Chapter 10
Forest Harvest and Transportation

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Introduction

Timber is harvested to produce economic returns from forest lands, but it also impacts the environment. Forestry operations are often viewed as a tradeoff between economic benefits and environmental impacts, in which any additional environmental protection is seen as reducing economic returns. In exploring the economic and environmental costs of forest harvest and roading however, it is common to find that options for improving the economics can often improve the environmental impacts as well. An understanding of the operational considerations of logging and roading is the first step for understanding current forest practices, and for identifying options for improving economic and environmental returns from the forest.

Every logging operation consists of the following phases:
1. Felling – The trees are cut down.
*. Processing – Trees are cut into logs and limbs are removed.
2. Yarding – Logs are moved from the stump to the landing.
3. Loading – Logs are loaded for transport to the mill.
4. Hauling – Transport to the mill (usually by truck).

* Processing can occur at different phases, depending on the harvest system used.

While there are many economic impacts of forest harvesting (from the chainsaw manufacturer to the paper consumer) in this chapter we will consider only the costs of those who pay the loggers, reap the benefits, and thus decide how the forest will be managed. Once a harvest unit has been delineated and trees to be harvested have been identified, then the total value of the resulting logs can be determined from current mill prices, and every other aspect of the harvest operation is just a cost.

return = value - felling - processing - yarding - loading - hauling

Each of these costs includes not just the cost of labor and fuel, but the depreciation and risk entailed in owning the equipment. These costs and benefits of logging are both economic and environmental. A thinning operation which improves habitat *value* also involves yarding (with its direct costs) and roads (with their sediment and habitat fragmentation costs).

Harvest operations can be divided between primary (stump-to-truck) transportation and haul (secondary transport) to the mill (Conway 1982). Primary transportation moves low log volumes slowly (from 1 tonne in a cable thinning operation to 10 tonnes in a forwarder moving at walking speeds). Secondary transportation on smooth road surfaces and straight road alignments moves large volumes at high speeds (25-35 tonnes at 30-100 km/hour).

Timber Harvest – Stump-to-Truck

The conversion of a stand of trees into truckloads of logs at the mill is an industrial process. Specialized equipment and workers are assigned to different tasks and must coordinate their outputs and timing to avoid slowdowns and bottlenecks in the process. The following sections outline options for felling the trees, delimbing, bucking into logs, yarding to the road, and loading onto trucks.

Felling and Processing

Felling is the first step in converting trees into lumber, paper, and other products (Staaf & Wiksten 1984). Trees are felled either manually with a chainsaw or mechanically with a feller-buncher or harvester (Figure 10.1). The felled tree can either be *processed* (delimbed and bucked into logs) there in the woods, or processed at the landing. Whether manual or mechanized, limbing and bucking can be time consuming. The lengths into which the logs are bucked, however, determine the price received at the mill and the profitability of the whole operation. Mills that turn logs into products such as lumber and plywood of specific sizes need logs at least that large. When bucking the downed tree into logs, the logger must identify the best possible combination of log sizes, while avoiding breaks and other log defects. As much as 40% of the possible value can be lost in felling and processing (Conway 1982).

Manual felling is the preferred method in large timber and on steep terrain inaccessible to mechanized equipment. Manual felling is also dangerous, resulting in high levels of injuries and even fatalities (Workers’ Compensation Board 1999), resulting in insurance rates as high as 60 % of the faller’s wage. Manual thinning in dense stands is difficult, since felled trees often are caught by the residual trees causing unsafe conditions and delays.

The high cost of manual felling facilitated the move towards mechanized felling and processing (limbing and bucking). *Feller-bunchers* can drop timber into bunches (Figure 10.1) that can be more easily gathered for yarding than the scattered pieces left by manual felling. Mechanized felling operations are limited by tree size and terrain. Mechanized felling operations are the preferred method in timber stands with tree diameters typically less than 50 centimeters. Most

Figure 10.1 A feller-buncher (top left) fells trees into bunches (bottom left). A harvester (top right) fells and then delimbs and bucks the trees in its path, creating a slash mat that protects the soil. Logs are dropped in bundles or bunches to both sides of the yarding corridor (bottom right).

operational machines are limited to slopes less than 40% although in Europe harvesters are being used on slopes as steep as 50-55% (Heinimann *et al*. 2001).

