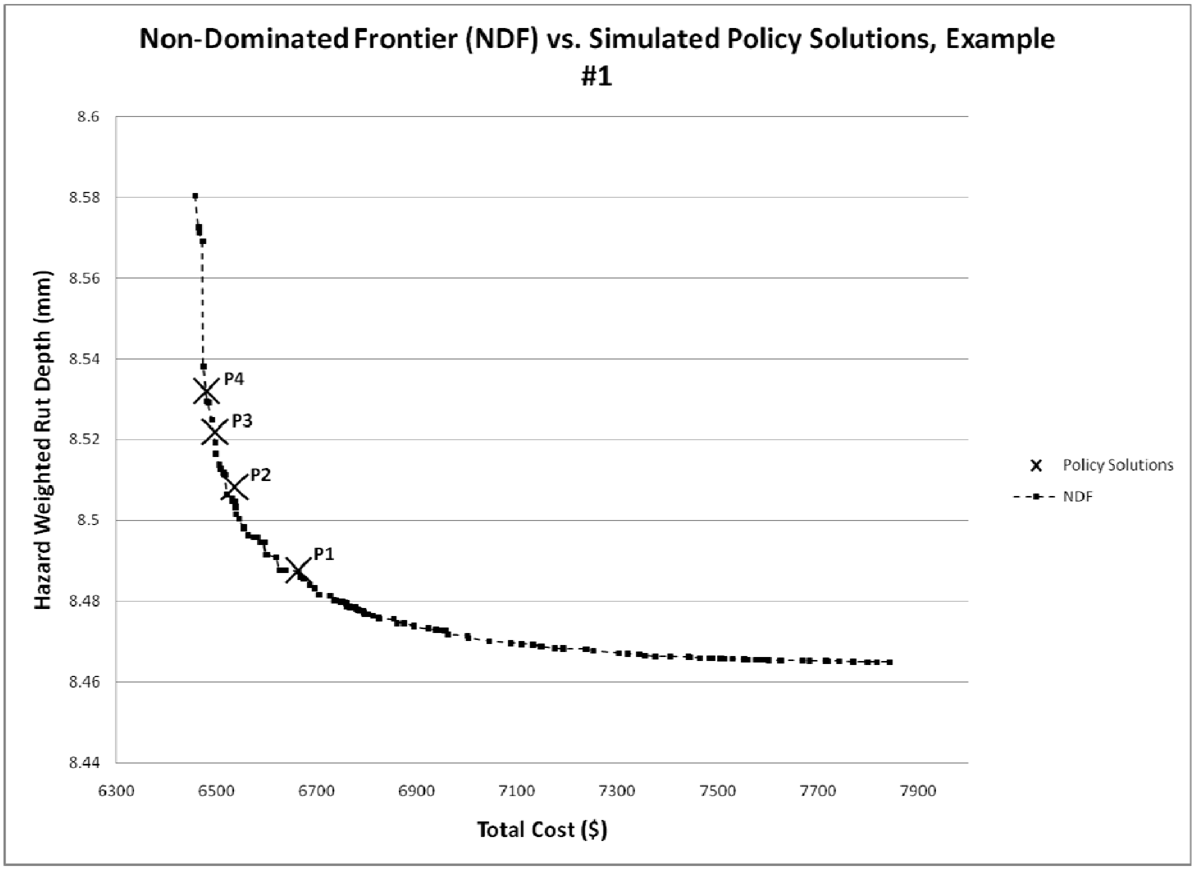

Figure 4.4: Non-Dominated Frontier (NDF) vs. Simulated Policy Solutions, Example #1. This figure provides a close-up of non-dominated frontier in region of objective space spanned by simulated policy objectives, Example #1. Though three of four policy simulations were dominated, all were near the non-dominated frontier for the network and traffic regime under consideration (i.e., the policy solutions are efficient).

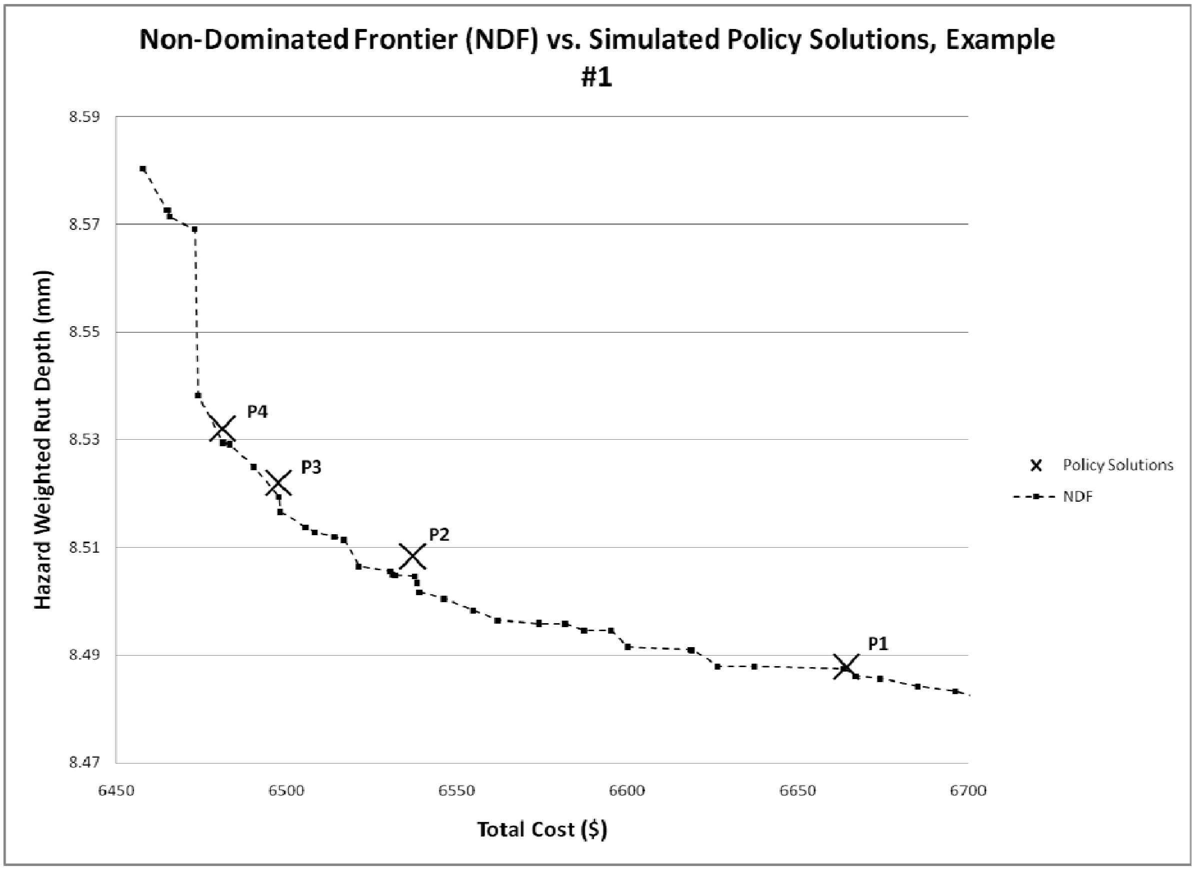

Figure 4.5: Road network for Example #2. Our graph representation contains 127 nodes and 141 undirected edges, and was originally used as a dataset by Thompson et al. (2007). Roads included in the forest ownership and modeled here are highlighted in bold. Other roads are presented in gray, as are stand boundaries.

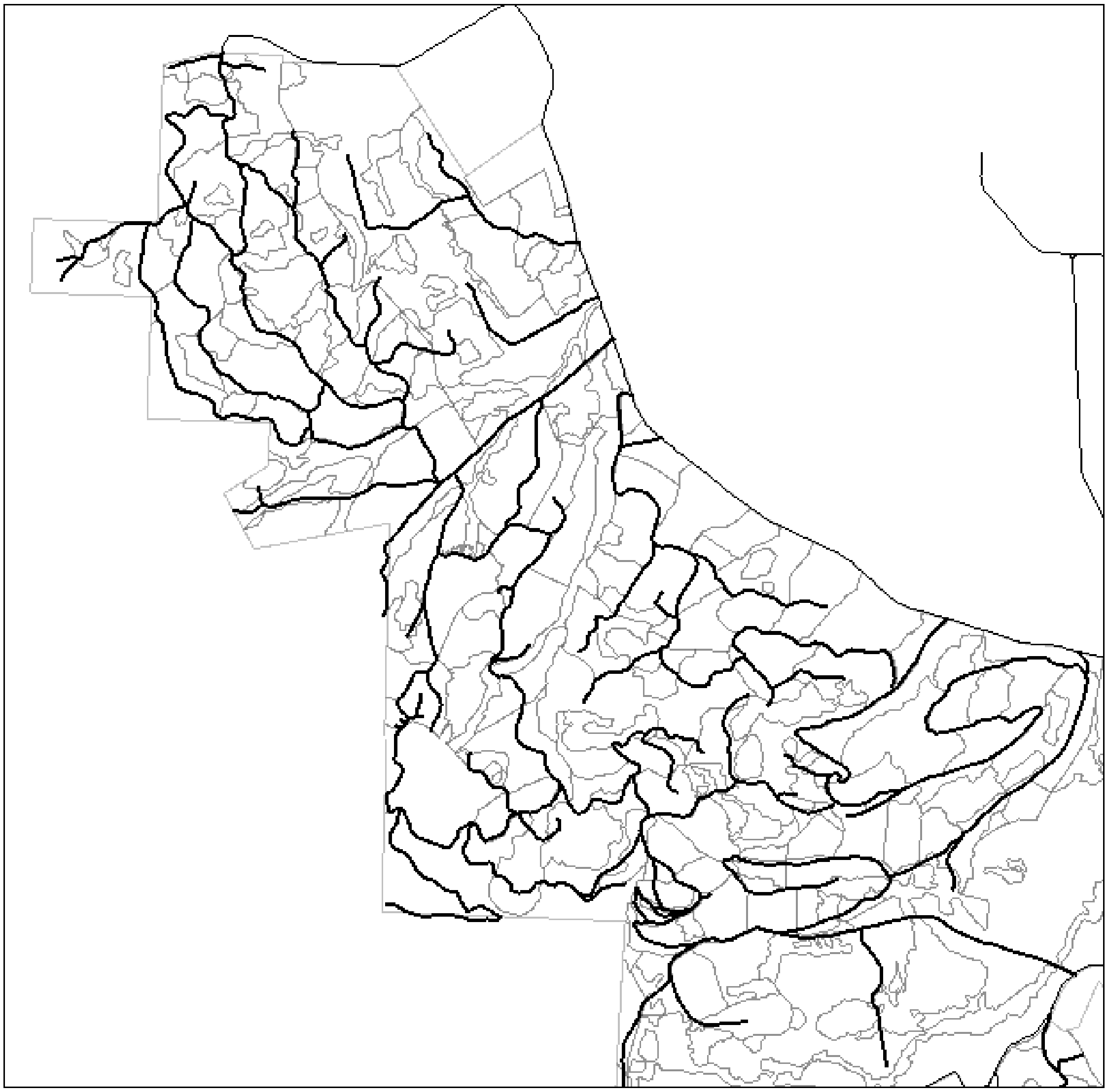

Figure 4.6: Non-Dominated Frontier (NDF) vs. Simulated Policy Solutions, Example #2. This figure provides a comparison of non-dominated frontier against simulated policy solutions, Example #2. All policy simulations are dominated by the frontier. That is, for a given level of total cost, it is possible to improve environmental performance relative to the simulated policy. As with Example #1, we see a steep decrease in cost/benefit ratio beyond Policy #4.

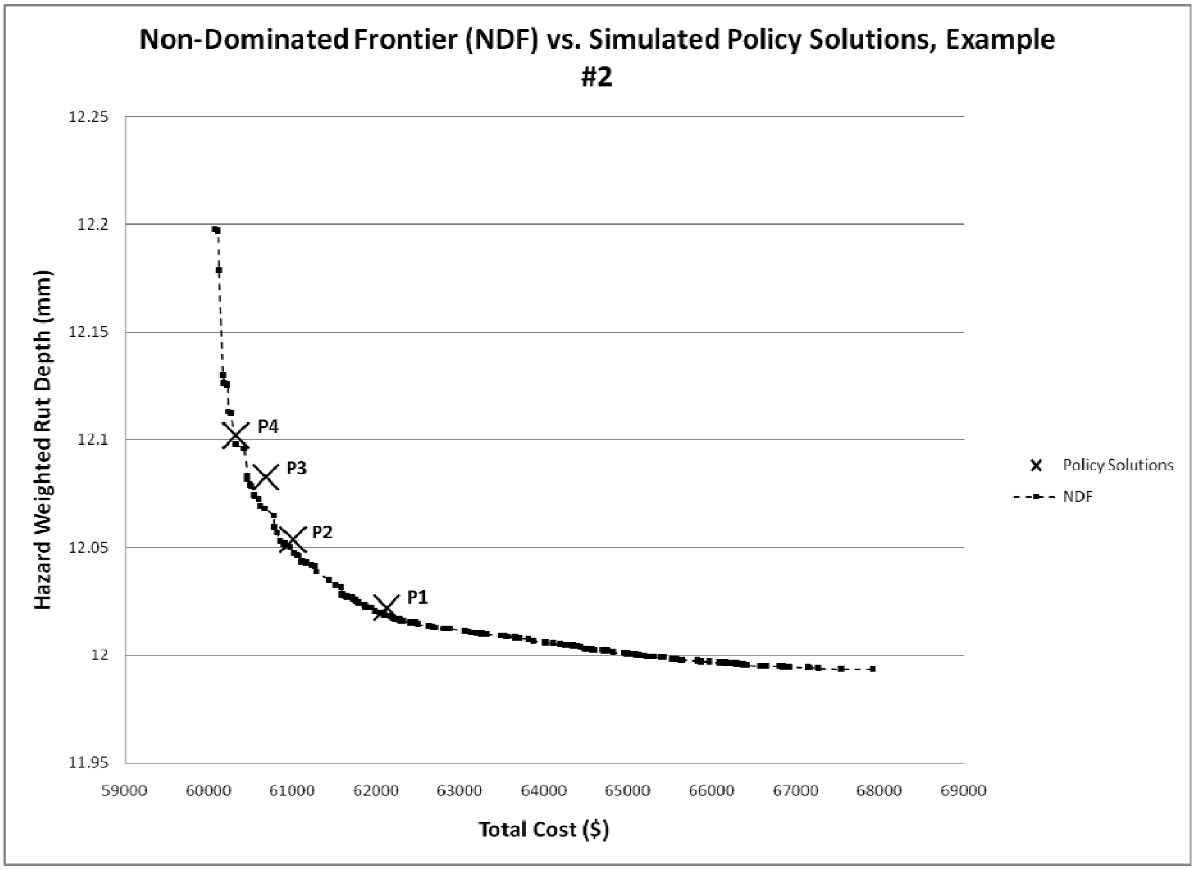

Table 4.1: Loaded Log Truck Traffic Regimes, Arranged by Timber Sale, Example #1. For each timber sale the log trucks' routes over the network, as identified by segment order, are presented. Each timber sale is modeled as having three landings, and subsequently three different input segments. The right column indicates the number of loads (4mbf / load) and the periods corresponding to each landing serving each timber sale.

Bean (179 loads; Pds 1-10):	
190.2 → 190.1 → 100.3 → 100.2 → 100.1	(60 loads; Pds 1-3)
190.1 → 100.3 → 100.2 → 100.1	(60 loads; Pds 4-6)
1010.1 → 100.1	(59 loads; Pds 7-10)
Berry (425 loads; Pds 1-22):	
142.1 → 140.1 → 100.2 → 100.1	(142 loads; Pds 1-8)
140.2 → 140.1 → 100.2 → 100.1	(142 loads; Pds 8-15)
100.2 → 100.1	(141 loads; Pds 15-22)
Racetrack (325 loads; Pds 3-19):	
100.3 → 100.2 → 100.1	(109 loads; Pds 3-8)
100.2 → 100.1	(108 loads; Pds 8-13)
1010.1 → 100.1	(108 loads; Pds 13-19)

Table 4.2: Total Traffic (Light Vehicle, Rock Haul, Log Truck) over all Road Segments, Example #1. Roundtrip traffic levels are provided. Road 100 is a mainline and hence accumulates the most traffic.

Period	Road Segment								
	100.1	100.2	100.3	140.1	140.2	142.1	190.1	190.2	1010.1
1	99	99	50	50	0	50	50	50	0
2	99	99	50	50	0	50	50	50	0
3	149	149	99	50	0	50	50	50	0
4	149	149	99	50	0	50	50	0	0
5	149	149	99	50	0	50	50	0	0
6	149	149	99	50	0	50	50	0	0
7	99	50	0	50	0	50	0	0	50
8	149	99	22	50	45	5	0	0	50
9	146	99	0	50	50	0	0	0	47
10	99	99	0	50	50	0	0	0	0
11	99	99	0	50	50	0	0	0	0
12	99	99	0	50	50	0	0	0	0
13	99	94	0	50	50	0	0	0	5
14	99	50	0	50	50	0	0	0	50
15	99	50	0	10	10	0	0	0	50
16	99	50	0	0	0	0	0	0	50
17	99	50	0	0	0	0	0	0	50
18	99	50	0	0	0	0	0	0	50
19	64	50	0	0	0	0	0	0	15
20	50	50	0	0	0	0	0	0	0
21	50	50	0	0	0	0	0	0	0
22	15	15	0	0	0	0	0	0	0

Table 4.3: Segment-level grading frequency for each simulated management policy, Example #1. Cumulative traffic levels associated with each level of cumulative timber haul were overlaid with the simulated grading policies to identify service periods for each road segment. The modified single-objective evolutionary algorithm was then invoked to identify efficient (minimal cost) individual tours prior to passing these solutions into SPEA. For the largest (2 MMBF) threshold only segments along the mainline (Road 100) are scheduled for grading, and then only once over the planning horizon.

Segment	**Service Periods, arranged by simulated management policy**			
	P1 (0.5 MMBF)	**P2 (1.0 MMBF)**	**P3 (1.5 MMBF)**	**P4 (2.0 MMBF)**
100.1	4, 7, 8, 14, 18	6, 12, 19	8, 18	11
100.2	4, 7, 9	6, 14	9	12
100.3	5, 16	-	-	-
140.1	7, 14	14		-
140.2	10	-	-	-
142.1	7	-	-	-
190.1	-	-	-	-
190.2	-	-	-	-
1010.1	17	-	-	-

Table 4.4: Size of the space covered (S) and coverage of two sets (C) for various mutation rates, Example #1. Larger values of S indicate a broader coverage of the solution space. Our results suggest higher mutation rates achieve a broader coverage (1% mutation being a minor outlier). C values for identical mutation rates are 1 (the diagonal of the C matrix), because a solution by definition covers itself. When comparing different mutation rates (reading across rows in the C matrix from left to right), values closer to 1 are undesirable. For instance, looking at C(1%, 80%), we see that 98% of the solutions generated using a mutation rate of 80% were covered (either dominated or equal) by solutions generated using a mutation rate of 1%. Solutions generated using a mutation rate of 5% covered all other rates, suggesting a 5% mutation rate is superior in terms of its ability to identify non-dominated points on the objective space.

Mutation Rate	***S*(*X*')**	***C*(*X*', *X*'')**						
		1%	**5%**	**10%**	**20%**	**40%**	**60%**	**80%**
1%	67218	1.00	0.46	0.66	0.71	0.83	0.93	0.98
5%	67145	1.00	1.00	1.00	1.00	1.00	1.00	1.00
10%	67172	0.16	0.20	1.00	0.68	0.90	0.93	0.97
20%	67335	0.08	0.11	0.14	1.00	0.87	0.91	0.97
40%	69231	0.08	0.11	0.08	0.10	1.00	0.84	0.98
60%	71534	0.07	0.04	0.07	0.06	0.17	1.00	0.98
80%	74105	0.03	0.01	0.05	0.05	0.05	0.05	1.00

Table 4.5: Loaded Log Truck Traffic Regimes, Arranged by Timber Sale, Example #2. For brevity we do not display all routes for all respective input segments (landings), as we do in Table #1. Rather, we display the input segments as well as their common route to the depot. Segments in parentheses indicate different initial routes to the common route. The first node of segment 0 represents the depot, to which the grader must return at the end of each tour.