Harvesters fell the trees, then limb, and buck them into logs. Processing the trees in front of the equipment creates a mat of slash, that protects the soil from compaction as the harvester and then the forwarder move over it. The slash is usually sufficiently mixed with soil so the fire hazard is not increased. Harvesters are used primarily in thinning. The short (< 8 m) logs produced by the harvesters can be efficiently handled in dense residual stands, improving production and reducing damage to residual trees - crucial considerations in thinning operations.

Yarding

There is a wide range of equipment systems used to transport the logs to the landing. For simplicity, we can group these systems according to whether the yarding equipment drives out to the stump (ground-based systems) or stays at the landing (cable-based systems) or flies to the log (helicopter yarding).

Ground-based Yarding

Ground-based systems (Figure 10.2) drive to the downed trees or logs and bring them back to the landing. Where topography, soils, and piece size permit, ground-based yarding is usually the most effective and flexible option for getting logs to the landing. Horses are one of the oldest ground-based systems, and still fill a limited niche. The advent of wheeled or tracked vehicles dramatically reduced yarding costs by increasing yarding speed and load size. Lifting the front end (skidding) or the entire log (forwarding) or swinging the log (shovel yarding) not only reduce the soil disturbance and erosion but also reduce the fuel and time costs of overcoming friction and hang-ups.

Figure 10.2. Ground-based equipment travels to the stump and brings logs/trees back to the landing. A wheeled grapple skidder (top left) can quickly grab bunches created by a feller-buncher, though a cable winch with chokers can replace the grapple in manually felled timber. A clam-bunk skidder (top right) can assemble and skid a much larger turn. A forwarder (bottom left) can collect a large turn from logs that have been felled and processed by a harvester. A shovel or log loader (bottom right) swings trees/logs towards the landing

Yarding productions rates (volume per hour) and production costs (cost per volume) are affected by stand density (trees per area), log sizes, yarding distances, payload, and operator skill. The skidder or forwarder drives to the felled trees or logs, collects these *pieces* to form a *turn*, which it brings back to the landing. The combination of high stand density and large piece size allows for fast accumulations of a turn. Low piece densities, such as in a partial cut, require more time to accumulate a comparable load, which can have an adverse effect on production rates and cost. Production rates and costs are also affected by skidding speed and payload brought to the landing. Wheeled skidders carry low payloads, but at 8-10 km/hour, are typically the fastest. The slow moving clam-bunk and forwarder carry a much larger payload. The wheeled skidders need to make two to four trips to equal the forwarding capacity of a forwarder or a clam-bunk, which can be important on sensitive soils where the number of trips over a skid trail may have to be limited to avoid site degradation. If the retention spacing of a thinning is large enough, skidders or forwarders can avoid damaging the retained trees, although the retained trees can still be at risk from soil compaction and root damage.

Ground-based systems are limited by soils (wheels/tracks on cohesive/frictional soils), obstacles (e.g., stumps, fallen logs, boulders) and terrain surface roughness (Malmberg 1989). Ground-based machinery typically is restricted to slopes less than 30–40% but can be limited to even lower slopes by any combination of soil conditions, obstacles, and ground roughness. Heavy or prolonged rain may further reduce or even prohibit the use of ground-based equipment. Mechanized felling-processing equipment is less affected by soil and slope conditions than skidders or forwarding equipment, which must cross this ground repeatedly.

Ground-based yarding on unfavorable soils and slopes can also cause soil compaction and erosion, although slash from harvesters can reduce these impacts. In the past, soil impacts were not fully recognized, and skidder trails disturbed much of the harvest area. More recently, the use of *designated* skid trails has resulted in significantly less ground disturbance. This disturbance is concentrated towards the landings, since relatively few logs come from the far side of the harvest area but all logs must travel to the landing. If the roads (and landings) are located near streams, then sediment eroded from these disturbed areas is more likely to be delivered to the streams than if the road network is not near the stream network.

Cable-based Yarding

Instead of moving the yarder to the log, cable systems move the log to the yarder. By stringing cables out into the woods and pulling the logs to the landing, cable systems overcome the topographic, soil, and speed limitations of ground-based logging systems. Cable systems however need considerable time to set up and to move to different parts of the harvested area.