<u>Timber Sale #1 (200 loads, Pds 1-10):</u>

Input Segments: 8, 54, 55

8 → 6 → 2 → 0

<u>Timber Sale #2 (300 loads, Pds 6-20):</u>

Input Segments: 46, 47, 50

50 → 104 → 101 → 99 → 98 → 16 → 12 → 14 → 11 → 4 → 1 → 0

<u>Timber Sale #3 (300 loads; Pds 4-18):</u>

Input Segments: 140, 139, 138

(130, 138) → 132 → 133 → 134 → 137 → 52 → 51 → 128 → 53 → 7 → 5 → 2 → 0

<u>Timber Sale #4 (300 loads; Pds 2-16):</u>

Input Segments: 84, 85, 88

88→ 90 → 48 → 49 → 93 → 95 → 97 → 98 → 16 → 12 → 14 → 1 → 0

<u>Timber Sale #5 (400 loads; Pds 1-20):</u>

Input Segments: 122, 123, 124

122→ 120 → 119 → 118 → 116 → 112 → 107 → 102 → 96 → 92 → 91 → 49 → 93 → 95 → 97 → 98 → 16 → 12 → 14 → 11 → 4 → 1 → 0

<u>Timber Sale #6 (200 loads; Pds 11-20):</u>

Input Segments: 57, 58, 59

59→ 60 → 61 → 63 → 67 → 76 → 79 → 80 → 81 → 89 → 90 → 48 →49 → 93 → 95 → 97 → 98 → 16 → 12 → 14 → 11 → 4 → 1 → 0

Table 4.6: Size of the space covered (S) and coverage of two sets (C) for various mutation rates, Example #2. Here a mutation rate of 10% is clearly dominant, as it spans the largest region of the objective space (S), and completely covers frontiers generated using other mutation rates (C). Higher mutation rates performed better in Example #2 than in Example #1, suggesting a positive association between mutation rate and problem size.

Mutation Rate	***S*(*X'*)**	***C*(*X'*, *X''*)**				
		1%	**5%**	**10%**	**20%**	**40%**
1%	822689	1.00	0.44	0.21	0.18	0.52
5%	826815	0.25	1.00	0.19	0.15	0.42
10%	827039	1.00	1.00	1.00	1.00	1.00
20%	825731	0.50	0.38	0.26	1.00	0.66
40%	817132	0.13	0.28	0.19	0.08	1.00