Highlead

Early cable systems consisted of a steam engine turning a drum around which a cable was wound, with the end of the cable pulled to the log by horse. A second *haulback* drum and a *block* (pulley) in the woods were soon added to haul the *mainline* back out (Samset 1985). To minimize log drag and hang-ups, some vertical lift is provided by passing the mainline through a pulley in a *spar tree* or tower, held upright by *guyline* cables. The main and a haulback line form a loop, connected by the *butt rigging*, to which several short cables called *chokers* are attached, that are wrapped around logs by the *choker setter* crew. This *highlead* system is the simplest of cable systems (Figure 10.3), with a crew of 5-8.

Highlead systems have no ability to reach sideways (lateral reach) beyond the length of the chokers, and must change cable locations frequently. Passing through two or more pulleys (tail and corner block) at the far side of the harvest, the main and haulback lines form a triangle or fan-shaped setting that allows rapid shifting in cable location. Once all the logs have been yarded from along the cable's path, a new block is added along the back of the loop, and the loop is shortened by releasing it from the current block and letting it snap to this next corner block. As

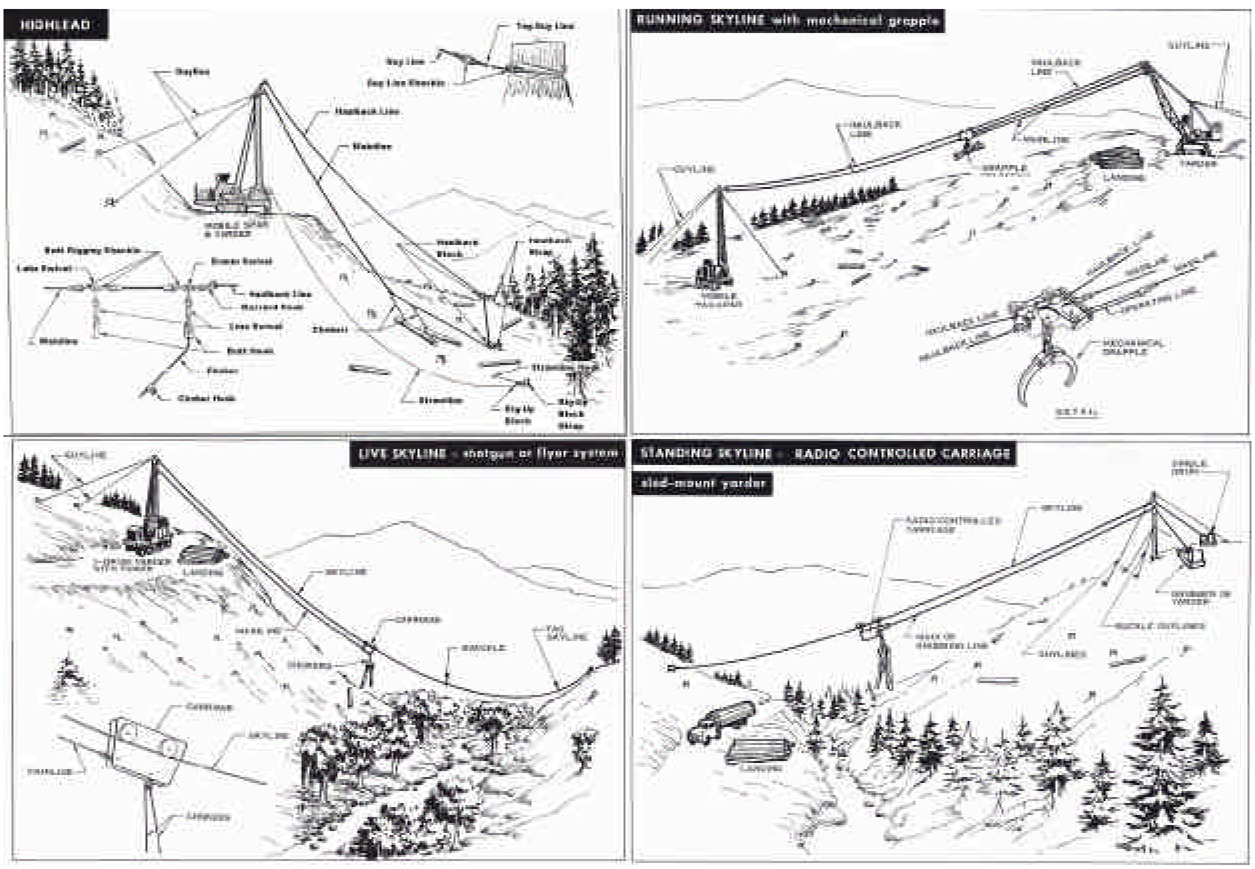

Figure 10.3 Cable yarders remain stationary while pulling logs to the landing. A highlead system (top left) provides limited vertical lift to the logs being pulled to the landing. A running skyline (bottom left) provides vertical lift by maintaining cable tension . The grapple carriage shown provides no lateral reach. A live skyline (top right) can lower the carriage to the ground or can be raised to provide lift. A standing skyline (bottom right) uses a radio-controlled carriage containing a winch with a dropline (Studier & Binkley 1974).

logging progresses, the cable sweeps across the harvest, successively producing a radial pattern of cable roads. Standing trees would get in the way, so this process is only appropriate in clearcuts. The highlead system has limited ability to provide vertical lift. Available vertical lift, log control, and production decrease rapidly away from the tower, so highlead yarding distances are usually less than 300 meters (Studier & Binkley 1974).

Highlead systems are not appropriate for most variable-retention silviculture systems, and are unsuited to dispersed retention such as thinning, although some pie-shaped retention aggregates at the end of corridors may be feasible. Soil disturbance and erosion from dragging logs is typically small compared to skidder yarding and is concentrated near the landing, so it is important that the landing is not located near the stream network (Megahan 1980).

Some vertical lift can be obtained by braking the haulback drum while pulling in on the mainline drum. Tension can be maintained more efficiently by mechanically *interlocking* the drums so that one pulls in while the other lets out. Replacing the butt rigging with a *carriage* that rides on the haulback line produces a *running skyline* (Figure 10.3). Set-up or rigging time can be improved by replacing the tower with a self-propelled crane and reducing the number of guylines to two. The mobility of the crane allows for rapid shifts in yarder location. When used with carriages with lateral reach, running skylines can be used for variable retention silviculture, especially if aggregated or in a heavy partial cut. They are not appropriate in thinning because the moving lines damage the residual trees.