Appendix 4.1: Listing of input segment-level input data for Example #2, Oregon State Research Forest planning example. For brevity data is presented in comma-delimited format. Data is presented according to the format: segment ID, node 1, node 2, distance, and cumulative traffic in periods 1-20.

```
0,0,1,1536.16713,99,149,149,198,198,248,248,248,248,248,248,248,248,248,248,248,198,198,149,149
1,1,2,1094.55235,50,99,99,99,99,149,149,149,149,149,198,198,198,198,198,198,149,149,149,149
2,1,3,224.89367,50,50,50,99,99,99,99,99,99,99,50,50,50,50,50,50,50,50,0,0
3,2,6,157.18054,50,99,99,99,99,149,149,149,149,149,198,198,198,198,198,198,149,149,149,149
4,3,4,2469.21762,0,0,0,50,50,50,50,50,50,50,50,50,50,50,50,50,50,50,0,0
5,3,5,668.45786,50,50,50,50,50,50,50,50,50,50,0,0,0,0,0,0,0,0,0,0
6,4,38,410.2114,0,0,0,50,50,50,50,50,50,50,50,50,50,50,50,50,50,50,0,0
7,5,39,291.70943,50,50,50,50,50,50,50,50,50,50,0,0,0,0,0,0,0,0,0,0
8,6,98,8.97443,50,99,99,99,99,149,149,149,149,149,198,198,198,198,198,198,149,149,149,149
9,7,8,1889.44167,50,99,99,99,99,149,149,149,149,149,198,198,198,198,198,198,149,149,149,149
10,7,98,1164.84609,50,99,99,99,99,149,149,149,149,149,198,198,198,198,198,198,149,149,149,149
11,8,80,2333.61589,50,99,99,99,99,149,149,149,149,149,198,198,198,198,198,198,149,149,149,149
12,32,33,903.26212,0,0,0,0,0,50,50,50,50,50,0,0,0,0,0,0,0,0,0,0
13,33,36,49.97247,0,0,0,0,0,50,50,50,50,50,50,50,50,50,50,0,0,0,0,0
14,35,71,1557.58417,0,50,50,50,50,50,50,50,50,50,99,99,99,99,99,99,50,50,50,50
15,35,73,207.20167,50,99,99,99,99,99,99,99,99,99,149,149,149,149,149,149,99,99,99,99
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17,37,112,2288.80415,0,0,0,50,50,50,50,50,50,50,50,50,50,50,50,50,50,50,0,0
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23,44,45,38.28541,0,0,0,0,0,0,0,0,0,0,50,50,50,50,50,50,50,50,0,0
24,45,46,1417.03203,0,0,0,0,0,0,0,0,0,0,50,50,50,50,50,50,50,50,50,50
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26,47,48,7.8559,0,0,0,0,0,0,0,0,0,0,50,50,50,50,50,50,50,50,50,50
27,48,51,210.49096,0,0,0,0,0,0,0,0,0,0,50,50,50,50,50,50,50,50,50,50
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```
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31,61,62,410.37684,0,0,0,0,0,0,0,0,0,0,50,50,50,50,50,50,50,50,50,50
32,62,69,2697.1344,0,0,0,0,0,0,0,0,0,0,50,50,50,50,50,50,50,50,50,50
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39,72,76,5820.27941,50,50,50,50,50,50,50,50,50,50,50,50,50,50,50,50,50,50,50,50
40,73,75,2310.62351,50,99,99,99,99,99,99,99,99,99,149,149,149,149,149,149,99,99,99,99
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42,76,82,975.74585,50,50,50,50,50,50,50,50,50,50,50,50,50,50,50,50,50,50,50,50
43,77,78,375.61719,50,99,99,99,99,99,99,99,99,99,149,149,149,149,149,149,99,99,99,99
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66,125,126,8.67252,0,0,0,50,50,50,50,50,0,0,0,0,0,0,0,0,0,0,0,0
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OPTIMAL POLICIES FOR AGGREGATE RECYCLING FROM DECOMMISSIONED FOREST ROADS

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Environmental Management

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5 Optimal Policies for Aggregate Recycling from Decommissioned Forest Roads

5.1 Abstract

To mitigate the adverse environmental impact of forest roads, especially degradation of endangered salmonid habitat, many public and private land managers in the western United States are actively decommissioning roads where practical and affordable. Road decommissioning is associated with reduced long-term environmental impact. When decommissioning a road it may be possible to recover some aggregate (crushed rock) from the road surface. Aggregate is used on many low volume forest roads to reduce wheel stresses transferred to the subgrade, reduce erosion, reduce maintenance costs, and improve driver comfort. Previous studies have demonstrated the potential for aggregate to be recovered and used elsewhere on the road network, at a reduced cost compared to purchasing aggregate from a quarry. This paper investigates the potential for aggregate recycling to provide an economic incentive to decommission additional roads by reducing transport distance and aggregate procurement costs for other actively used roads. Decommissioning additional roads may in turn result in improved aquatic habitat. We present real-world examples of aggregate recycling and discuss the advantages of doing so. Further, we present mixed integer formulations to determine optimal levels of aggregate recycling under economic and environmental objectives. Tested on an example road network, incorporation of aggregate recycling demonstrates substantial cost-savings relative to a baseline scenario without recycling, increasing the likelihood of road decommissioning and reduced habitat degradation. We find that

aggregate recycling can result in up to 24% in cost savings (economic objective) and up to 890% in additional length of roads decommissioned (environmental objective).

5.2 Introduction

Public and private land managers in the western United States are increasingly removing forest roads to mitigate negative environmental impacts associated with the presence of roads on the landscape. The USDA Forest Service's Road Management Policy, for instance, states the agency's intent to "reverse adverse ecological impacts associated with roads" by, in part, "decommissioning unnecessary and unclassified roads." (USDA 2001) Other federal agencies have also sought to decommission roads for ecological reasons, such as the USDI National Park Service within Redwood National Park in 1978 (Madej 2001). Some private land managers are seeking to remove roads to restore ecosystems, such as the Nature Conservancy's Ellsworth Creek project (Tom Kollasch, project manager, personal communication). Though roads provide many benefits such as access for timber extraction, fire prevention, recreation and research, roads can also adversely influence hydrology, geomorphology, and ecosystem processes (Switalski et al. 2004). Road decommissioning has been identified as a pro-active mechanism for preventing future habitat degradation and increasing the likelihood of endangered salmonid survival (Harr and Nichols 1993).

Forest roads are associated with accelerated erosion and can be a major source of sediment delivery to streams, which can degrade aquatic ecosystems (Jones et al. 2000; Lugo and Gucinski 2000; Forman and Alexander 1998). Chronic erosion contributes fine sediment and is generated by surface erosion processes along the road prism (Reid and Dunne, 1984). Episodic erosion occurs in the form of mass-wasting and fluvial erosion due to culvert failures and is often triggered by intense rain events (Reid and Dunne, 1984). Roads have been found to contribute as much as 40% of the total erosion associated with forest management activities (Gucinski et al. 2001) and are responsible for the majority of episodic erosion events such as hillslope failures in steep forested areas subject to logging (Furniss et al. 1991). Elevated levels of in-stream sediment can negatively affect salmonids through mortality, reduced growth rates, disruption of egg and larvae development, and reduction in available food (Newcombe and MacDonald 1991; Hicks et al. 1991). Degradation of aquatic habitat is of special concern in the western United States where endangered salmonid species spawn and rear in watersheds containing potentially erosive forest roads.

Appropriate road management can mitigate the environmental impact of the road system by limiting chronic erosion and reducing the risk associated with large-scale episodic events (Weaver and Hagans 1999). Roads no longer required for transportation can be closed and/or decommissioned. High maintenance needs or high levels of environmental damage are also reasons to decommission a road. Closing a road frequently consists of barricading or gating the road to prevent unauthorized use, particularly during wet seasons, outsloping the surface and installing rolling dips and/or waterbars, and may involve removing some high-risk culverts. A closed road can be re-opened for future use or later decommissioned, and generally requires only periodic inspection. Decommissioning a road may involve removing culverts under significant fills, ripping the roadbed, recontouring hillslopes, and may include planting or seeding the road surface. A decommissioned road is not passable and requires no future maintenance. A common goal of decommissioning is to restore the natural hydrologic processes and prevent future sedimentation; a decommissioned road has lower longer-term environmental impacts than a closed road due to significantly reduced risk of chronic and episodic erosion (Switalski et al. 2004; Kolka et al. 2004; Madej 2001; Trombulak et al. 2000; Weaver and Hagans 1999; Harr and Nichols 1993).

Unfortunately decommissioning costs can be high and that may prevent desirable projects from being undertaken. This is especially true with federal agencies such as the USDA Forest Service, which has a minimal road maintenance budget due in large part to substantial reductions in their timber sale program. Forest road networks under federal ownership are often characterized by sub-standard conditions. As of 2002 less than twenty percent of national forest roads were maintained to planned safety and environmental standards (USDA 2002). A recent report from the Pinchot Institute for Conservation found that four of five case study national forests (Allegheny (PA), Chequamegon-Nicolet (WI), Fremont-Winema (OR) and Mt. Hood (OR)) had a backlog of road maintenance and decommission needs, stating that there were "…some or, in other cases, numerous inadequately maintained roads, many of which are no longer needed for land management." (Sample et al. 2007, p. 68) The report recommended that national forests complete roads analyses to determine essential transportation networks and to identify surplus roads that can be decommissioned. Efficient planning and implementation is therefore crucial to achieve restoration objectives in this resource-constrained environment.

Road decommissioning decisions are complex and influenced by a variety of factors, such as road location, sediment delivery risk, and available resources. Often only a few “problem” roads produce the majority of the sediment, and it therefore may be efficient to direct efforts towards those roads first (Luce and Black 1999). Weaver and Hagans (1999) contend that it is rarely cost-effective to undertake a decommission project without first evaluating its relative importance to overall watershed condition. Similarly, Luce et al. (2001) state that road removal efforts must be prioritized, and argue that management criteria should include economic and social concerns. Lugo and Gucinski (2000) agree that decommissioning decisions should not be made based upon ecological criteria alone, and caution that in some cases the environmental disruption from decommissioning may be less desirable than leaving the road to reach some level of stability. Anderson et al. (2006) point out that decommissioning decisions involve weighing the relative risks of road failure, limited access for fire suppression, and limited access for future market opportunities. Managers are thus faced with the difficult task to develop efficient road management strategies that satisfy economic, ecological and social goals, subject to legal and practical realities.

In such planning environments, decision aids can and have been used to facilitate decision-making. For instance, federal land management agencies in the Pacific Northwest used the Ecosystem Management Decision Support (EMDS[3]) system to

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[3] http://www.institute.redlands.edu/emds/

characterize the ecological condition and help prioritize restoration of watersheds and aquatic ecosystems on public land (Reeves et al. 2006). To date, monitoring results indicate that watershed condition is being improved, in part, through road removal (Reeves et al. 2006). Watersheds with the greatest assessed improvement had relatively extensive road removal programs (Gallo et al. 2005), and a majority of the funding to date has been allocated for road-related treatments (Heller 2002). Girvetz and Shilling (2003) used EMDS to analyze the Tahoe National Forest road system for potential environmental impacts according to the USDA Forest Service's "Roads Analysis" guidance document (USDA 1999). Roads with greater potential to cause environmental damage were assigned higher scores and these scores were used to negatively weight roads for a least-cost network analysis. The authors found that over 50% of the total road length, and 40% of aggregate road length, could be removed while ensuring access to critical points in the road network. Relevant characteristics of the road network included in the analysis were the number of stream crossings, distance from the road to a stream, position of the road on a slope, slope steepness, soil erodibility, and road surface type.

In other applications, researchers have based road removal decisions on economic or sediment-related objectives. Anderson et al. (2006) used dynamic programming to determine optimal road class and deactivation strategies, but did not include environmental considerations in the formulation. Thompson and Tomberlin (2005) applied stochastic dynamic programming to minimize the cost of erosion control on an unused logging road in the Caspar Creek watershed in northern California (also see Tomberlin et al. 2002), where the decisions included whether to maintain, upgrade, or decommission the road. Allison et al. (2004) applied a decision analysis framework to generate a ranking of the expected benefits of proposed deactivation strategies for forest roads in steep terrain, where benefits were expressed in terms of avoided damages from road-related slope failures. Bettinger et al. (1998) used a tabu search metaheuristic procedure to schedule harvest and road activities with sediment production constraints to achieve aquatic habitat goals. Madej et al. (2006) and Eschenbach et al. (2005) employed dynamic programming and a genetic algorithm to maximize the sediment saved from entering stream channels as a result of applying various road removal treatments in the Lost Man Creek Basin in Redwood National Park.

5.3 Aggregate Recovery and Reuse

Aggregate (crushed rock) is often placed on low volume forestry roads to reduce wheel load stresses to the subgrade, reduce chronic erosion from the roadbed, reduce maintenance costs, and improve driver comfort. Aggregate surfaced roads generally produce significantly less sediment than native-surfaced (dirt) roads, and enable operations to continue during the wet season in areas with high precipitation, such as western Oregon and Washington. Over time aggregate degrades or is lost from the roadway and no longer functions as intended, so that aggregate must be reapplied, with associated maintenance costs. Demand for aggregate also stems from road upgrading and construction.

Although aggregate is typically procured from a local pit or quarry, existing forest roads can also be sources of aggregate. It is often possible to recover aggregate from the road surface during decommissioning. Depending on quality and intended use, the recovered aggregate can be used interchangeably with new rock, or screened, or mixed with fresh aggregate. Sessions et al. (2006) discuss rock recycling for timber production scenarios where mixing with fresh aggregate is necessary. The rock may also be washed to remove silt, clay, or leftover vegetative matter. Unprocessed, screened recycled rock can be used for a base layer on construction projects or as a surface layer for roads reserved for timber haul. If the recovered rock is of sufficient quality it could be processed (crushed) for use as a surface layer on roads serving public traffic. Quarries are commonly the source for higher quality aggregate with smaller particle sizes for use as a surface layer, whereas local borrow pits, if available, are more generally used to obtain aggregate for the base layer.

The presence of geotextiles can increase the percentage of aggregate recovery. Geotextiles are used to prevent contamination of the base layer by the subgrade material, but they can also increase recovery rates. Forward-looking managers seeking to keep the option to recover aggregate in the future may opt to construct new roads using geotextiles.

Opportunities for recovery from forest roads are site specific. On private ownerships where road construction and reconstruction is common, there is likely high potential for recovery and reuse of aggregate material, especially if managers opt to use geotextiles. On public land opportunities may be more limited. In some wet areas vegetation can grow to cover the road template, effectively preventing recovery, and in some dry locations aggregate placed for erosion control is applied thinly and provides a minimal amount to recover (Tom Erkert, Group Leader, Transportation Planning, Operations and Maintenance, USFS Pacific Northwest Region, personal communication). Limited use and maintenance, however, keep many suitable roads free of vegetation. For example, many forest roads in the Pacific Northwest considered for decommissioning generally have 15-30 cm of aggregate depth available for recovery (Mark Truebe, Assistant Forest Engineer, Willamette National Forest, personal communication).

The quality of aggregate available to be recovered is another important variable. Foltz and Truebe (2003) tested a variety of aggregates available from local sources in the Pacific Northwest, including alluvial surfacing material recovered from forest roads in the Willamette National Forest in Oregon. The recycled surfacing was consistent with fresh aggregates in terms of runoff volume and sediment production from simulated rainfall, but produced above average rut depths in response to simulated passes from a logging truck. Overall the recycled aggregate was within the range of variability of the eighteen aggregates tested. Notably, the recovered aggregate had been “in place” for at least 20 years, suggesting that aggregate from legacy forest roads can still provide utility if recovered. This is significant as on many national forests roads now being decommissioned were constructed many years ago.

Recovered aggregate can be delivered to other roads for concurrent maintenance or construction projects, with associated recovery and delivery costs. Alternatively, aggregate required for maintenance or construction can be obtained from either local pits or quarries with associated procurement and delivery costs. Re-use of the recovered aggregate within the forest road network may significantly reduce rock transport distance, especially when quarries are far away. Delivery costs (vehicle costs and associated road wear costs associated with delivery of aggregate) vary depending upon vehicle type, speed, and surface type (paved or aggregate roads.) As we will demonstrate, there are opportunities for significant cost savings even for small-scale projects, and these savings can be expected to increase as fuel costs rise.

The option to recycle aggregate therefore presents an opportunity to offset decommissioning costs, wherein the recovered aggregate can provide a lower cost alternative for road construction or maintenance projects. This suggests federal land management agencies, and others, could perform more road management projects at a particular budget, in theory decommissioning additional roads and improving aquatic habitat.

5.4 Applications of Aggregate Recycling

Numerous aggregate recycling projects have been implemented on publicly and privately owned lands throughout the western United States. On the Umpqua National Forest in Oregon, for example, 2300 m^3 were recovered and stockpiled for re-use from a road decommissioned in 2003 at a cost of \$5.35/m^3. Four years later 230 m^3 were recovered from a short spur road and stockpiled at a cost of \$6.90/m^3, with the cost increase largely attributable to increased fuel costs (Michael Karr, Work Supervisor, Road Maintenance and Project Team, Umpqua National Forest, personal communication). The Umpqua National Forest is actively pursuing future opportunities to salvage rock from decommissioning projects in the future. Industrial owners, such as

Plum Creek, the largest forestland owner in the United States, while not decommissioning many roads, are experimenting with aggregate recovery because of the high cost of transporting quarry rock long distances.

Sessions et al. (2006) described two recovery operations by the Oregon Department of Forestry. After the Vesper No. 2 Timber Sale in 1989, aggregate was recovered from spur roads that had been constructed using geotextiles. A grader made consecutive passes gradually lifting the aggregate from the fabric, and windrowed the material to be picked up by a front-end loader. The rock was then loaded into dump trucks and transported for use as a base layer on a collector road being constructed nearby. In 2003 the Cow Creek mainline road was relocated from a stream to a ridge top, and aggregate recovered during the decommissioning process was used as a base layer for the new mainline. In that case a hydraulic excavator with a ditching bucket lifted the rock from the road surface and loaded dump trucks and off-road trucks. In both cases estimates for recovery reached as high as 90%, and minimal processing was required.

We now describe in greater detail an aggregate recycling application by the Washington Department of Natural Resources (WADNR). In particular we examine the road plan for the Highway Alder Timber Sale, which occurred in the winter of 2007, using data provided by Jennie Cornell, Straits District Engineer. Our intent is to illustrate the cost-savings potential of aggregate recovery and reuse.

The WADNR road plan included reclamation of rock from four decommissioned roads to serve as base layer for maintenance and construction projects. Specifically the project called for “medium abandonment”, which consisted of: 1) reclaiming base layer and surfacing to within 3 cm of the geotextile fabric and endhauling to a stockpile; 2) constructing non-drivable water bars at a maximum spacing of 30 m; 3) removing all culverts; 4) ripping road and landing surfaces to a minimum depth of 46 cm; 5) seeding and mulching; and 6) constructing tank traps. All abandoned roads had been constructed using geotextiles, and new spurs were also constructed using geotextiles, presumably preventing contamination and improving recovery rates. Hereafter for consistency we refer to abandonment as decommissioning.

Table 1 presents the unit costs for procuring aggregate from the various sources (abandoned/decommissioned roads, pit, and quarry). Had spur roads not been slated for decommissioning or had WADNR not pursued recycling, base rock could alternatively have been procured from a borrow pit located 18 km away. Aggregate for surfacing was purchased from a commercial quarry located 41 km away. Recovered aggregate on the other hand was brought to a nearby stockpile (< 2 km), greatly reducing transport cost. Table 1 demonstrates the potential substantial cost savings from reuse of aggregate recovered from decommissioned roads.

Table 2 describes the maintenance and construction projects, their respective needs for aggregate, and total aggregate-related costs. The table also presents costs for a contrasting hypothetical scenario wherein no recycling is permitted and aggregate must be procured from the local pit. In total, using recovered aggregate was $19,232 less than the hypothetical alternative of using the local borrow pit. The total amount of aggregate recovered from the decommissioned roads was 1988 m^3, which supplied all the necessary aggregate. We exclude surfacing needs as the suitability of the recovered aggregate for processing is unknown, and because in this case surfacing was procured solely from the quarry. If fuel costs continue to rise, recycling aggregate, and possibly processing for use as surfacing where appropriate, will become increasingly attractive options.

Our understanding is that most projects have been planned on a case-by-case basis. We propose that more comprehensive analyses might yield opportunities for increased efficiency, resulting in improved transportation systems with less negative environmental impacts. In the next section we present tactical planning frameworks to generate optimal policies for aggregate recovery and reuse.

5.5 Optimal Aggregate Management Policies

In practice, managers often make decisions regarding road removal treatments according to some set of decision rules. Some may, as a policy, seek to minimize total costs by treating as few roads as practicable. Other managers may seek to treat the greatest length of road for a given budget, a common policy among public managers in the western United States (Madej et al. 2006). In this paper we present two mixed integer formulations representative of general policies a transportation manager may follow: to minimize costs and maximize environmental benefits.

Here we consider two road treatments, (a) closure and (b) decommissioning, with the expectation that decommissioning entails significantly greater environmental benefits. We assume an experienced professional has identified which road segments require removal, and that the decision variable is whether to close or decommission a particular road segment. If a road is decommissioned, the aggregate can be recovered and used for other scheduled maintenance and construction projects.

Previous mathematical formulations regarding aggregate management include Kirby and Lowe (1975) and Sessions et al. (2006). Kirby and Lowe (1975) presented a model to schedule the opening/closing of pits and assign roads to pits in order to minimize the discounted sum of manufacturing, transport and fixed costs. Their model is an integer formulation with multiple pits, roads and planning periods. Sessions et al. (2006) presented a tactical planning model that maximizes net present value of timber harvest less crushed aggregate costs, where the decision variables are when to harvest a unit and from where to procure aggregate for spur roads, which can come from either a pit or previously used spur roads. Our models build on previous work, broadening the context to watershed restoration with environmental objectives, and including road removal treatment as a decision variable.

Model I: Minimize Costs

The first model seeks to minimize the discounted costs of the sum of treatment costs for roads that have been identified for removal, plus the cost of aggregate procurement and delivery costs for roads that are to be maintained or constructed on the road network (Equation 1).

Minimize:

$$\sum_i \sum_j \sum_t p_t c_{ijt} X_{ijt} + \sum_s \sum_j \sum_t p_t g_{sjt} Y_{sjt} + \sum_i \sum_k \sum_t p_t h_{ikt} Z_{ikt} \tag{1}$$

Subject to:

$$\sum_i X_{ijt} + \sum_s Y_{sjt} = D_{jt} \qquad \forall\, j,t \qquad (2)$$

$$\sum_j X_{ijt} \le \sum_k rf_{ikt} A_{it} Z_{ikt} \qquad \forall\, i,t \qquad (3)$$

$$\sum_k Z_{ikt} = 1 \qquad \forall\, i,t \qquad (4)$$

$$Z_{ikt} \in \{0,1\} \qquad \forall\, i,k,t \qquad (5)$$

where p_t = present net value factor for period *t*, dimensionless; X_{ijt} = aggregate recovered from road *i* and delivered to road *j* in period *t*, m^3; Y_{sjt} = aggregate taken from source *s* (pit or quarry) and delivered to road *j* in period *t*, m^3; Z_{ikt} = 1 if road *i* is removed at treatment level *k* in period *t*, 0 otherwise; c_{ijt} = cost to recover aggregate from road *i* and deliver to road *j* in period *t*, \$/ m^3; g_{sjt} = cost to procure aggregate from source *s* and deliver to road *j* in period *t*, \$/ m^3; h_{ikt} = cost to remove road *i* at treatment level *k* in period *t*, \$; A_{it} = aggregate available for recovery from road *i* in period *t*, m^3; D_{jt} = aggregate required for road *j* in period *t*, m^3; and rf_{ikt} = aggregate recovery factor for road *i* removed at treatment level *k* in period *t*, m^3/m^3. Implicit in our formulation is that the subscript *i* is indexed over only the set of roads slated for removal, rather than all road segments. Likewise, *j* is indexed over the set of all roads requiring aggregate for construction or maintenance, *k* the set of possible treatments, *s* the set of possible sources, and *t* the periods in the planning horizon.

Equation 2 specifies that demand for aggregate be met from decommissioned roads and/or quarries. Equation 3 specifies the upper limit on aggregate able to be recovered in a given period, conditional on the level of treatment (if any) in that period;

in our framework the recovery factor is set to zero for closure. Equation 4 ensures that all roads scheduled for removal must be assigned to either closure or decommissioning. Equation 5 declares that the removal treatment variables are binary (0/1).

Intuitively the best answer would seem to be assigning all appropriate road segments to closure, which minimizes costs, but may not provide as large an environmental benefit. However, recycling aggregate may be the superior option, given reduced transport costs and avoidance of aggregate purchase costs. As procurement and delivery costs for quarry aggregate rise, this model will likely schedule additional roads to be decommissioned. Thus, although not specifically represented in the objective function, the economics of the situation may induce a manager to decommission more roads, thereby providing ecological benefits over the alternative of merely closing a road to remove it from the transportation network.

Model I is readily extendible to situations involving road construction and the decision of whether to use geotextiles. Constructing temporary roads using geotextiles may substantially improve aggregate recovery rates, although incurring a higher upfront cost (Sessions et al. 2006). The example applications we presented demonstrated that some landowners, in this case state agencies, have and continue to utilize geotextiles. In such scenarios the objective function becomes Equation 6. Additional constraints are necessary to ensure appropriate aggregate recovery rates are used conditional on whether a road was constructed with geotextiles, and to ensure the geotextile decision remains binary. If the planning horizon extends through the time period in which a constructed road is decommissioned, Equation 6 implicitly captures the economic benefits associated with use of geotextiles.

Minimize:

$$\sum_i \sum_j \sum_t p_t c_{ijt} X_{ijt} + \sum_s \sum_j \sum_t p_t g_{sjt} Y_{sjt} + \sum_i \sum_k \sum_t p_t h_{ikt} Z_{ikt} + \sum_{j \in CJ} \sum_t p_t m_{jt} W_{jt} \qquad (6)$$

where $W_{jt} = 1$ if geotextiles are used in the construction of road j in period t, 0 otherwise; m_{jt} = cost to purchase and install geotextiles for road j; and CJ the subset of roads requiring aggregate that are scheduled to be constructed.

Model II: Maximize Environmental Benefit

The second model seeks to maximize the hazard-weighted length of roads decommissioned, as a proxy for environmental benefit (Equation 7). To account for differences between road segments, we can define α_i to be the hazard rating for road segment i, perhaps identified using EMDS or some other decision aid. This method is similar to that employed by Girvetz and Shilling (2003), who assigned a score to each segment based upon its likely environmental impact and then maximized the hazard-weighted length of roads decommissioned. Another possible method is that employed by Madej et al. (2006), who estimated expected erosion and delivery from sediment estimates by segment rather than by length.

Maximize:

$$\sum_i \sum_k \sum_t \alpha_i l_i Z_{ikt} \qquad (7)$$

Subject to:

$$\sum_{i}\sum_{j} c_{ijt} X_{ijt} + \sum_{s}\sum_{j} g_{sjt} Y_{sjt} + \sum_{i}\sum_{k} h_{ikt} Z_{ikt} \leq b_t \qquad \forall\, t \qquad (8)$$

where l_i = length of road segment i; b_t = budget in period t; and all other variables and parameters are as defined above.

Equation 8 ensures that the total costs of road closure, decommissioning, and aggregate procurement and delivery do not exceed periodic budgets. Additional constraints are identical to Equations 2-5 in the first model.

5.6 Example Application

We examine four scenarios in total, wherein we solve our two models with and without the option to recycle aggregate. We expect that in the first (minimize cost) model, recycling aggregate will reduce overall total cost, while still decommissioning more roads than would occur under a scenario where recycling does not occur. In the second (maximize environmental benefit) model we expect that a greater length of roads will be decommissioned. In general we hypothesize that considering recovery and reuse as a decision variable in tactical transportation planning with environmental objectives will lead to more efficient and effective restoration policies.

We present a two period hypothetical planning example using the transportation network of the South Zone of the McDonald-Dunn Research Forest, managed by the College of Forestry, Oregon State University. The South Zone spans 1910 hectares and encompasses 72 kilometers of unpaved forest roads. Roads within this zone are managed for a variety of uses, including access for teaching, research, demonstration, recreation, and timber transport. Although the opportunity to recover aggregate has been discussed in the past, the Forest has not yet pursued any recovery projects. Aggregate can be purchased from a quarry located ~18 km north of the Forest, and there are no working pits in the forest due to low rock quality (Dave Young, Roads and Trails Specialist, OSU College Forests). Alternatively, we assume, aggregate may be recovered from decommissioned spur roads.

Figure 1 displays the South Zone's road network and identifies the project types considered. In our example, 7 road segments require removal (0.21, 0.35, 0.39, 0.59, 0.73, 0.84, and 2.42 km), 5 segments require construction (0.21, 0.28, 0.63, 0.90, and 2.34 km), and 2 require maintenance (0.75 and 3.20 km). The roads in need of maintenance are a connector (Rd. 660) and mainline (Rd. 600) that serve public traffic, meaning if recovered aggregate is to be used as a surface course it must first be processed. A portable rock crusher is used for the processing requirements. The segments to be constructed are low-standard roads reserved for timber transport, and thus require no processing of recovered aggregate beyond screening. For now we exclude the option to construct using geotextiles and therefore do not consider the extension to Model I (Equation 6). While maintenance on a road can take a variety of forms, we limit our discussion here to re-surfacing, and assume that recovered aggregate can be used interchangeably with quarry aggregate.

In this model we assume that all road segments slated for removal are equally detrimental, and therefore the optimal treatment from an environmental perspective is simply a function of length. In other words, we set the hazard rating (α) to one for each road segment. This assumption is reasonable if we also assume an experienced professional has identified appropriate levels of decommissioning such that the expected future impacts per unit length from each segment are nearly identical.

Tables 3-6 provide input data used for the models. Table 3 presents the aggregate required for maintenance and construction projects (D_{jt}), and Table 4 presents the aggregate available for recovery (A_{it}) from the roads slated for removal along with removal costs (h_{ikt}). Note that different segments of Road 660 are slated for removal and maintenance. Aggregate quantity for maintenance purposes was estimated assuming 15 cm of re-surfacing was required along the length of the road, with connector roads and mainlines having a width of 4.3 m and 4.9 m, respectively. Aggregate quantity on spur roads was estimated assuming a surface width of 3.7 m and a road depth of 25 cm.

Table 5 presents costs for aggregate purchase, recovery, and processing, estimated from Sessions et al. (2006). Recovered aggregate used as a base layer (recovery + screening) costs \$2.65/m^3, whereas aggregate to be used as a surface layer costs \$5.70/m^3 (recovery + screening + crushing), exclusive of transport costs. Delivery costs were estimated to be \$0.35/m^3-km (Sessions et al. 2006). We used a real discount rate of 4% and values of 70% and 90% for the aggregate recovery factor (rf_{ikt}), where the higher value is roughly representative of situations where geotextiles are present. Table 6 presents estimated procurement, processing and delivery costs (\$ / m^3) for aggregate (g_{sjt}). For simplicity we based all costs on "in place" cubic meters, although in practice transport costs are expected to be slightly higher because the volume of rock is about 30% larger prior to compaction on the road surface.

For road removal costs, we obtained values from Weaver and Hagans (2007). Closure costs may vary greatly depending upon the intensity of management and road specific conditions. We estimated $7500/km, assuming closure is defined as filling ditches and outsloping the road surface. Likewise, decommissioning costs may vary; the estimates from (Weaver and Hagans 2007) range from $1,200 to $32,000/km depending upon road type and complexity of decommissioning. For this example we used a range of values from $10,000/km - $25,000/km in $5000 intervals. Table 4 presents removal costs assuming an intermediate value of $20,000/km. We felt it was sufficient to only vary decommissioning costs for sensitivity analysis because it is largely the relative cost difference between the treatments that drives the decision to pursue one treatment over another.

To arrive at appropriate annual budgets for the benefit maximization objective we calculated total expenditures excluding the option to recycle. The budgets were $95,000 and $115,000 for periods 1 and 2, respectively.

All models were solved to optimality using What'sBest 8.0, a spreadsheet optimization tool that is an add-in for Microsoft Excel, provided by Lindo Systems, Inc.

5.7 Results

Tables 7 and 8 present the results of the McDonald Dunn South Zone planning example. The baseline, no recycling, cost minimization scenario resulted in a total discounted cost of $198,413, with no road segments scheduled to be decommissioned. Allowing the model to assign segments for decommissioning and to recycle the aggregate provided for cost savings and additional environmental benefit, as measured by length of roads decommissioned. In the best case scenario ($10,000/km decommissioning cost, 90% recovery rate), the model decommissions all roads requiring removal, for an overall cost reduction of over $47,000, or 24%. Clearly this is a preferable outcome over the baseline. Including recycling as a decision variable generally yields improvements in terms of economic and ecologic objectives.

Table 7 presents the results of our different cost-minimization scenarios, which vary by aggregate recovery rate and decommissioning cost; all results use a closure cost of $7,500/km. At low decommissioning costs (relative to closure costs) the model schedules all or most roads to be decommissioned in order to take advantage of the additional cost savings from using recovered versus quarry-purchased aggregate (see Table 6). At the same decommissioning cost, a higher recovery rate provides for cost savings and additional roads decommissioned. This finding, which was expected, could be viewed as an incentive to use geotextiles in construction.

Baseline results for the environmental benefit maximization scenario vary with decommissioning cost. At $10,000/km, the model schedules 1.79 km for decommissioning at a total cost of $202,803. Total benefits and costs are (0.56 km, $202,609), (0.35 km, $202,741), and (0.35 km, $204,473) for decommissioning costs of $15,000, $20,000, and $25,000/km, respectively. Including the option to recycle aggregate resulted in increased environmental benefits. Unlike the cost minimization scenario, wherein some results achieved total costs no better than the baseline (i.e., no objective function improvements), here the model always generated improvements in terms of additional kilometers of road slated for decommissioning.

Table 8 presents the results of our environmental benefit maximization scenarios, which vary with recovery rate and decommissioning cost. In some instances costs are greater than the baseline scenario, which makes sense given the objective to decommission a greater length of roads. However, for the most part, decommissioning additional roads also yielded cost savings due to lower aggregate costs. As with the above model, length of roads decommissioned decreases with increasing decommissioning cost. Higher recovery rates lead to substantial improvements both in terms of cost savings as well as total length decommissioned, again providing a possible incentive for use of geotextiles.

For brevity we limit our presentation of detailed results to a single scenario, that in which the objective was to minimize total cost, decommissioning cost was \$15,000/km, and the recovery factor was 70%. In the first period, all roads slated for removal (620, 630, and 660) were decommissioned rather than closed. From road 620, 287 m^3 of recovered aggregate was delivered to road 761. Note this represents the entirety of the aggregate that can be recovered (70% of 410 m^3 is 287 m^3; see Table 4). Recovered aggregate from decommissioned road 630 was delivered to road 761 (116 m^3) and to road 6021 (39 m^3), and recovered aggregate from road 660 was delivered to road 6021 (252 m^3). Aggregate required for maintenance on road 600 came entirely from the quarry, as did the remainder of the aggregate required for roads 660 (518 m^3) and 761 (536 m^3). Although decommissioning these roads resulted in a cost increase of \$7148 over the option to close, cost savings still occurred due to recycling rather than purchasing quarry aggregate. Had aggregate for road 761 been obtained from the quarry instead of from decommissioned roads 620 and 630, procurement and transport costs would have risen to \$8705, an increase of \$5816. Likewise, costs would have increased by \$4892 had aggregate for road 6021 been obtained from the quarry instead of from decommissioned roads 630 and 660. In the first period, then, decommissioning and aggregate recovery resulted in a net cost decrease of \$3560.

In the second period, two roads (762 and 771) were closed, and two were decommissioned (681 and 720). From road 681, 608 m^3 were delivered to road 650. Recovered aggregate from road 720 was delivered to roads 600 (759 m^3), 650 (135 m^3), 800 (654 m^3), and 811 (213 m^3). This arrangement satisfied all aggregate demand for roads 650, 800, and 811, and the remaining 1761 m^3 required by road 600 was obtained from the quarry. Decommissioning roads 681 and 720 increased total removal costs by \$24,392, but recycling rock versus obtaining purely from the quarry saved \$31,951, for a net reduction of \$7559. When discounted, this amounts to a savings of \$7268; summing the savings from periods 1 and 2 results in approximate total savings of \$10,828, which agrees with the value presented in Table 7.

5.8 Discussion

Incorporating aggregate recycling into the decommission process can provide for significant cost savings, effectively subsidizing the decommissioning project. This “subsidy” may pay for additional decommissioning projects or may be re-invested into other road improvement projects. If implemented successfully, public land managers should see improvements in overall mitigation efforts at a given budget. Private owners should also be interested in recycling due to the cost-saving potential and the opportunity to demonstrate responsible stewardship.

We first demonstrated this finding in our Washington Department of Natural Resources case study, where recycling resulted in over $19,000 of savings relative to a hypothetical alternative of using a local borrow pit. Where local pits are not available and more distant quarries must be used, cost savings can be expected to increase. As fuel costs continue to rise, these cost savings are expected to increase. In our McDonald Dunn Research Forest example we showed that cost savings could reach $47,000, which represents a 24% reduction over the no recycling scenario. Maximum savings are achieved in concert with the maximum possible length of roads decommissioned, 5.53 km (Table 7). Compared to the no recycling, cost minimization scenario in which no roads were decommissioned, this obviously represents substantial environmental and economic benefit. Under the no recycling, environmental benefit maximization scenario there is always some length of roads slated for decommissioning, although including the opportunity to recycle can increase benefit by up to 890%, often with the co-benefit of cost savings (Table 8). Again, this emphasizes the point that aggregate recycling may subsidize environmentally beneficial road decommissioning projects.

Haul distance appears to be a primary factor influencing the relative merits of aggregate recycling. In our McDonald Dunn Research Forest example no local pits were available, which highlighted the haul distance differential between quarry-purchased and recovered aggregate. In other circumstances where local rock is available results may be different, though we still expect that aggregate recovery and reuse could be an economical alternative. Of course, this also depends on other factors such as rock quality and intended use; where processing requirements are higher than those presented we would expect the relative merits of aggregate recycling to decrease.

Absent from our models are the ecological costs of not taking action to decommission at-risk roads. As we cite in the introduction, unused forest roads can be a source of both chronic and episodic sediment to fish-bearing streams, with associated adverse impacts to aquatic species. For instance, unmaintained and/or under-maintained culverts may become blocked during high flow events, preventing effective drainage in subsequent storms. When water is redirected over the surface of the road the fill may become saturated and ultimately fail, in some situations releasing massive quantities of sediment down slope (Flanagan et al. 1998). On abandoned, unmaintained roads in the Redwood Creek watershed in northern California, stream-crossing diversions were found to be the leading cause of sediment production (Weaver and Hagans 1999). The potential for future ecological damage is clearly high, especially considering that many legacy roads are located near streams home to threatened and endangered salmonids. Pursuing valuation methods for quantifying the ecological damages however is beyond the scope of this paper.

A more immediate addition to the model, one that could be the subject of future research, is to include expected monetary damages from possible road failure. Thompson and Tomberlin (2005) and Tomberlin et al. (2002) included probability distributions for landslide and stream crossing erosion when calculating expected erosion control costs. Allison et al. (2004) also assigned a risk-weighted cost for damage control after possible road failure. Extending the planning horizon and including discounted expected costs from erosion control after failure may induce a cost-minimization model to schedule more road segments for decommissioning, with associated environmental benefits.

Another possible extension to our work is to consider the cost effectiveness of implementing geotextiles. The tradeoffs are increased construction costs today versus increased recovery rates should aggregate recycling be pursued at some point in the future, and the associated cost savings. Our results indicate that geotextiles offer substantial economic benefit: when the recovery factor raises to 90% from 70% cost savings increased by as much as \$10,000 (Table 7). Whether that cost savings offsets the implementation costs is not an avenue we pursued here however. It may be interesting at the road segment and network scale to relate the costs of implementation today to the benefit of implementation some years into the future. Of course, the benefits that geotextiles provide by preventing contamination of the base layer by the subgrade material should also be considered.

Recycling rock also increases the attractiveness of using reduced tire inflation for aggregate transport. Rock transport vehicles, with heavy wheel loads and rigid suspensions, can be the most damaging to a road surface. Since moving from one road to another will usually involve short distances at low speeds, transport vehicles can run at reduced inflation pressures without needing expensive pressure controls. Reduced tire pressures reduce stresses to the subgrade, impact loadings and rut depth. If the trucks will not be run at highway speeds (i.e. maintained speeds of less than 60 km/hr), the air pressure can be manually reduced for the duration of the recycling project. The advantages of reduced tire inflation pressure are reduced road and truck maintenance needs, and if used during the wet season, reduced sedimentation from forest roads (Brown and Sessions 1999; Foltz and Burroughs 1991).

5.9 Conclusions

We presented a cost minimization model for aggregate recovery and reuse, and demonstrated that use of such a model could result in substantial cost savings to landowners, possibly freeing up resources to implement other restoration-oriented projects. We also presented a model to maximize environmental benefit from road removal, using the total length of roads decommissioned as a proxy. Use of these models with appropriate computer applications constitutes a decision support aid that can be used to facilitate road removal decisions. Our models are general and easily extendable to other formulations, and should scale up to larger planning problems readily given advancements in computing capacity and commercially available solvers.

While several simplifying assumptions were made for expository purposes, the management models presented here have practical applications. Aggregate recycling does occur in practice, as we demonstrated, and the formulation and data can be adjusted accordingly for specific situations. Future research could incorporate a broader road management optimization procedure, including additional removal treatments, maintenance regimes, and the decision of when to remove a road. Further work could also seek to apply an appropriate environmental hazard weighting techniques to maximize the hazard-weighted kilometers of road decommissioned.

We believe this manuscript demonstrates the advantages of recycling aggregate, which are both economic and environmental. Where feasible, transportation managers should investigate opportunities to recover and reuse suitable aggregate, thereby increasing efficiency while yielding environmental benefits. Using models such as we presented here, it should be possible to identify which roads should be treated at a given level and how aggregate sources should be allocated, in order to best achieve landowner objectives.

5.10 Acknowledgements

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Figure 5.1: Road Plan for the South Zone, with project types labeled.

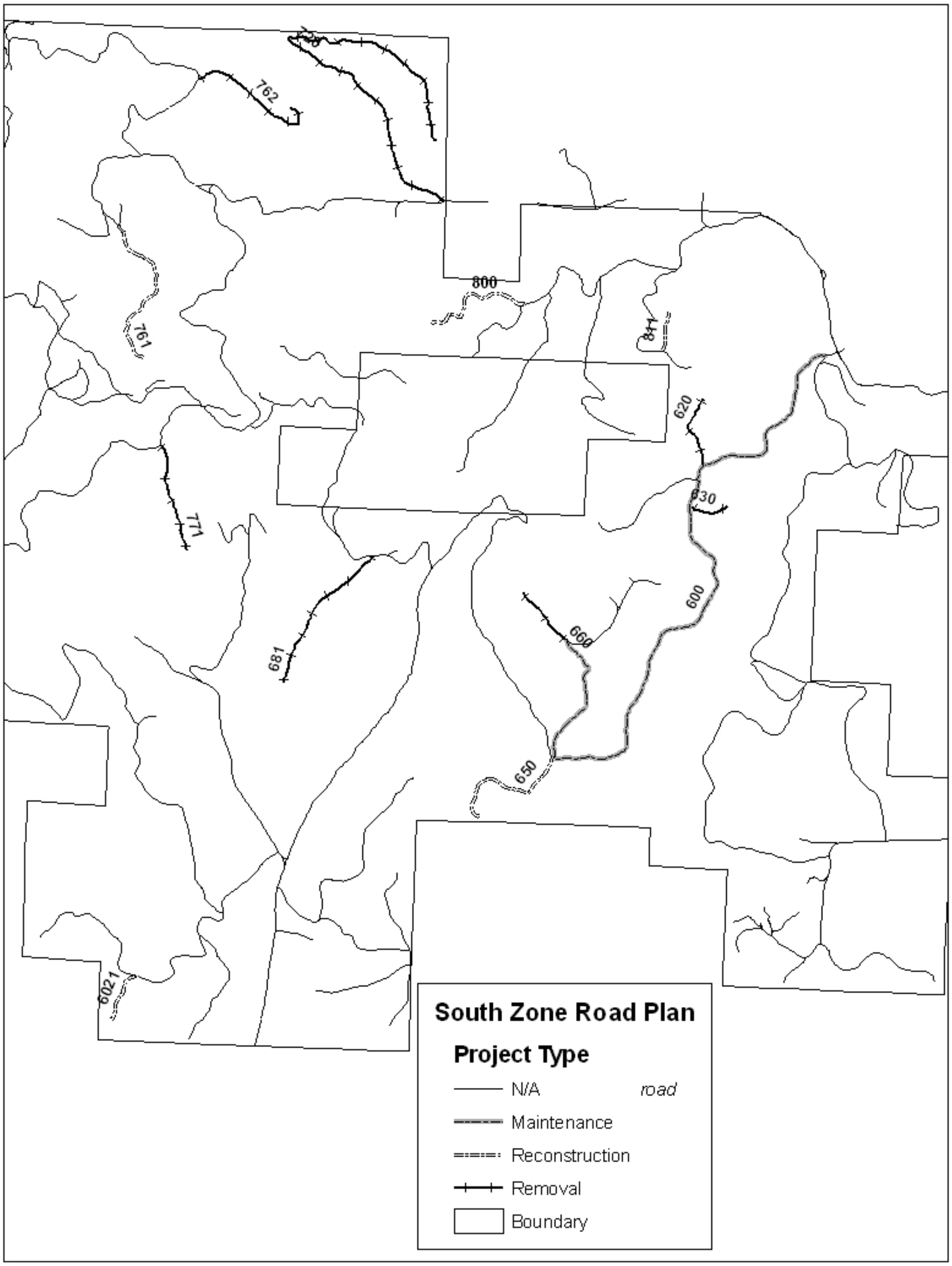

Table 5.1: Unit costs ($ / m^3) for aggregate from decommissioned roads, local borrow pit, and quarry; WADNR example.

Operation / Source	**Decommissioned roads**	**Pit**	**Quarry**
Dig and load	$0.00	$0.57	$0.00
Purchase	$0.00	$0.00	$7.26
Haul	$1.43	$7.14	$8.46
Spread	$0.46	$0.46	$0.46
Compact	$0.52	$0.52	$0.52
Reclamation	$0.57	$0.00	$0.00
Totals	**$2.99**	**$8.69**	**$16.70**

Table 5.2: Total aggregate costs, with and without aggregate recycling, for scheduled maintenance and construction projects in the road plan for the WADNR Highway Alder Timber Sale.

Project Type	Road	Aggregate Demanded (m^3)	Total Aggregate Cost ($)	
			Decommissioned Roads	Local Pit (hypothetical)
Maintenance	PA-S-2500	23	$117	$341
	PA-S-2550	31	$156	$455
Construction	1+17 spur	83	$426	$1,239
	1+40 spur	96	$492	$1,433
	1+44 spur	98	$500	$1,455
	1+60 spur	107	$547	$1,592
	1+70 spur	83	$574	$1,672
	5+00 spur	289	$1,476	$4,298
	12+35 spur	708	$3,616	$10,529
Reconstruction	7+36 spur	422	$2,156	$6,277
Totals		**1969**	**$10,059**	**$29,291**

Table 5.3: Aggregate demanded (D_{jt}) for maintenance and construction projects (m^3), by period for the South Zone example. Maintenance projects require higher quality surfacing rock whereas construction projects require base layer quality.

Project Type	Road	Length (m)	Period	Aggregate Demanded (m^3)
Maintenance	600	3189	1, 2	2520
	660	747	1	518
Construction	650	2343	2	743
	761	902	1	939
	800	628	2	654
	811	205	2	213
	6021	280	1	292
Totals		**6666**		**5879**

Table 5.4: Removal costs (h_{ikt}) and aggregate available (A_{it}) from spurs slated for removal (m^3); South Zone example. Costs presented were calculated using $7500/km for closure and $20000/km for decommissioning.

Road	Removal Period	Length (m)	Aggregate Available (m^3)	Closure Cost ($)	Decommissioning Cost ($)
620	1	393.61	410	$2,952	$7,872
630	1	213.23	222	$1,599	$4,265
660	1	346.27	360	$2,597	$6,925
681	2	835.06	869	$6,263	$16,701
720	2	2,417.22	2,515	$18,129	$48,344
762	2	732.97	763	$5,497	$14,659
771	2	588.47	612	$4,413	$11,769
Totals		**5,526.80**	**5,751**	**$41,451**	**$110,536**

Table 5.5: Unit costs ($ / m^3) for aggregate procured from decommissioned roads and quarry; South Zone example. Aggregate procured from quarries entails purchase costs, whereas aggregate procured from decommissioned roads entails recovery and processing (screening and/or crushing) costs.

Operation / Source	**Decommissioned roads**	**Quarry**
Purchase	$0.00	$5.75
Recovery	$1.15	$0.00
Screening	$1.50	$0.00
Crushing	$3.05	$0.00
Totals	**$2.65 – 5.70**	**$5.75**

Table 5.6: Unit Costs (\$/m^3) for procurement, processing and delivery (g_{sjt}) of aggregate from sources (abandoned roads and quarry) to other road segments in need of aggregate. Maintenance projects have higher processing costs if the source is recovered aggregate.

Aggregate Sources	**Segments Demanding Aggregate**						
	Maintenance		**Construction**				
Decommissioned Roads	**600**	**660**	**650**	**761**	**800**	**811**	**6021**
620	$5.97	$8.00	$4.43	$7.12	$5.41	$5.17	$8.26
630	$5.85	$7.71	$4.14	$7.29	$5.49	$5.25	$7.86
660	$6.46	$5.94	$3.41	$9.15	$7.37	$7.12	$7.13
681	$8.23	$8.23	$5.18	$5.70	$9.04	$8.79	$5.61
720	$7.74	$10.48	$6.91	$5.58	$4.76	$4.52	$10.79
762	$9.45	$12.19	$8.62	$4.07	$6.54	$6.30	$9.71
771	$9.24	$9.76	$6.19	$5.31	$7.35	$7.11	$7.17
Quarry	$18.10	$20.32	$20.32	$21.60	$19.84	$19.59	$24.04

Table 5.7: Cost savings and additional kilometers of road decommissioned over the baseline, cost-minimization scenario; South Zone example.

Recovery Rate	Decommissioning Cost ($ / km)	Cost Savings ($)	Length Decommissioned (km)	Roads Decommissioned
70%	$10,000	$36,430	5.53	All
	$15,000	$10,828	4.21	620, 630, 660, 681, 720
	$20,000	$0.00	0.00	None
	$25,000	$0.00	0.00	None
90%	$10,000	$47,009	5.53	All
	$15,000	$21,108	4.79	620, 630, 660, 681, 720, 771
	$20,000	$2,866	1.79	620, 630, 660, 681
	$25,000	$0.00	0.00	None

Table 5.8: Results for the environmental benefit maximization model; South Zone example. Cost savings and additional decommissioning are presented relative to a scenario where no aggregate recycling is permitted. Values in parentheses in the 4th column represent total length of roads decommissioned.

Recovery Rate	Decommissioning Cost ($ / km)	Cost Savings ($)	Additional Decommissioning (km)	Roads Decommissioned
70%	$10,000	$28,548	3.74 (5.53)	All
	$15,000	$-2,967	4.97 (5.53)	All
	$20,000	$960	1.44 (1.79)	620, 630, 660, 681
	$25,000	$2,282	0.26 (0.61)	620, 630
90%	$10,000	$33,856	3.74 (5.53)	All
	$15,000	$6,908	4.97 (5.53)	All
	$20,000	$993	3.86 (4.21)	620, 630, 660, 681, 720
	$25,000	$-791	1.20 (1.55)	620, 630, 660, 771

6 Exploring Environmental and Economic Tradeoffs Associated with Aggregate Recycling From Decommissioned Forest Roads

6.1 Abstract

Forest road decommissioning is a pro-active mechanism for preventing future habitat degradation and for increasing the likelihood of endangered salmonid survival in the western U.S. High implementation costs however preclude many desirable projects from being undertaken, especially on federally owned land. Previous research and real-world applications have demonstrated the cost-savings potential of reusing aggregate recovered from forest roads during decommissioning. These cost savings can effectively subsidize decommissioning projects, suggesting an economic benefit associated with improving environmental benefit. We present a mixed-integer, multiple-objective formulation to identify the efficient tradeoff surface between conflicting economic and environmental criteria, where environmental benefit is defined as the hazard weighed length of roads decommissioned. We compare non-dominated frontiers identified with and without the opportunity to recycle aggregate. Our results suggest that aggregate recycling promotes a synergistic relationship between cost-savings (subsidy) and environmental performance, where subsidies generally increase with increasing environmental performance. Effective subsidy values can reach 31% of total expenditure, at the maximum level of environmental benefit. Transportation managers are therefore able to recover and reuse a non-renewable resource, while at the same time promoting economic and environmental efficiency.

6.2 Introduction

Maintenance of high quality, unobstructed habitat is crucial to successful conservation of threatened and endangered salmonids in the Pacific Northwest (GAO 2001). Federal lands in this region managed under the Northwest Forest Plan implement the Aquatic Conservation Strategy (ACS), the intent of which is to restore habitat and prevent further degradation across landscapes (Heller 2002). A major component of the ACS is strategic restoration of entire watersheds (Gallo et al. 2005). As defined by the ACS, watershed restoration is designed to restore critical ecological processes and to recover degraded habitat (Reeves et al. 2006).

Watershed restoration planning should prioritize reducing human-caused habitat degradation and loss (Roper et al. 1997). This entails restoring isolated habitats and improving or decommissioning roads, among other treatments (Roni et al. 2002). The ACS cites preventing road-related runoff and sediment production as two important components of its watershed restoration program (Reeves et al. 2006; USDA and USDI 1994). Monitoring of ACS implementation indicates that the most improved watersheds had relatively extensive road removal programs (Gallo et al. 2005). These road removal programs generally focused on removing roads from riparian areas and areas with high landslide hazard (Reeves et al. 2006). As of 2002, a majority of restoration funding had been allocated for road-related treatments (Heller 2002).

Watershed restoration focuses on forest roads because their presence can substantially and detrimentally alter natural hillslope hydrologic and geomorphic processes. Forest roads intercept rainfall and subsurface flow, concentrate flow on the surface or adjacent ditches, and divert or reroute water from natural flow paths (Gucinski et al. 2001). They also accelerate chronic and episodic erosion processes, alter channel structure and geometry, alter surface flowpaths, and cause interactions of water, sediment and woody debris at engineered stream crossings (Gucinski et al. 2001). In areas with steep slopes, landslides and other mass movements are responsible for the majority of episodic road-related erosion (Furniss et al. 1991). Chronic inputs from road surface erosion can also be a significant source of sediment related input to streams (Gucinski et al. 2001; Reid and Dunne 1984).

Forest roads therefore contribute to accelerated sediment delivery to streams (Jones et al. 2000), which can negatively affect salmonids through mortality, reduced growth rates, disruption of egg and larvae development, and reduction in available food (Newcombe and MacDonald 1991; Hicks et al. 1991). Poorly located or designed stream-crossing culverts on forest roads create barriers to fish passage, which can reduce salmon productivity (Nehlsen et al. 1991). Road decommissioning is a pro-active mechanism for preventing future habitat degradation and for increasing the likelihood of endangered salmonid survival (Harr and Nichols 1993). In this context, the goal of decommissioning is to restore natural hydrologic and geomorphic processes. A decommissioned road is thought to have minimal long-term environmental impacts because the risk of episodic and chronic erosion is significantly reduced (Switalski et al. 2004; Kolka et al. 2004; Madej 2001; Trombulak et al. 2000).

The emphasis on removing forest roads in the ACS is, in part, a reflection of the poor state of many of the transportation networks on federally owned lands. Though the

USDA Forest Service's Road Management Policy (USDA 2001) states the goal of reversing adverse ecological impacts associated with roads, the unfortunate reality is that most roads in the national forest system are chronically under-maintained, with a backlog of necessary improvement and removal needs (Sample et al. 2007; USDA 2002). As of 2002, less than 20% of the roads in the national forest system were maintained to the desired standard (USDA 2001). A report by the Pinchot Institute for Conservation recommended that national forests analyze their road systems to identify surplus roads that can be decommissioned (Sample et al. 2007).

The high cost of decommissioning can preclude adoption of many desirable restoration-oriented projects. Reduced road maintenance budgets due to reduced harvest levels on national forests exacerbate this resource-constrained decision-making environment. Strategic watershed restoration planning on federal lands involves identification of a suite of road treatments that best achieve conflicting economic and environmental criteria. Other ownerships, both public and private, also face tradeoffs when evaluating alternate road management regimes. Thus, research has been directed towards development of appropriate decision support tools to help prioritize watersheds for restoration (e.g., Aquatic Riparian Effectiveness Monitoring Program 2005; Pess et al. 2003), to help identify which roads should be removed (e.g., Allison et al. 2004; Girvetz and Shilling 2003), and to help identify cost-effective allocations of removal treatments (e.g., Thompson and Sessions 2008; Madej et al. 2006). Facilitating identification of efficient resource allocations relating to forest road management thus remains an important avenue of research.

Previous research has demonstrated that reusing aggregate recovered from forest roads during decommissioning may be a low cost alternative to procuring aggregate from other sources (Thompson and Sessions 2008; Sessions et al. 2006). Demand for aggregate stems from road construction and upgrading as well as periodic reapplication due to road surface degradation associated with repeated traffic and weathering. Where recovered aggregate is to be used as a base layer or as a surface layer on roads reserved for timber haul, it may require only screening and/or washing to remove silt, clay and other debris. Processing (crushing) may be required where the aggregate is to be used as a surface layer on roads serving public traffic. More commonly, quarries are the source for higher quality aggregate for surfacing, whereas local borrow pits, if available, can provide aggregate for a base layer. Reusing recovered aggregate within the forest transportation network can significantly reduce transport distance, which in turn can significantly reduce overall costs associated with aggregate procurement and delivery.

The degree to which recycled aggregate will provide utility is a function of both the quantity and quality of the aggregate available to be recovered. The amount available to be recovered is, of course, site specific and may be limited in certain circumstances, although many roads under consideration for decommissioning in the Pacific Northwest generally have 15-30 cm of available aggregate (Mark Truebe, Assistant Forest Engineer, Willamette National Forest, personal communication). Foltz and Truebe (2003) examined the environmental performance[4] of a variety of aggregates, including alluvial surfacing material recovered from roads in the Willamette National Forest in Oregon.

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[4] Foltz and Truebe (2003) considered runoff volume and sediment production in response to simulated rainfall, and rut depth in response to simulated log truck traffic.

The recovered aggregate's performance was within the range of variability of the eighteen aggregate types tested, which suggests that aggregate recovered from forest roads could be put to beneficial use. In practice, this has proven to be the case. Thompson and Sessions (2008) describe applications of aggregate recycling by the Washington Department of Natural Resources and by the Umpqua National Forest, and Sessions et al. (2006) describe successful operations by the Oregon Department of Forestry.

Thompson and Sessions (2008) demonstrated that aggregate recycling presents an opportunity to offset decommissioning costs, wherein the recovered aggregate can provide a lower cost alternative for road construction or maintenance projects. The authors presented mixed integer formulations to identify optimal road deactivation levels (close / decommission) and aggregate recycling policies so as to either minimize total cost or maximize total environmental benefit, measured as the hazard-weighted length of roads decommissioned. Reusing aggregate can effectively subsidize decommissioning projects, meaning landowners could perform more restoration projects at a particular budget, in theory decommissioning additional roads and improving aquatic habitat. Alternatively, cost minimizing landowners might find that the optimal solution actually schedules additional roads for decommissioning, and thereby provides synergistic benefits.

In this manuscript we expand upon the work of Thompson and Sessions (2008), seeking to identify the entire realm of efficient solutions rather than just the boundary (minimal cost, maximal benefit) solutions. This approach recognizes that there is likely a gradient of possible solutions and that the decision maker's preferences may not best be satisfied with either boundary solution. We seek to better understand the tradeoffs between economic and environmental criteria, and in particular to understand what role aggregate recycling may play in improving the efficiency of road restoration activities. To do so we employ a multi-objective mixed-integer formulation and generate solutions using the epsilon constraint method (Haimes et al. 1971). This constitutes an *a posteriori* optimization approach, wherein the frontier of non-dominated solutions is presented to the decision maker prior to rendering an opinion on what constitutes an ideal compromise between competing objectives (Van Veldhuizen and Lamont 2000). This multi-objective paradigm is considered appropriate for natural resource management, in that it does not require prior articulation of preferences nor the identification of methods to appropriately scale and weight non-commensurate objectives, and should ultimately lead to informed compromise (Kennedy et al. 2008).

6.3 Formulating Optimal Aggregate Recycling and Road Removal Policies

To prioritize treatments, and to assess how well environmental objectives are met as a result of treatment, environmental performance measures for forest roads are required (Mills 2006). Common metrics include estimates of sediment production and/or delivery, road roughness, rut depth, road density within sensitive areas, and length of roads treated. Another approach is to assign road segments a hazard score based upon some defined set of criteria and attributes (e.g., Madej et al. 2006; Allison et al. 2004; Olson and Orr 1999). Girvetz and Shilling (2003) employed this method to analyze the

Tahoe National Forest road system for potential environmental impacts according to the USDA Forest Service's "Roads Analysis" guidance document (USDA 1999). Roads with greater potential to cause environmental damage were assigned higher scores and these scores were used to negatively weight roads for a least-cost network analysis. The authors found that over 50% of the total road length, and 40% of aggregate-surfaced road length, could be removed while ensuring access to critical points in the road network. Relevant characteristics of the road network included in the analysis were the number of stream crossings, distance from the road to a stream, position of the road on a slope, and slope steepness.

Federal land management agencies in the Pacific Northwest adopted a similar approach, using the Ecosystem Management Decision Support (EMDS[5]) system to characterize the ecological condition and help prioritize restoration of watersheds and aquatic ecosystems on public land (Reeves et al. 2006). EMDS employs fuzzy logic and knowledge-based reasoning integrated into a geographic information system (GIS) to provide decision support for ecological assessment (Reynolds 1999). EMDS assesses ecological condition according to a hierarchical, multi-criteria framework. At the bottom of the hierarchy are data observations, or attributes, that are evaluated according to pre-defined criteria and assigned scores on a (-1, 1) scale. An assigned score reflects the degree to which a premise is true, where +1 indicates the premise is completely true and -1 completely false. The Aquatic and Riparian Effectiveness Monitoring Program (AREMP), for instance, evaluates the premise that a watershed is in a "good" condition,

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[5] http://www.institute.redlands.edu/emds/

defined as a state wherein the physical attributes are adequate to maintain or improve biological integrity, in particular for native and desired fish species (Reeves et al. 2004). Drilling down into the model, scores are assigned to attributes such as road/stream crossing frequency and riparian road density (AREMP 2005). Attribute scores are aggregated to assign an overall ecological condition score. Aggregation proceeds through the hierarchy according to user-defined rules such as “AND” and “OR” operands. The “AND” relationship combines scores for a set of attributes or sub-assertions θ according to Equation 1, offering a conservative estimate of the truth. This is analogous to a minimum operator, which indicates the presence of a limiting factor (AREMP 2005). The “OR” relationship to the contrary is effectively a maximum operand, assigned the value of the most true sub-assertion, and is used where the truth value of the assertion could be based on any of the sub-assertions (Girvetz and Shilling 2003).

$$AND(\theta) = min(\theta) + [average(\theta) - min(\theta)] * [min(\theta) + 1] / 2 \qquad (1)$$

The use of fuzzy, or approximate, logic is thought to extend the ability to reason with the imprecise or qualitative information common to natural resource management (Reynolds et al. 2000). EMDS has been employed for a variety of purposes, including watershed assessment in the Chewaucan Basin (Reynolds and Peets 2001), assessment of habitat and basin-wide health in the Rogue River drainage (Pess et al. 2003), sediment total maximum daily load monitoring in a northern California watershed (Dai et al. 2004), and landscape evaluation of the eastern Washington Cascades (Reynolds and Hessburg 2005). Here we propose adoption of a knowledge base to assign road segments a hazard weight based upon likely negative aquatic impact, similar to the approach presented in Girvetz and Shilling (2003). We then use hazard-weighted length of roads decommissioned as a proxy for environmental benefit stemming from road decommissioning treatments.

Consider a road network with a subset of segments scheduled for removal. Removal can consist of either closure or decommissioning, with the expectation that decommissioning provides significantly greater environmental benefits. The set of roads scheduled for removal is assumed to have been identified by an experienced professional, perhaps as the result of a watershed analysis using methods outlined above. If a road is scheduled to be decommissioned, aggregate can be recovered and used for other scheduled maintenance and construction projects.

The multi-objective mixed-integer formulation is presented below. First, we present the formal definitions of the model's parameters and variables:

I	set of road segments scheduled for removal, indexed by i
J	set of road segmented requiring aggregate for construction or maintenance, indexed by j
K	set of road removal treatments, indexed by k
T	set of time periods in the planning horizon, indexed by t
p_t	present net value factor for period t
α_i	hazard rating for road segment i, (0,1)
l_i	length of road segment i, m^3
A_{it}	aggregate available for recovery from road i in period t, m^3

D_{jt}	aggregate required for road *j* in period *t*, m^3
c_{ijt}	cost to recover aggregate from road *i* and deliver to road *j* in period *t*, \$/m^3
g_{sjt}	cost to procure aggregate from source *s* and deliver to road *j* in period *t*, \$/m^3
h_{ikt}	cost to remove road *i* at treatment level *k* in period *t*, \$
rf_{ikt}	aggregate recovery factor for road *i* removed at treatment level *k* in period *t*, m^3/m^3
X_{ijt}	aggregate recovered from road *i* and delivered to road *j* in period *t*, m^3
Y_{sjt}	aggregate taken from source *s* (pit or quarry) and delivered to road *j* in period *t*, m^3
β_{ikt}	binary variable indicating whether road *i* is removed at treatment level *k* in period *t*

Minimize:

$$Z_{econ} = \sum_{i \in I} \sum_{j \in J} \sum_{t \in T} p_t c_{ijt} X_{ijt} + \sum_{s \in S} \sum_{j \in J} \sum_{t \in T} p_t g_{sjt} Y_{sjt} + \sum_{i \in I} \sum_{k \in K} \sum_{t \in T} p_t h_{ikt} \beta_{ikt} \qquad (2)$$

Maximize:

$$Z_{env} = \sum_{i \in I} \sum_{k \in K} \sum_{t \in T} \alpha_i l_i \beta_{ikt} \qquad (3)$$

Subject to:

$$\sum_{i \in I} X_{ijt} + \sum_{s \in S} Y_{sjt} = D_{jt} \qquad \forall\ j \in J, t \in T \qquad (4)$$

$$\sum_{j \in J} X_{ijt} \le \sum_{k \in K} rf_{ikt} A_{it} \beta_{ikt} \qquad \forall\ i \in I, t \in T \qquad (5)$$

$$\sum_{k \in K} \beta_{ikt} = 1 \qquad \forall\ i \in I, t \in T \qquad (6)$$

$$\beta_{ikt} \in \{0, 1\} \qquad \forall\, i \in I, k \in K, t \in T \quad (7)$$

Our formulation seeks solutions that are non-dominated with respect to economic and environmental criteria. The economic criterion (Equation 2) seeks to minimize the total cost of aggregate procurement and delivery plus road removal costs. The environmental criterion (Equation 3) seeks to maximize the hazard-weighted length of roads decommissioned, where the hazard score is identified as described above. In this context, non-dominated (or efficient) solutions are those for which it is impossible to improve one objective (e.g., decrease cost) without degrading the other objective (e.g., decrease hazard-weighted length of roads decommissioned). Non-dominated solutions are formally defined as follows: let *a* and *b* be feasible decision vectors; *a* is said to *dominate b* $(a \prec b)$ iff:

$$\forall\, i \in \{1, 2, ..., n\} : f_i(a) \le f_i(b) \quad \cap \quad \exists\, j \in \{1, 2, ..., n\} : f_j(a) < f_j(b) \qquad (8)$$

Equation 4 ensures that all aggregate demand (stemming from construction and maintenance projects) is fully met by some combination of recycled aggregate and aggregate procured from a local pit or quarry. Equation 5 limits the total aggregate available to be recovered from a road segment to the total volume of rock available, multiplied by a recovery factor. Sessions et al. (2006) relate from experience recovery rates as high as 90%. Here we conservatively estimate a recovery rate of 70%. Higher recovery rates can be enabled by the use of geotextiles on new construction; Thompson and Sessions (2008) present formulations that incorporate geotextiles, and assume a recovery rate of 90% to model scenarios in which geotextiles are used. Equation 6 ensures each segment is assigned at most one treatment, and Equation 7 requires removal treatment decisions remain binary.

Thompson and Sessions (2008) present cost savings associated with aggregate recycling as an effective subsidy. Here we formalize that notion mathematically. Let p indicate a particular level of environmental performance (measured here by hazard weighted length of roads decommissioned, m^3). Consider a non-dominated tuple in the objective space defined by $(Z_{econ}(p), p)$, where $Z_{econ}(p)$ is the total (minimized) cost associated with environmental performance level p. Now define $Z_{NR\_econ}(p)$ as the total (minimized) cost associated with environmental performance level p, but under a scenario with no aggregate recycling. The effective subsidy (ES) associated with recycling aggregate for a particular environmental performance level p can be calculated as shown in Equation 9.

$$ES(p) = Z_{econ}(p) - Z_{NR\_econ}(p) \tag{9}$$

This formulation is useful for interpreting the differences between aggregate utilization policies. Our hypothesis is that the effective subsidy increases with increasing levels of environmental performance. That is, the marginal cost savings due to aggregate recycling increase as more roads are decommissioned. This suggests a synergistic benefit between reducing costs and improving overall environmental performance.

6.4 Example Application

To test our hypothesis of aggregate recycling providing increasing marginal environmental benefit, we now turn to an example application. The input data for our example was originally presented in Thompson and Sessions (2008). We now employ a multi-objective mathematical programming technique to identify the non-dominated frontier. Specifically, we employ a modified version of the epsilon-constraint method (Haimes et al. 1971), wherein an algorithm iteratively optimizes for a single objective subject to constraints representing other objectives. Because our example problem is sufficiently small, we use exact mixed-integer programming techniques to generate known optimal solutions for all iterations of the algorithm. Solutions are generated using GAMS v22.7 with the CPLEX solver. The modification involves an inserted step to ensure that output solutions are in fact non-dominated (Toth et al. 2006). A cost-minimizing solution subject to environmental performance level p is not necessarily non-dominated, because it may be possible to identify a solution for which environmental performance can be improved while maintaining the same low cost solution output from the previous iteration. Thus for each iteration of the algorithm two single-objective problems are solved to optimality. Per iteration the epsilon value, representing the constraint level for one objective, is updated. In this example we iterate over environmental performance metrics, with epsilon set to 1 hazard-weighted meter. The algorithm proceeds from one boundary solution to the other, along the way defining the efficient frontier of non-dominated solutions.

Here we model a two-period planning example, using the road network of the South Zone of the McDonald-Dunn Research Forest, managed by the College of Forestry, Oregon State University. Figure 1 displays the road network under consideration. We assume 7 road segments have been slated for removal, 5 for construction, and 2 for maintenance, where maintenance here is defined as reapplication of aggregate. Roads requiring maintenance are mainlines serving public traffic, meaning any recycled aggregate must first be processed prior to use as a surface layer. Newly constructed segments are to serve timber traffic only, meaning no processing besides screening is necessary. As an alternative to recovered aggregate from decommissioned roads, a quarry located ~18 km north of the forest can provide aggregate. There are no working borrow pits within the forest because of perceived low aggregate quality (Dave Young, Roads and Trails Specialist, OSU College Forests, personal communication, 2007).

Road removal costs are estimated from Weaver and Hagans (2009). Here we assume closure is defined as filling ditches and outsloping the road surface, for an average cost of $7500 / km. Decommissioning treatments vary, and may include removing culverts under significant fills, ripping the roadbed, recontouring hillslopes, planting or seeding the road surface. The expectation is that a decommissioned road is not passable and requires no future maintenance. We consider a range of decommissioning costs, from $10,000 to $25,000 / km. Because it is largely the relative cost difference between closure and decommissioning treatments that drives the decision to opt for one approach over another, we opted to only consider a range of decommissioning costs.

Table 1 presents information on quantity of aggregate demanded (D_{jt}) for maintenance and construction projects. Recall that maintenance projects require higher quality aggregate to be applied as a surface layer. Table 2 presents removal costs (h_{ikt})

and quantity of aggregate available (A_{it}) from spur roads slated for removal. Note that different segments of Road 660 are slated for different treatments (removal and maintenance). Removal costs presented in the table were estimated at \$7,500 / km for road closure, and \$20,000 / km for decommissioning. Table 3 presents unit costs (\$ / m^3) for aggregate procurement, processing and delivery from various possible sources (c_{ijt} and g_{sjt}). Recovered aggregate to be used for maintenance projects has higher total costs due to processing requirements. Larger g_{sjt} values for quarry-supplied aggregate reflect both the purchase cost as well as significantly higher transportation costs. Data in Tables 1-3 was originally presented in Thompson and Sessions (2008).

Figure 2 presents the knowledge base model used to assign hazard scores to each segment. We use an abbreviated version[6] of the model presented initially by Girvetz and Shilling (2003), wherein we evaluate the degree of support for the assertion, "the road segment has a high potential for causing environmental damage." Truth values scores are used to assign a hazard weight to each road segment under consideration for decommissioning. In this hazard assessment model, truth value scores are limited to the range (0, 1), reflecting the conservative assumption that at best, we can only be indeterminate about a road's likelihood of negatively impacting the environment (as opposed to being certain about the lack of risk). Scores are assigned linearly based upon predetermined lower and upper bounds for each criterion. Table 4 presents the segment-

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[6] Attributes removed from our abbreviated model include information on precipitation, road surface type, a soil erodibility factor, and metrics on the biological condition of aquatic habitat. Since the intent is to describe the relative risk of each road segment, attributes that would be identical for all segments were removed from the model.

level information passed into the simulated knowledge base to assign hazard scores to each road segment.

The potential for each segment to detrimentally impact the aquatic environment depends on the degree to which the segment impacts either stream channel integrity or presents a high erosion risk (Figure 2). Due to use of the "OR" operator, a segment's overall likelihood of causing damage is assigned based upon the higher score between stream channel integrity and erosion risk. Indicators of stream channel integrity include the number stream crossings per kilometer of road, and the distance of the road to the stream. More crossings per km is less desirable (lower bound = 0.0 crossing / km, upper bound = 5.0 crossings / km), as is lower distance to the stream; distances greater than 100 m are assumed not to contribute to stream channel degradation. Erosion risk is estimated as a function of hillslope position and road slope steepness. Mid-slope roads are considered to constitute the highest risk (TV = 1), followed by ridge-top roads (TV = 0.5) and then streamside roads (TV = 0). The steeper a slope is, the greater the associated erosion risk (upper bound = 15%).

Table 5 presents each road segment's score for each criterion, as well as the aggregated truth value score. Again, segments with values closer to 1 are assumed to present a greater risk of causing environmental damage. Based upon this model, we expect segment 630 to present the greatest risk per unit length, attributable largely to the segment's steep slope. Segment 762 is also thought to present a relatively high erosion risk because of slope steepness. Segment 720, with the third highest score, is instead considered hazardous because its proximity to stream may threaten the stream channel integrity. Readers are referred to Girvetz and Shilling (2003) for more details on this model.

A common policy among public managers in the western United States is to treat the greatest length of road possible at a given budget (Madej et al. 2006). A drawback to this approach is the lack of differentiation between other risk factors beyond segment length. Based upon length alone, the ordered priority list for decommissioning roads would be 720 → 681 → 762 → 771 → 620 → 660 → 630 (see Table 2 for segment lengths). Based upon hazard-weighted length however, the ordered priority list becomes 720 → 762 → 681 → 630 → 771 → 660 → 620. Segment 720 is by far the longest segment, and therefore remains prioritized first according to either metric. Segments 762 and 630 however, identified above as having high hazard scores, move up in the priority list when hazard-weighted length becomes the metric. Road 620, which has the lowest hazard score, moves to the bottom of the priority list.

6.5 Results

Figure 3 presents identified non-dominated frontiers across a range of decommissioning costs (DC), assuming aggregate recycling is permitted. Because we are solving a minimize cost (x-axis), maximize benefit (y-axis) problem, we can expect frontiers to have a positive slope in the objective space. That is, we expect cost to increase with benefit. The maximum benefit possible across all scenarios is 2248.6 hazard-weighted meters decommissioned (5526.81 total meters). The minimum cost varies with decommissioning cost. At $10,000 / km, the cost-minimizing solution *is* the benefit-maximizing solution, meaning the frontier consists of a single point in the objective space. Here the relatively low cost of decommissioning paired with potential cost savings from recycling combine to yield a solution frontier without tradeoffs. We anticipate that this situation is uncommon.

As the relative cost of decommissioning increases, the frontiers expand downward towards lower cost solutions, with associated reductions in decommissioning and recycling. For decommission costs ≥ \$20,000 / km, the low cost solution is to decommission no roads, despite the cost savings relative to purchasing rock from the quarry. This figure allows decision makers to better understand the tradeoffs associated with economic and environmental criteria. The frontier for DC = \$15,000 / km is nearly vertical, suggesting a high benefit/cost ratio associated with incremental increases in expenditure. As DC increases however the slopes of the frontiers decline, suggesting a lower cost/benefit ratio.

To demonstrate the utility of recycling we compare frontiers generated with and without adoption of aggregate recycling. Figure 4 displays these frontiers for a decommissioning cost of \$10,000 / km. Recall that here the “frontier” with recycling is actually a single point in the objective space. There simply is no lower cost alternative without recycling, and to achieve identical levels of environmental performance requires an additional expenditure of \$49,818.47, or 30.76%. At DC = \$15,000 / km, 26.50% of additional expenditure is required to achieve the maximum environmental benefit.

Figure 5 compares non-dominated frontiers solved with and without the opportunity to recycle aggregate from decommissioned roads (DC = \$20,000 / km). As the environmental benefit from treatment increases, so does the effective subsidy (ES) due to recycling. ES is displayed on the figure as the horizontal distance between the two frontiers, i.e., the difference in total expenditure between scenarios with and without aggregate recycling. The figure also demonstrates increasing marginal cost savings associated with reuse of recovered aggregate as the level of environmental performance increases. Alternatively, this tradeoff analysis could be framed as demonstrating the opportunity costs of not recycling aggregate where the opportunity exists.

Figure 6 supplements the information presented in Figure 5. Effective subsidy (ES) values are graphed, as they vary with environmental performance levels (DC = \$20,000 / km). As the level of environmental performance increases, the effective subsidy associated with aggregate recycling generally increases. The rationale here is intuitive: as more roads are decommissioned more local (low-cost) aggregate becomes available for reuse elsewhere in the road network. Marginal cost savings associated with aggregate recycling in this scenario range from 0% to 23.12%. At DC = \$25,000 / km, maximum cost savings reach 20.57%, achievable at the maximum level of environmental benefit.

Figure 7 compares non-dominated frontiers identified using various aggregate recovery rates. As described above, here we generate solutions using a conservative estimate of 70%. In reality recovery rates may be much higher, as alluded to earlier. Further, construction using geotextiles can increase recovery rates. The horizontal distance between frontiers in Figure 7 represents additional costs savings possible by installing geotextiles or implementing other techniques to increase the recovery rate (exclusive of installation or implementation costs). The 90% recovery rate frontier does not intersect the x-axis, indicating that the low cost solution schedules at least some roads for decommissioning.

Often when evaluating tradeoffs between competing objectives one expects to see a “bend of the knee” in the curve, or the point where marginal benefits per dollar spent begin to markedly decline. Decision-makers may choose not to adopt efficient solutions beyond this point, a rule of thumb that can help decision-makers tie management policy formulation to output from the mathematical model. In the efficient frontiers displayed in Figures 3-5, however, no such point is readily apparent. In particular consider Figure 5: the slope of the frontier with recycling has a near constant slope, which suggests the possibility of a synergistic relationship between cost-savings that accrue from aggregate recycling, and environmental benefits associated with decommissioning additional forest roads.

6.6 Concluding Remarks

This manuscript presented mixed-integer, multi-objective mathematical programming formulations to identify optimal aggregate recycling and road removal policies. Previous research and real-world application have demonstrated the cost savings potential of recovering and reusing aggregate from decommissioned forest roads. We extended previous work by employing techniques to identify the efficient frontier of non-dominated solutions, and to include hazard factors to differentially weight road segments scheduled for removal. Identifying the frontier of non-dominated solutions facilitates tradeoff analysis and the selection of compromise solutions. Decision makers whose preferences are not best satisfied with boundary (minimal cost, maximal benefit) solutions are able to explore other efficient possibilities.

Further, tradeoff analysis lets us better understand the role that aggregate recycling may play in effectively subsidizing decommissioning projects. Our results suggest a synergistic relationship between this subsidy and environmental performance, where subsidies generally increase with increasing environmental performance. Transportation managers are therefore able to recover and reuse a non-renewable resource, while at the same time promoting economic and environmental efficiency.

The type of analysis we present here should ultimately facilitate watershed restoration planning on federal lands in the Pacific Northwest. The utility of this approach is not however limited to federal ownerships or to the specific region discussed here. Our proposed approach should help any class of landowners to manage their aggregate resources. On private lands with high levels of timber harvest, landowners may now be more likely to construct new temporary spurs with the intention of later recovering aggregate. This may entail construction with geotextiles, which as we demonstrate above may increase cost savings.

Our findings are not limited to the scenarios presented here where recovered aggregate is to be used within the same planning period. The recovered aggregate tested by Foltz and Truebe (2003), for instance, had been stockpiled for over 20 years. Similarly, aggregate recovered from decommissioned forest roads on the Umpqua National Forest was stockpiled for future use (Michael Karr, Work Supervisor, Road

Maintenance and Project Team, Umpqua National Forest, personal communication, 2007). Forward thinking managers may therefore opt to incur aggregate recovery costs today in order to reduce aggregate procurements costs in the future.

Future work could seek to manage aggregate resources over a larger ownership, or to incorporate additional decision variables such as aggregate stockpiling, road improvement treatments, identification of which road segments to remove, and identification of when to remove segments. Practitioners could also employ more sophisticated and/or regionally-specific risk models. Here we intentionally adopted a decision support system that is also used by federal agencies to prioritize watershed restoration treatments and that has previously been used to prioritize road segments for removal. Certainly other approaches are valid, and may in fact be more appropriate depending on circumstances. For instance, the AREMP models employed by the Forest Service to characterize watershed condition over time did not include an indicator of road condition, which resulted in no change to assessed watershed condition scores despite implementation of road improvements on nearly 5000 km of road (Reeves et al. 2006). One might also ask, to what extent do user-defined relationships nested within the EMDS hierarchy (AND, OR, etc.) reflect scientific rigor versus opinion, and how might the hierarchy design process be structured to avoid introducing bias on the part of designers. Other approaches from the literature include discriminant analysis (Rice and Lewis 1991), Bayesian decision analysis (Allison et al. 2004), and sediment production estimation (Rackley and Chung 2008; Madej et al. 2006). Generally speaking, all methods have respective strengths and weaknesses, and researchers should carefully consider which method to employ.

We hope this research note stimulates additional interest into aggregate recycling, and ultimately leads to improved economic and environmental efficiency in the management of forest transportation networks.

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Figure 6.1: Road plan for the South Zone of the McDonald Dunn Research Forest, with project types labeled. This figure was originally published in Thompson and Sessions (2008).

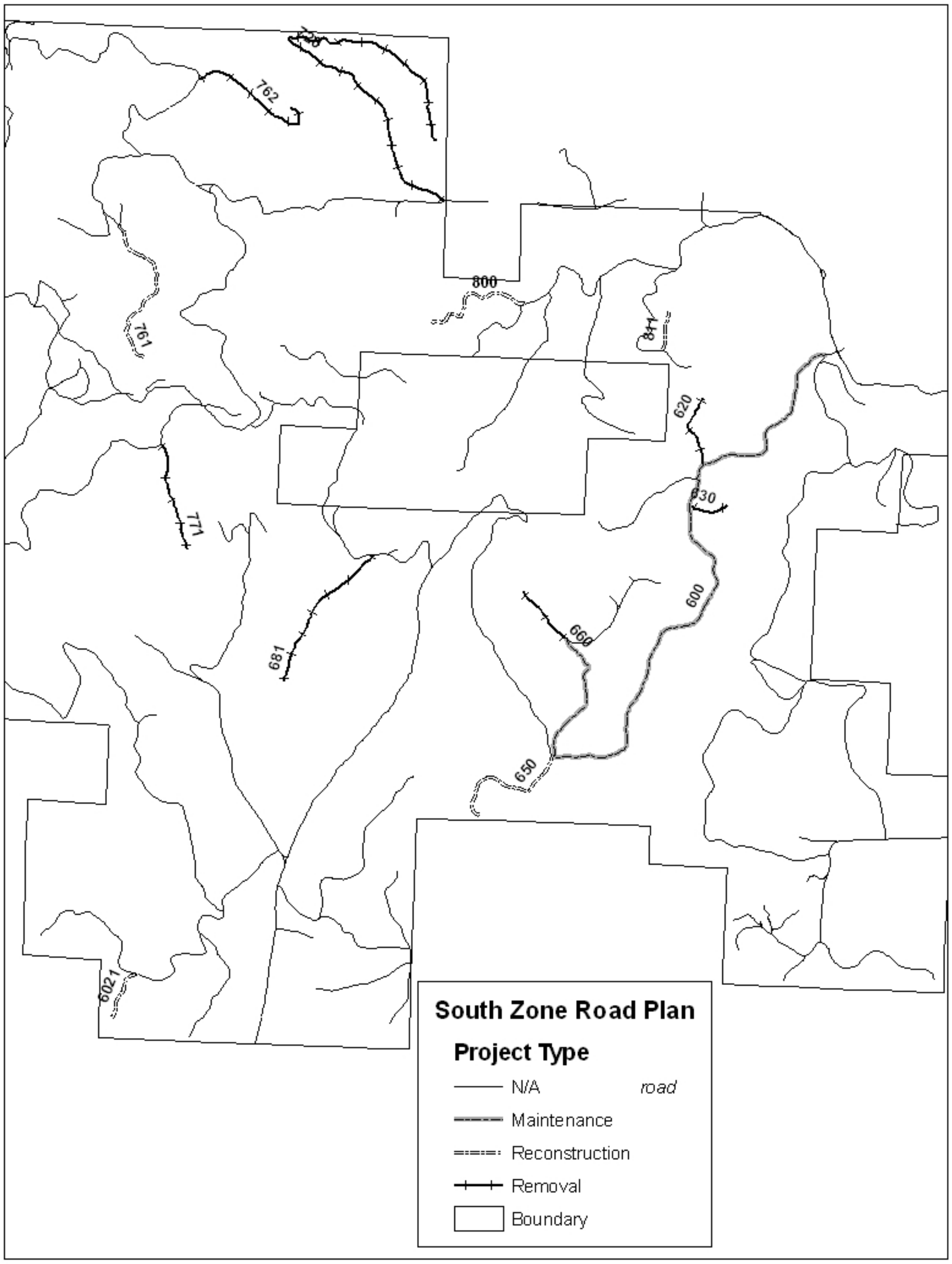

Figure 6.2: Knowledge base used to evaluate the potential aquatic environmental impact of each road segment slated for decommissioning. Rectangles represent assertions (e.g., “the road has a high potential for causing damage to the aquatic environment”), circles the segment-level data used to evaluate these assertions, and diamonds the AND/OR fuzzy logic relationships. Here the overall truth value score is the score of the most true sub-assertion (i.e., OR is a maximum operand). Model adapted from Girvetz and Shilling (2003).

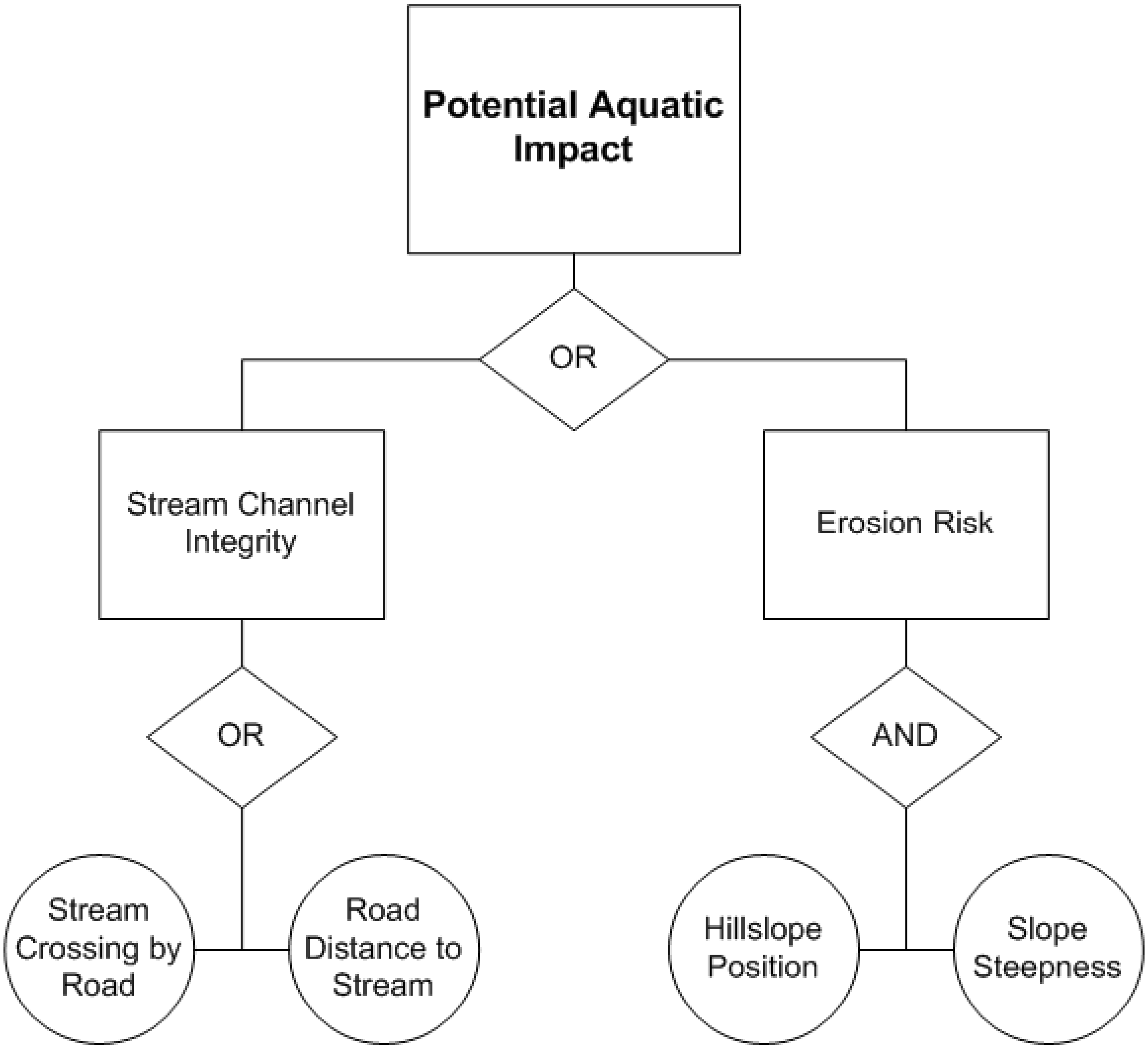

Figure 6.3: Comparison of non-dominated frontiers identified using various decommissioning costs ($/km), with aggregate recycling permitted. At the upper left hand corner of the figure the non-dominated frontier consists of a single point (DC = $10,000 / km). That is, the cost-minimizing solution is also the benefit-maximizing solution. As the cost of decommissioning increases, the frontiers expand downward towards lower cost solutions, with associated reductions in decommissioning and recycling. For decommission costs ≥ $20,000 / km, the low cost solution is to decommission no roads, despite the cost savings relative to purchasing rock from the quarry.

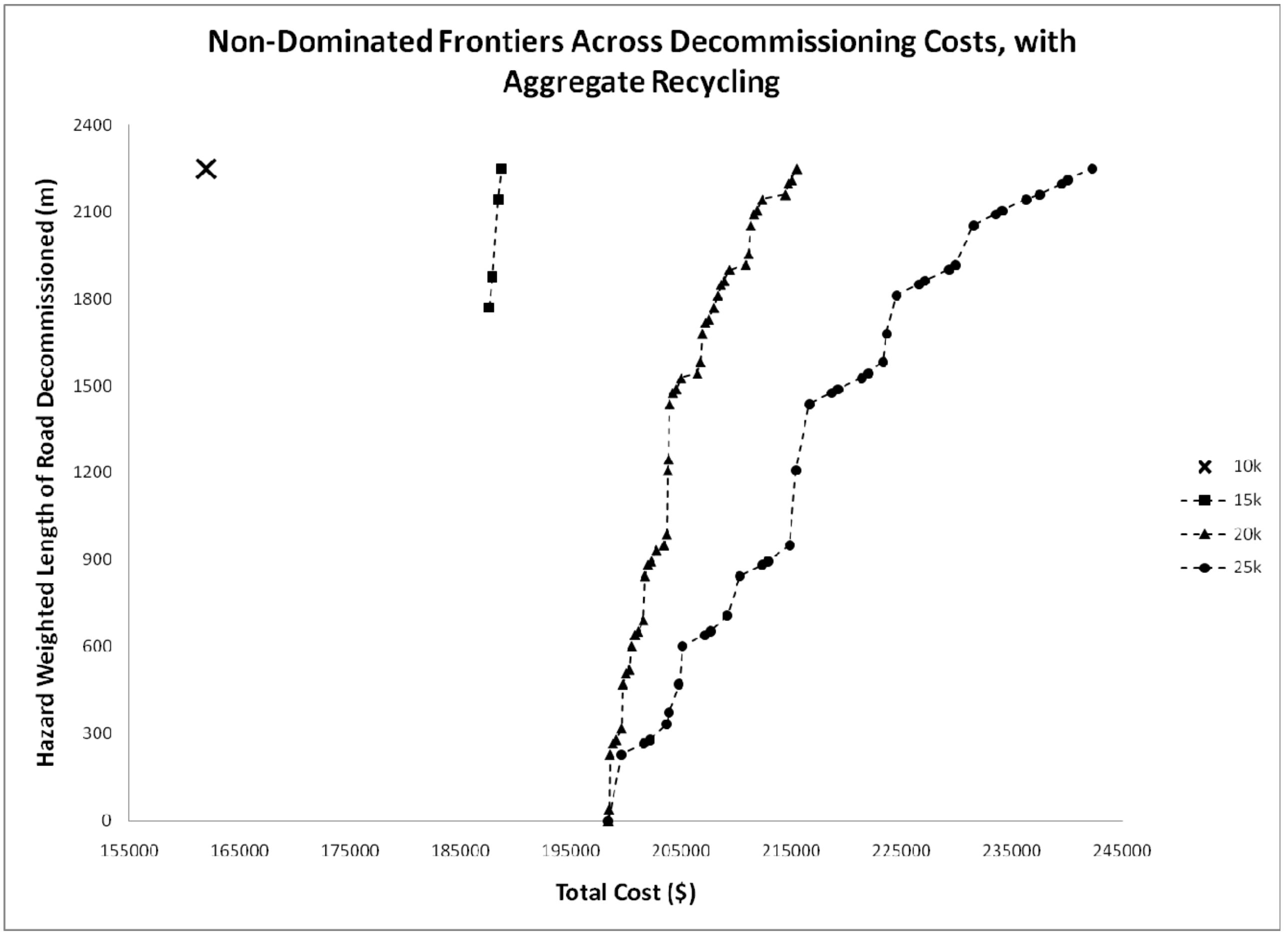

Figure 6.4: Comparison of non-dominated frontiers, solved with and without the opportunity to recycle aggregate from decommissioned roads. Frontiers displayed below were calculated using a decommissioning cost (DC) of $10,000/km. Here the "frontier" with recycling is actually a single point in the objective space, as denoted by the "X" in the figure. There simply is no lower cost alternative without recycling, and to achieve identical levels of environmental performance requires an additional expenditure of $49,818.47, or 30.76% of total expenditures under the recycling scenario.

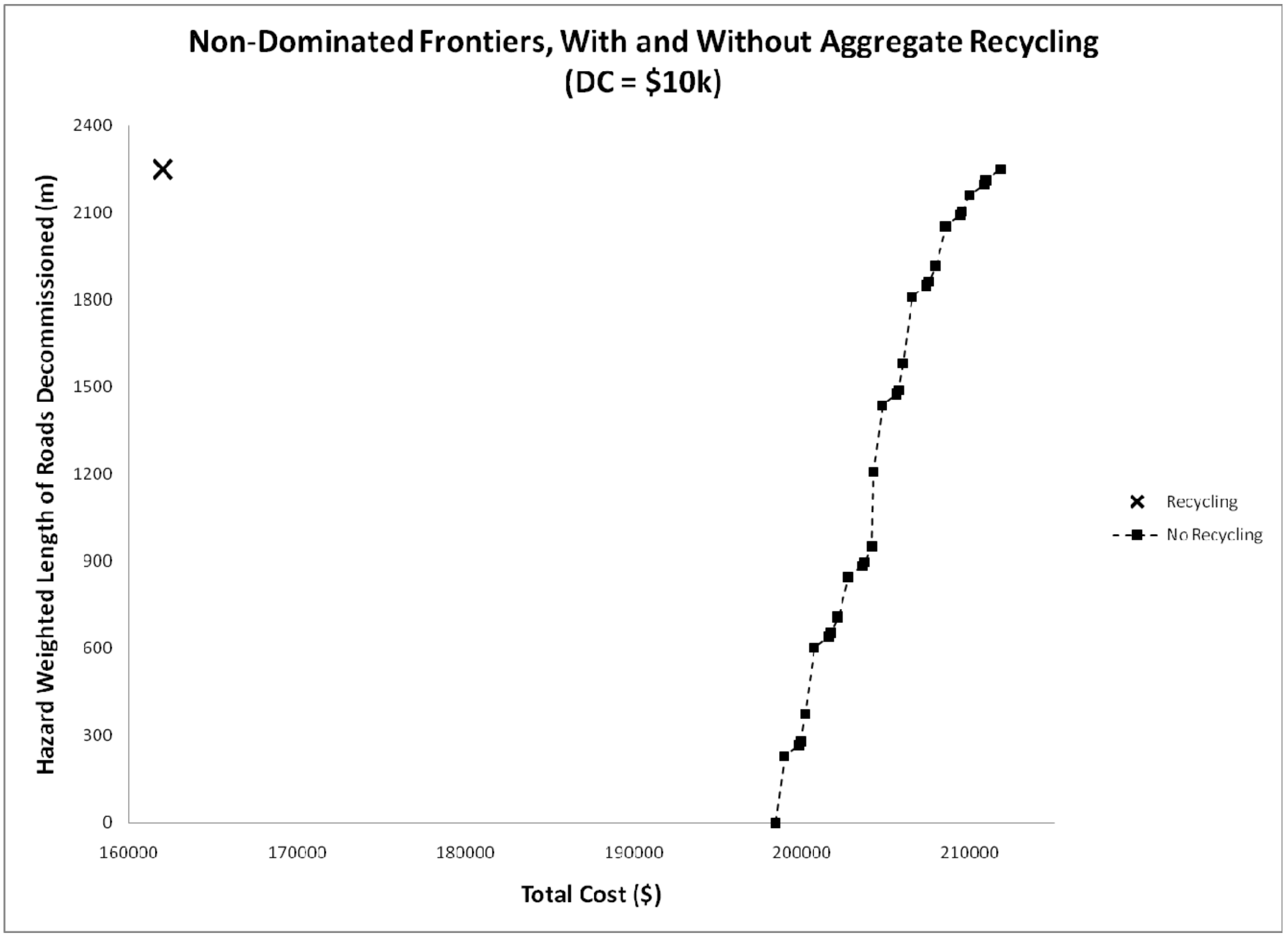

Figure 6.5: Comparison of non-dominated frontiers, solved with and without the opportunity to recycle aggregate from decommissioned roads. Frontiers displayed below were calculated using a decommissioning cost (DC) of $20,000/km. As the environmental benefit from treatment increases, so does the effective subsidy due to recycling aggregate. This figure demonstrates increasing marginal cost savings associated with reuse of recovered aggregate as the level of environmental performance increases.

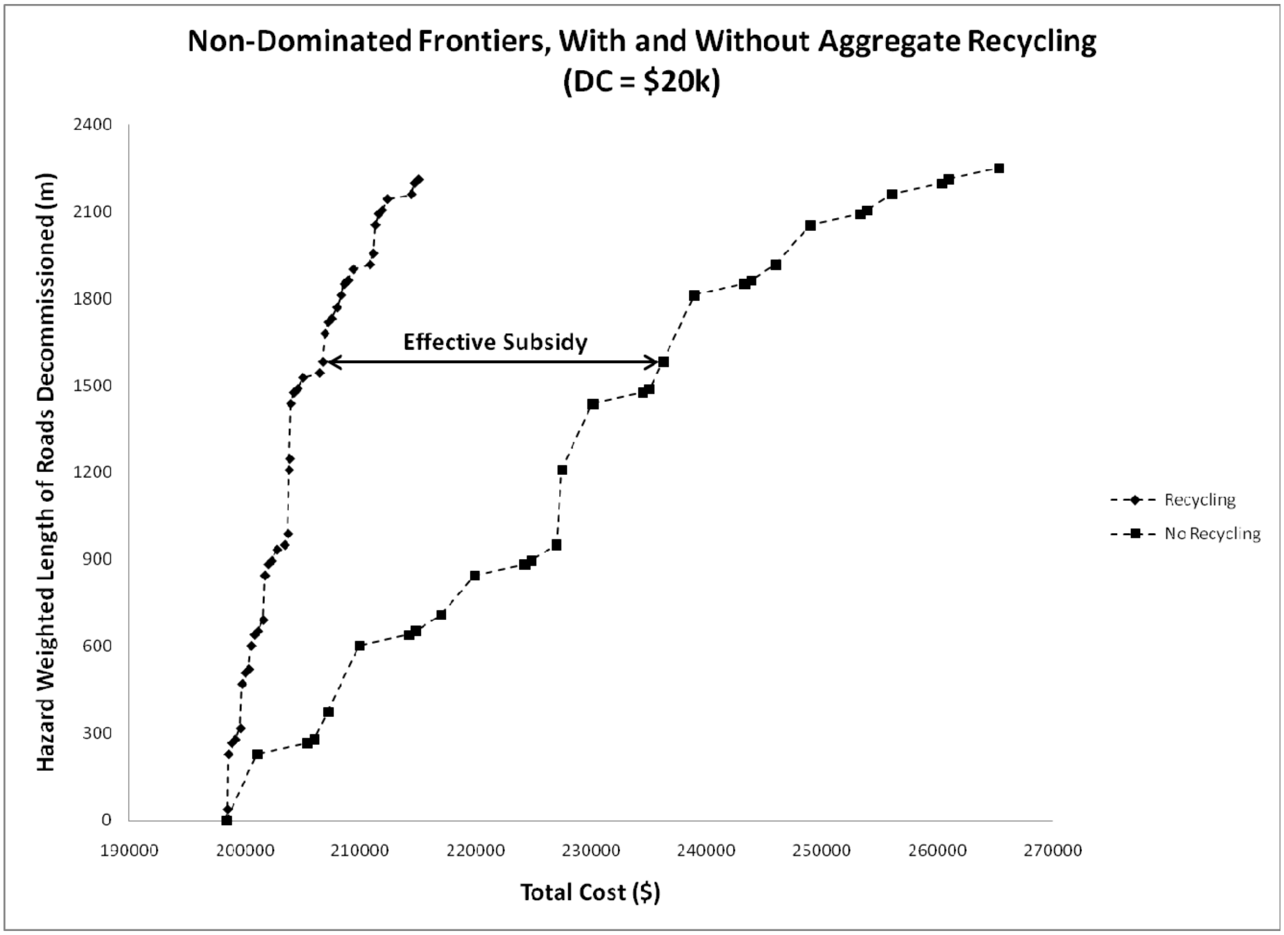

Figure 6.6: Effective subsidy (ES), as it varies with environmental performance levels. This figure displays the difference in total expenditure between scenarios with and without aggregate recycling, calculated assuming a decommissioning cost (DC) of $20,000/km. As the level of environmental performance increases, the effective subsidy associated with aggregate recycling generally increases. The rationale here is intuitive: as more roads are decommissioned more local (low-cost) aggregate becomes available for reuse elsewhere in the road network.

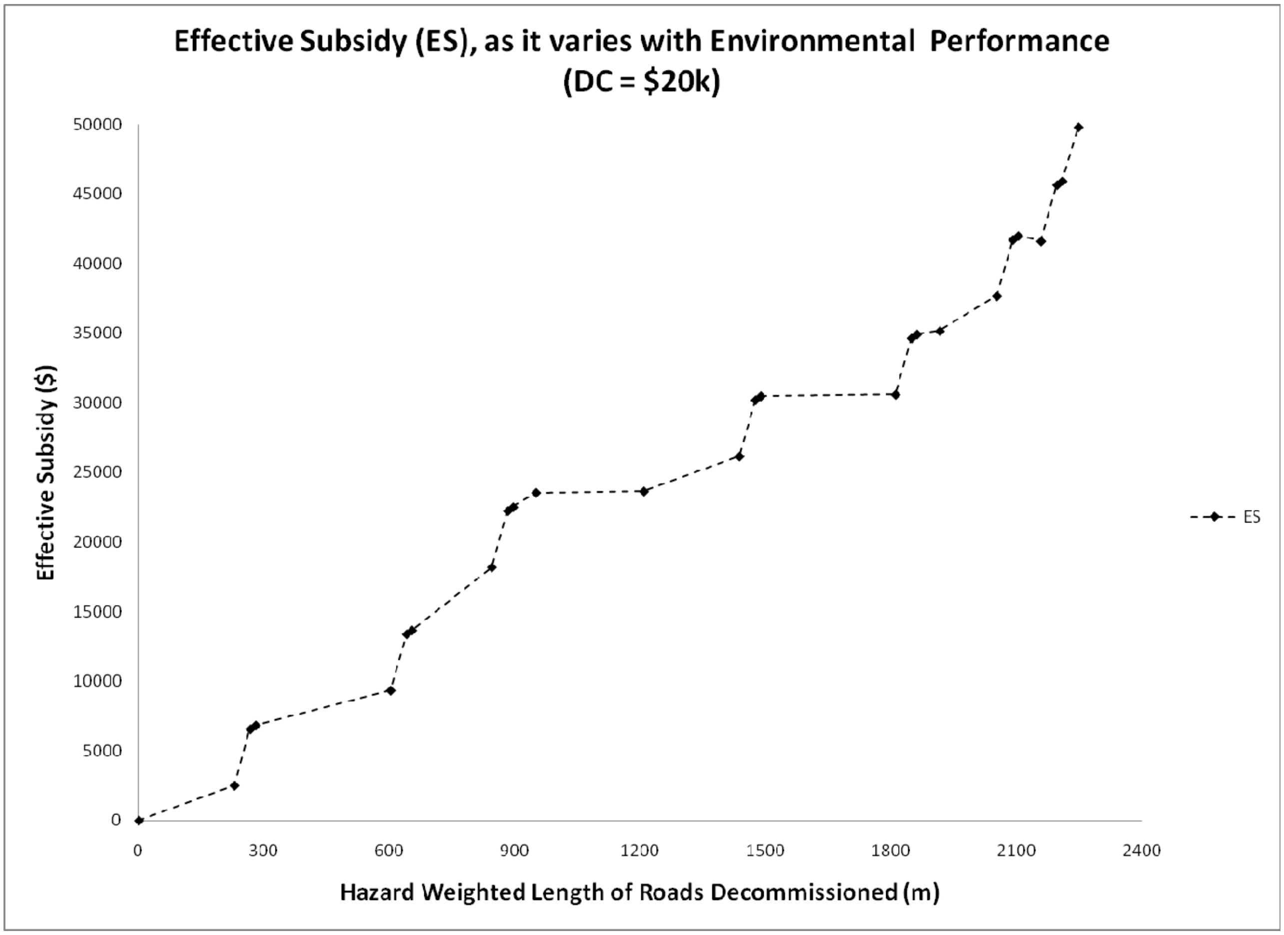

Figure 6.7: Influence of the recovery factor on non-dominated frontiers, calculated assuming a decommissioning cost (DC) of $20,000/km. The higher recovery factor of 0.9 is assumed to reflect a scenario in which geotextiles were used during road construction, thereby facilitating recovery during decommissioning. The horizontal distance between frontiers represents additional cost savings made possible by investing in geotextiles or other techniques to increase recovery rate. That the frontier generated using a recovery factor of 90% does not intersect the x-axis indicates that the low-cost solution does involve decommissioning, in order to reap cost savings associated with recycling. The marginal gain in aggregate from the higher recovery rate makes additional decommissioning attractive relative to a recovery factor of 70%.

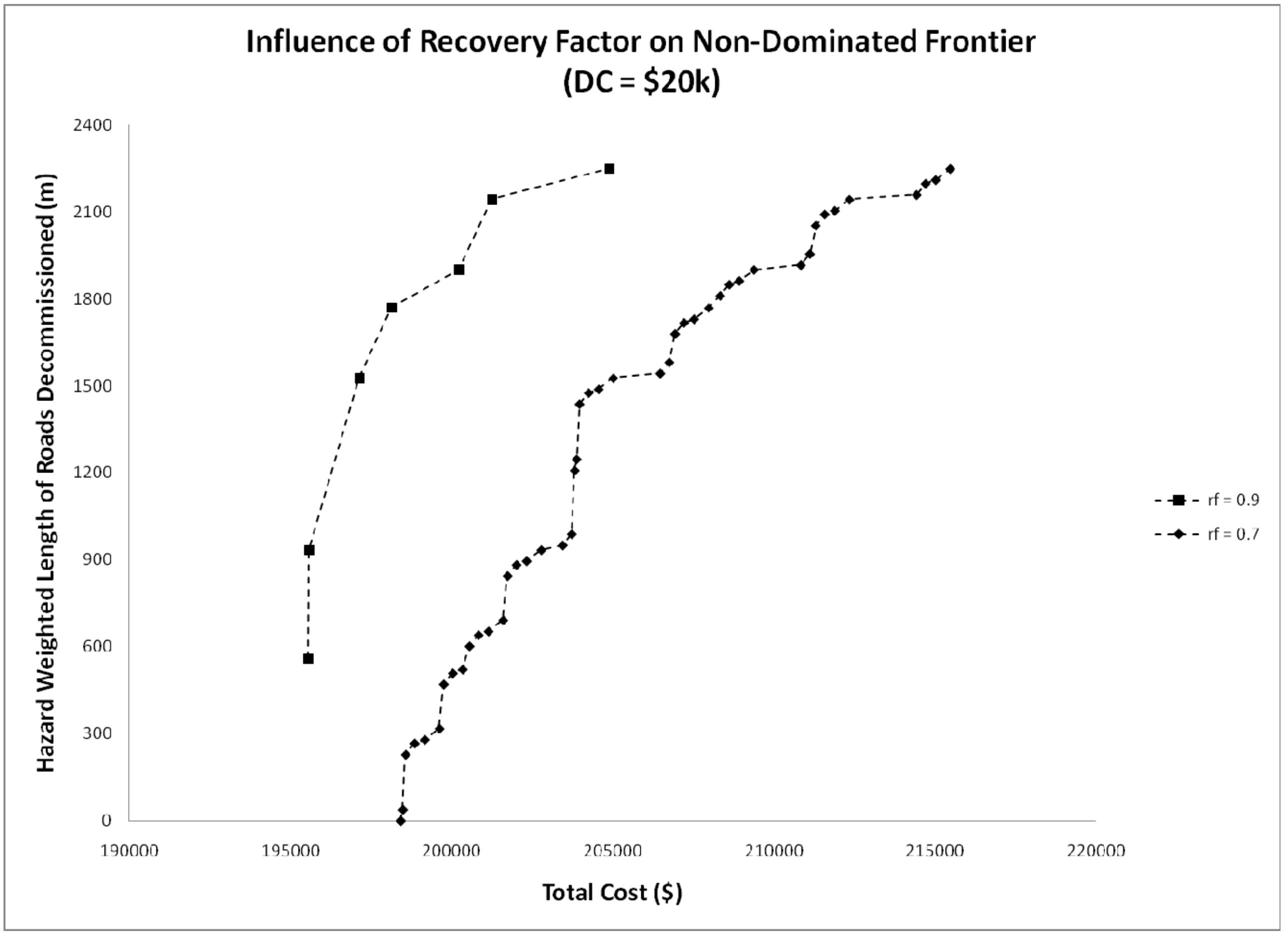
Influence of Recovery Factor on Non-Dominated Frontier
(DC = $20k)
Hazard Weighted Length of Roads Decommissioned (m)
2400
2100
1800
1500
1200
900
600
300
0
190000
195000
200000
205000
210000
215000
220000
Total Cost ($)
rf = 0.9
rf = 0.7

Table 6.1: Aggregate demanded (D_{jt}) for maintenance and construction projects (m^3), by period for the South Zone example. Maintenance projects require higher quality surfacing rock whereas construction projects require base layer quality. Data originally presented in Thompson and Sessions (2008).

Project Type	Road	Length (m)	Period	Aggregate Demanded (m^3)
Maintenance	600	3189	1, 2	2520
	660	747	1	518
Construction	650	2343	2	743
	761	902	1	939
	800	628	2	654
	811	205	2	213
	6021	280	1	292
Totals		**6666**		**5879**

Table 6.2: Removal costs (*h_{ikt}*) and aggregate available (*A_{it}*) from spurs slated for removal (m^3); South Zone example. Costs presented were calculated using $7500/km for closure and $20,000/km for decommissioning. Data originally presented in Thompson and Sessions (2008).

Road	Removal Period	Length (m)	Aggregate Available (m^3)	Closure Cost ($)	Decommissioning Cost ($)
620	1	393.61	410	$2,952	$7,872
630	1	213.23	222	$1,599	$4,265
660	1	346.27	360	$2,597	$6,925
681	2	835.06	869	$6,263	$16,701
720	2	2,417.22	2,515	$18,129	$48,344
762	2	732.97	763	$5,497	$14,659
771	2	588.47	612	$4,413	$11,769
Totals		**5,526.80**	**5,751**	**$41,451**	**$110,536**

Table 6.3: Unit Costs (\$/m^3) for procurement, processing and delivery (g_{sjt}) of aggregate from sources (abandoned roads and quarry) to other road segments in need of aggregate. Maintenance projects have higher processing costs if the source is recovered aggregate. Data originally presented in Thompson and Sessions (2008).

Aggregate Sources	**Segments Demanding Aggregate**						
	Maintenance		**Construction**				
Decommissioned Roads	**600**	**660**	**650**	**761**	**800**	**811**	**6021**
620	\$5.97	\$8.00	\$4.43	\$7.12	\$5.41	\$5.17	\$8.26
630	\$5.85	\$7.71	\$4.14	\$7.29	\$5.49	\$5.25	\$7.86
660	\$6.46	\$5.94	\$3.41	\$9.15	\$7.37	\$7.12	\$7.13
681	\$8.23	\$8.23	\$5.18	\$5.70	\$9.04	\$8.79	\$5.61
720	\$7.74	\$10.48	\$6.91	\$5.58	\$4.76	\$4.52	\$10.79
762	\$9.45	\$12.19	\$8.62	\$4.07	\$6.54	\$6.30	\$9.71
771	\$9.24	\$9.76	\$6.19	\$5.31	\$7.35	\$7.11	\$7.17
Quarry	\$18.10	\$20.32	\$20.32	\$21.60	\$19.84	\$19.59	\$24.04

Table 6.4: Road segment information passed into knowledge base to evaluate each road segment's relative effect on the aquatic environment. Columns, from left to right, present information on number of stream crossing per kilometer, distance from the road segment to a stream, and the road segment's position on hillslope.

Road Segment	Stream Crossings	Distance to Stream	Hillslope Position	Slope
620	0 / km	> 100 m	Ridge	0%
630	0 / km	> 100 m	Ridge	14%
660	0 / km	> 100 m	Ridge	1%
681	0 / km	71 m	Ridge	0%
720	1.70 / km	50 m	Streamside	6%
762	0 / km	> 100 m	Ridge	8%
771	0 / km	> 100 m	Ridge	1%

Table 6.5: Calculated truth values scores representing the degree of truth of the assertion, "the road has a high potential for causing damage to the aquatic environment." These hazard scores were used to weight the length of each road to arrive at a proxy for environmental performance, hazard-weighted length of roads decommissioned.

Road Segment	Potential Environmental Impact				Truth Value Score
	Stream Channel Integrity		Erosion Risk		
	Stream Crossings	Distance to Stream	Hillslope Position	Slope	
620	0.00	0.00	0.50	0.00	0.13
630	0.00	0.00	0.50	0.93	0.66
660	0.00	0.00	0.50	0.07	0.18
681	0.00	0.29	0.50	0.00	0.29
720	0.34	0.50	0.00	0.40	0.50
762	0.00	0.00	0.50	0.53	0.51
771	0.00	0.00	0.50	0.07	0.18

7 Conclusion

The purpose of this dissertation was to develop decision support models that will lead to improved economic and environmental efficiency in the management of forest road networks. In particular, I focused on developing methods to quantify the inherent tradeoffs associated with forest road management and protection of aquatic resources. A major contribution is the formulation and implementation of optimization approaches that explicitly consider multiple objectives, in order to identify the tradeoff surface comprised of efficient, or non-dominated, solutions. This, in turn, allows for an improved understanding of the relationship between increased expenditures and the associated marginal environmental benefits. It also allows for landowners to evaluate their current practices and identify where improvements can be made. To the author's knowledge this dissertation constitutes the first application of technical efficiency to forest road erosion control. Transitioning to a multi-objective planning paradigm is appropriate for forest road management, where uncertainty exists with regard to identification of target environmental performance levels, where objectives are quantitatively expressed in non-commensurate scales, and where road management decisions necessarily involve informed compromise.

My work reflects an interdisciplinary approach, integrating forest engineering principles with a diverse array of other fields, including applied economics, combinatorial optimization, multi-objective optimization, multi-criteria decision making, graph and network theory, computer science, and evolutionary computation. Drawing from these fields, I developed computer-based decision aids, which pair mathematical formulations with appropriate solution methods. In Chapter 2, I introduced the notion of technical efficiency and illustrated application of the concept to forest road erosion control. The intent of the chapter was to demonstrate the utility of adopting an a posteriori optimization approach, wherein the decision maker's preferences are elicited only after being presented with the realm of feasible and efficient possibilities. Though methods exist to systematically elicit and weight preferences, a priori optimization approaches suffer from the facts that preferences can change, and there generally is no single answer that simultaneously optimizes all objectives. In subsequent chapters I focus on application of technical efficiency to improve efficiency of specific road management activities: regular maintenance (grading), and road removal and aggregate resource management.

Another contribution of this dissertation is the extension of decision support frameworks from single to multiple objective formulations. Chapters 3-4 illustrate this extension for vehicle routing algorithms designed to intelligently deploy forest road maintenance vehicles. Chapters 5-6 illustrate this extension for mixed-integer formulations that identify optimal aggregate recycling and road removal policies. Extending analyses to multi-objective frameworks requires the explicit definition of metrics for environmental performance. Generating estimates of treatment efficacy is a prerequisite for prioritizing treatments on the basis of cost/benefit, as well as for evaluating how well environmental objectives are met as a result of treatment. In some locales, generation of a predictive sediment inventory is also a regulatory requirement, as I described in Chapter 1. For this dissertation I relied upon published, peer-reviewed models that estimate sediment production and delivery (Chapter 2), estimate rut depth formation in response to traffic (Chapter 4), and assign segment-level hazard, or risk, scores (Chapter 6). I also considered an implicit benefit from treatment (Chapter 3) and adopted a common policy among managers in the western U.S., to maximize the length of roads treated (Chapter 5).

Lastly, this dissertation contributes to the discipline by advancing the notion that aggregate recycling can effectively subsidize road decommissioning projects. Procurement and delivery costs associated with recovering aggregate from decommissioned roads can be significantly less than aggregate procured from quarries, providing opportunities for substantial cost savings. On federal land, recognizing this potential and planning appropriately could help managers improve and/or remove additional roads given their limited budgets. Other state and private landowners more concerned with timber production will be interested in improving the overall efficiency of their aggregate management practices. As I demonstrate, aggregate recycling projects have and continue to be implemented in practice, and my work facilitates these activities by providing a framework for systematic analysis.

My work is immediately relevant and is intended to benefit both public and private forest transportation managers. On public lands in the Pacific Northwest, where watershed restoration is a dominant management objective, this research should facilitate strategic road removal and improvement planning. Incorporating aggregate recycling into current management practices, where practical, should release resources for other restoration-oriented activities, ideally resulting in better achievement of the goals of the

Aquatic Conservation Strategy. Private landowners can adopt formulations recommended here to improve their overall erosion control strategies, to improve grading practices, and to reduce the overall cost of aggregate management. Identifying the efficient frontier provides valuable information on what is and what is not possible with respect to efficient management, and should help landowners better understand their respective tradeoff curves, possibly to demonstrate that additional regulatory restrictions are unnecessary or impractical.

Perhaps the greatest rationale for private landowners to adopt a multi-objective planning paradigm is the specter of additional regulatory restrictions stemming from the Clean Water Act. Already, road-related sediment is targeted as a contributing source of pollution in many water quality limited streams subject to total maximum daily loads (TMDLs), and regional water quality management plans, such as the General Waste Discharge Requirement program administered by the California North Coast Regional Water Quality Board, can place additional limitations on landowners. Perhaps most worrisome to landowners, forest roads and their associated drainage structures may be considered as "point sources" of pollution, and therefore subject to National Pollutant Discharge Elimination System (NPDES) permitting requirements. District courts in California and Oregon have reached conflicting decisions on this matter, with an appeal currently before the 9th Circuit Court of Appeals. As outlined in Chapters 1-2, the NPDES permitting process for conventional pollutants (including sediment) is entirely premised upon tradeoff analysis. Forest landowners subject to permit requirements would be forced to reduce road-related pollution up to the point where the marginal benefits per dollar spent begin to markedly decline. Multi-objective programming methods presented here are exactly the type of decision support system required in this context.

The remainder of this conclusion is dedicated to summarizing the major findings and implications of each chapter in the dissertation, and discussing future work.

As the intent of this dissertation was to illustrate the potential for multi-objective optimization techniques to improve efficiency in the objective space, we did not focus on the decision space. An interesting area of research, therefore, is the search for commonalities between efficient solutions, perhaps through pattern analysis or a similar technique. For instance, it might be that a similar subset of road treatments appears in most non-dominated solutions. The identification of emergent patterns might facilitate on the ground decision-making, a more intuitive process driven by experience and informed by pattern analysis. When analyzing optimal grading policies, we may begin to see certain road segments assigned significantly higher grading frequencies, and begin to formulate simpler heuristics with respect to grading decisions, such as grade proximal segments in clusters, or target only specific problematic road segments irrespective of their distance from each other. We might likewise develop overarching strategies for road erosion control treatments such as focusing on removing hydrologic road/stream connections, or applying additional aggregate on roads serving high levels of traffic, etc.

It is my belief that moving to multi-objective planning frameworks is both appropriate and preferable for contemporary forest road management moving forward. I hope this work will stimulate additional research into tradeoff analysis, and ultimately will lead to improved economic and environmental efficiency in the management of forest transportation networks.

7.1 Forest Road Erosion Control Using Technical Efficiency (Chapter 2)

Chapter 2 presented a novel application of decision support applied to forest road management, wherein I made use of the principles of forest and industrial engineering to identify efficient road management alternatives. Specifically I proposed the use of multi-objective programming techniques to identify the efficient frontier between sediment reduction and management costs. In natural resources management, road management in particular, incorporation of competing objectives is common and therefore having a tool to facilitate tradeoff analysis should prove useful. Ultimately, the tradeoff-analysis techniques promoted in this chapter should facilitate improved and efficient forest road management.

Future research could seek to apply the methods presented here across a larger ownership, or to include a broader scope of possible treatments. For instance, researchers could include as decision variables maintenance regimes, traffic levels, seasonal road closure, and reduced tire inflation. Also important to include in the tradeoff analysis are the opportunity costs of such management actions. Toman et al. (2007) for example demonstrated that the opportunity costs associated with restricting wet weather timber haul and harvest could be up to 18% of total net revenue. Work pairing tradeoff analysis with adaptive management paradigms would also be a promising direction. For instance, it may be possible to incorporate model uncertainty into our multi-objective programming approach, perhaps through robust optimization or other techniques. Alternatively, it may be possible to develop approaches that identify not only optimal allocations of resources between monitoring and treatment, but what types of monitoring and treatment to apply.

Advancements in computing capacity and in algorithmic development increasingly make solving more complex problems, such as those with multiple objectives, possible. I therefore expect that techniques to identify efficient frontiers will become preferable to traditional methods that seek to condense multiple objectives into a single objective function. It is my hope that this manuscript demonstrating the utility of technical efficiency for road management will spur future research into environmentally and economically efficient multi-objective road management.

7.2 Intelligent Deployment of Forest Road Graders (Chapter 3)

Chapter 3 presented the design and application of a combinatorial heuristic to route a forest road maintenance vehicle (grader) across a road network. The particular solution method employed was tabu search paired with two local search routines, and sought minimal cost tours, using tour length as a proxy. The local search routines sought to increase overall tour efficiency by identifying instances where segments requiring grading are traversed when en route to other segments requiring grading, and by intelligently partitioning the tour if necessary due to exceeding the daily time limit. The problem is modeled as an instance of the rural postman problem, where some subset of edges in a network requires service. Other applications of the rural postman problem include street sweeping and garbage collection. Road segments requiring grading were identified according to a rubric based on road standard and road roughness index.

Initial testing on small road networks suggested the heuristic performed quite well, reaching the known optimal solution in 2107 of 2400 runs (87.79%) for problem instances with no operating constraints, and in 1037 of 1200 runs (86.42%) for instances with operational time constraints. Aggregate percent deviation was 0.52% and 0.71%, for the constraint-free scenario and operating time limit scenario, respectively. Even in instances where the optimal solution was achieved only a relatively small proportion of the time, the algorithm output the known 2^{nd} best solution for a number of trials, suggesting overall high performance.

For the much larger forest road network (modeled after a portion of the actual road network of the McDonald Dunn Forest), the low average deviation suggests that the heuristic consistently obtains good results, although there is no optimal solution as a basis for comparison. Since it is difficult to compare solutions against a known or estimated optimal value, it might be informative to learn if the heuristic would yield improvements over current practices. To validate the model I developed a greedy heuristic, which might mimic how a grader operator would traverse the network to grade the segments. Starting from the depot, the grader first travels to the closest segment requiring grading and services that segment. From there, the grader travels to the next nearest segment requiring grading, and so on until all segments requiring grading have been serviced. When tested on the largest network, the tabu search heuristic achieved a 12.5% reduction in total grading time as compared to the greedy heuristic. Given that in practice an operator may not know with certainty which is the nearest segment requiring service, it is possible savings could be even higher. Further, given that in practice many grading decisions are assigned not based on road condition but on time since the last grading, the overall decision framework presented here may yield substantial reductions in overall maintenance cost.

Future research should focus on both the solution methodology and the problem definition. Improvements might be achievable by increasing the complexity of the tabu search heuristic, such as utilizing a dynamic tabu list size or implementing harmonic oscillation. The tour partition heuristic could also be expanded and possibly implemented as a combinatorial heuristic such as tabu search or simulated annealing. This method would be of great benefit in cases where the initial tour's length is so great as to require multiple partitions; the world of possible partitions increases exponentially with respect to a unit increase in the number of partitions required. Incorporation of time-windows would create a more realistic model, applicable perhaps to a high volume network experiencing simultaneous haul and maintenance traffic. Some industrial applications might involve a fleet of graders, operating from different depots or perhaps without an assigned depot. Operational time constraints may not be quite so limiting, allowing for a small exceedance in order to gain overall tour efficiency.

Future work could also be devoted to creating a broader decision framework for determining which segments to grade. Rather than utilize a binary decision rule, priorities could be established for segments requiring service. Thus the heuristic would ensure that some segments of the highest priority are graded, but in addition would seek opportunities to grade other high priority segments. If successfully implemented this framework could free up future resources for other maintenance activities, hopefully preventing future drainage and transportation problems. Perhaps this method would best be employed in scenarios where the manager's goal is to achieve the highest level of maintenance possible, rather than a goal of cost minimization.

The intent of Chapter 3 is to demonstrate the potential for cost savings in grader scheduling and deployment. My developed heuristic performed well on both cyclical and dendritic networks, the latter being more common in mountainous terrain. Results demonstrate the gains possible from using computational methods to evaluate complex decisions, especially in light of the current management practices, which cannot or do not account for the combinatorial nature of the networks. The tabu search heuristic presented in this chapter can provide for improved decision making with regard to routing graders, and could improve overall road maintenance.

7.3 Identifying Optimal Forest Road Grading Policies Using a Multi-Objective Evolutionary Algorithm (Chapter 4)

Chapter 4 extended the work of chapter 3 to consider vehicle operating costs in addition to maintenance costs, and to simultaneously seek to optimize an environmental objective. The hazard-weighted rut depth for each road segment was identified as a suitable proxy for environmental performance. Rut depth was selected because it is an indicator of the degree to which the surface of the road is degraded, because higher rut depths increase vehicle operating costs, because the presence of ruts can substantially increase the risk of environmental degradation, and because the act of grading is designed specifically to remove ruts and other surface failures (washboarding, potholes, etc.). Hazard weights were assigned based upon segment length, recognizing the importance of flow path length in sediment delivery.

Substantial sums are expended on gravel road maintenance throughout the world, but there has been limited research directed towards systematically managing gravel roads. Road maintenance and transport activities have been linked to sediment production, but again, there has been limited research directed toward systematically managing roads for sediment production. In the U.S., roads are receiving increasing attention for their negative impacts on water quality, particularly relating to impacts on fish. Although this attention has primarily been focused on forest lands, increasing attention is being directed toward aggregate surfaced roads on non-forested lands as well. I brought together the ideas for managing roads to simultaneously minimize user costs and environmental degradation associated with formation of ruts and other road surface failures. My examples have drawn coefficients from empirical results from the literature. They are not intended to be handbook ready formulas, but are drawn from specific studies and are intended to illustrate a conceptual system for approaching aggregate road management.

Future work in this area could focus on improving development of both the solution algorithm and the operational model. Though solutions did appear to span large regions of the objective space, it may be fruitful to consider using the notion entropy to promote diversity along the non-dominated front (Farhang-Mehr and Azarm 2002). One option mentioned earlier is to move to a parallel processing setup to speed up fitness evaluations, and possibly to include much larger populations to offer a wider look into the decision space. As we emphasized the role of mutation, considering other MOEAs that focus on mutation could also be interesting. The Pareto Archived Evolution Strategy of Knowles and Corne (2000), for instance, abandons recombination and only uses mutation to introduce diversity into the solution space.

On the operational model side, there exists the possibility to employ alternate models forms for both economic and environmental objectives. Perhaps most promising would be the adoption of alternate equations to model rut depth formation. A formulation developed by the Army Corps of Engineers (Barber et al. 1978) and used by the U.S. Forest Service for aggregate surface depth considers as input variables subgrade strength, surface strength, tire pressure, and traffic. Using this approach would allow for rut depth calculations more in line with what is expected for forest roads in the western U.S. The model might also be expanded to incorporate log truck routing, or time windows during which grading operations should not occur. Multiple maintenance vehicles and multiple depots would be appropriate for larger networks.

My results demonstrate the utility of using a multi-objective approach; using the Strength Pareto Evolutionary Algorithm I was able to identify efficient solutions that dominated simulated management policies in terms of economic and environmental performance. Adoption of an a posteriori optimization approach should facilitate tradeoff analysis and lead to informed compromise. Ultimately this manuscript demonstrates that use of computerized decision aids could lead to increased efficiency when determining routes for graders to take over a road network. The multi-objective programming techniques employed here should help landowners to “jointly produce” environmentally benign, low-cost road networks. I hope this discussion will stimulate additional research in road management of aggregate surfaced roads.

7.4 Optimal Policies for Aggregate Recycling from Decommissioned Forest Roads (Chapter 5)

Chapter 5 presented a cost minimization model for aggregate recovery and reuse, and demonstrated that use of such a model could result in substantial cost savings to landowners, possibly freeing up resources to implement other restoration-oriented projects. The chapter also presented a model to maximize environmental benefit from road removal, using the total length of roads decommissioned as a proxy. Tested on an example road network, incorporation of aggregate recycling demonstrates substantial cost-savings relative to a baseline scenario without recycling, increasing the likelihood of road decommissioning and reduced habitat degradation. I found that aggregate recycling can result in up to 24% in cost savings (economic objective) and up to 890% in additional length of roads decommissioned (environmental objective).

Use of these models with appropriate computer applications constitutes a decision support aid that can be used to facilitate road removal decisions. These models are general and easily extendable to other formulations, and should scale up to larger planning problems readily given advancements in computing capacity and commercially available solvers. While several simplifying assumptions were made for expository purposes, the management models presented here have practical applications. Aggregate recycling does occur in practice, as I demonstrated, and the formulation and data can be adjusted accordingly for specific situations. Future research could incorporate a broader road management optimization procedure, including additional removal treatments, maintenance regimes, and the decision of when to remove a road. Further work could also seek to apply an appropriate environmental hazard weighting techniques to maximize the hazard-weighted kilometers of road decommissioned.

I believe this manuscript demonstrates the advantages of recycling aggregate, which are both economic and environmental. Where feasible, transportation managers should investigate opportunities to recover and reuse suitable aggregate, thereby increasing efficiency while yielding environmental benefits. Using models such as those presented here, it should be possible to identify which roads should be treated at a given level and how aggregate sources should be allocated, in order to best achieve landowner objectives.

7.5 Exploring Environmental and Economic Tradeoffs Associated with Aggregate Recycling from Decommissioned Forest Roads (Chapter 6)

Chapter 6 extends the analysis from Chapter 5 in several significant ways. As described above, the major change is the simultaneous consideration of both economic and environmental objectives. That is, I seek to identify the entire frontier of efficient solutions, not just the boundary (minimal cost, maximal benefit) solutions identified in Chapter 5. Chapter 6 also extends the analysis of the role of aggregate recycling in effectively subsidizing removal projects. I defined an accounting variable ES (effective subsidy) as the difference in minimized cost between scenarios with and without the opportunity to recycle aggregate, at a given level of environmental performance. I then examined how ES varies with increasing levels of environmental performance. Results suggest a synergistic relationship between this subsidy and environmental performance, where subsidies generally increase with increasing environmental performance. Transportation managers are therefore able to recover and reuse a non-renewable resource, while at the same time promoting economic and environmental efficiency.

Chapter 6 also extends the work of Chapter 5 to include explicit calculation of a hazard factor. In Chapter 5, the model assumes that all road segments slated for removal are equally detrimental, and therefore the optimal treatment from an environmental perspective is simply a function of length. This assumption is reasonable if it is also assumed an experienced professional has identified appropriate levels of decommissioning such that the expected future impacts per unit length from each segment are nearly identical. With Chapter 6 to the contrary each segment is assigned a score on the scale (0, 1) reflecting the degree to which the segment has potential to cause environmental damage. Scores are assigned according to a model originally presented by Girvetz and Shilling (2003), who analyzed the Tahoe National Forest road system for potential environmental impacts according to the USDA Forest Service's "Roads Analysis" guidance document (USDA 1999).

This chapter presented mixed-integer, multi-objective mathematical programming formulations to identify optimal aggregate recycling and road removal policies. Previous research and real-world application have demonstrated the cost savings potential of recovering and reusing aggregate from decommissioned forest roads. I extended previous work by employing techniques to identify the efficient frontier of non-dominated solutions, and to include hazard factors to differentially weight road segments scheduled for removal. Identifying the frontier of non-dominated solutions facilitates tradeoff analysis and the selection of compromise solutions. Decision makers whose preferences are not best satisfied with boundary (minimal cost, maximal benefit) solutions are able to explore other efficient possibilities.

The type of analysis presented here should ultimately facilitate watershed restoration planning on federal lands in the Pacific Northwest. The utility of this approach is not however limited to federal ownerships or to the specific region discussed here. My proposed approach should help any class of landowners to manage their aggregate resources. On private lands with high levels of timber harvest, landowners may now be more likely to construct new temporary spurs with the intention of later recovering aggregate. This may entail construction with geotextiles, which as I demonstrated may increase cost savings.

My findings are not limited to the scenarios I modeled, where recovered aggregate is to be used within the same planning period. The recovered aggregate tested by Foltz and Truebe (2003), for instance, had been stockpiled for over 20 years. Similarly, aggregate recovered from decommissioned forest roads on the Umpqua National Forest was stockpiled for future use (Michael Karr, Work Supervisor, Road Maintenance and Project Team, Umpqua National Forest, personal communication, 2007). Forward thinking managers may therefore opt to incur aggregate recovery costs today in order to reduce aggregate procurements costs in the future.

Future work could seek to manage aggregate resources over a larger ownership, or to incorporate additional decision variables such as aggregate stockpiling, road improvement treatments, identification of which road segments to remove, and identification of when to remove segments. Practitioners could also employ more sophisticated and/or regionally-specific risk models. Here I intentionally adopted a decision support system that is also used by federal agencies to prioritize watershed restoration treatments and that has previously been used to prioritize road segments for removal, but certainly other approaches are valid.

I hope this research stimulates additional interest into aggregate recycling, and ultimately leads to improved economic and environmental efficiency in the management of forest transportation networks.

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