Adding a grapple attachment (Figure 10.3) to the running skyline carriage allows *grapple yarding*. This remotely operated mechanical grapple eliminates the inherently dangerous job of manually looping chokers around the logs. A mobile backspar (often an excavator) is used to increase lift and to more quickly move the whole operation from one corridor to the next. The grapple yarder has no lateral reach so these yarding corridors are parallel and narrowly spaced. Where slopes are too steep (> 40-45%) to serve as a landing, logs can be landed at the roadside or on the road itself, in which case roads should be wider than normal (MacDonald 1999). Grapple yarding is usually limited to about 150-200 meters, preferably less. The combination of short yarding distances, fast line speeds, minimal hook times and deployment in areas with large log dimensions can yield high production rates of 400-500 m^3 per shift. Lacking lateral reach, grapple yarders are not appropriate systems for most retention silviculture, especially if the retained trees are dispersed.

True Skylines

Vertical lift can also be provided by adding a *carriage* that runs on a dedicated *skyline* suspended between the yarder and the *backspar*, such as a tree or stump (Figure 10.3). These systems are usually employed in steep terrain, where road access is difficult and therefore longer yarding distances are required. When logging uphill, gravity is sufficient to return the carriage to the woods and no haulback line is needed. When yarding down to the yarder, skylines require a haulback, requiring additional rigging or set-up time.

Simple carriages with chokers directly attached access only the wood in the yarding corridor. Carriages with chokers attached to a *dropline* that can be pulled laterally to yard 10-30 meters on each side of the skyline corridor. The dropline can be attached to the mainline (mechanical slackpulling), or attached to a small, radio-controlled winch in the carriage.

If both ends of the skyline cable are anchored, then the skyline cannot be lowered or raised, and a dropline is usually needed to reach the wood. This *standing skyline* system is typically used where full suspension along the full length of the yarding corridor is required or desired, such as to move logs from one side of a stream to the other, or for yarding long distances up to 1000-1500 meters. Where topography allows, the system can even carry logs over the tops of standing trees. Topographic liminations can be overcome by hanging the skyline over *intermediate supports*.

Alternately, the skyline can be raised and lowered by running one end of the skyline to a drum on the yarder to create a *live skyline* or *slackline* system (Figure 10.3). Where chokers are attached directly to the carriage, the skyline must be lowered to the choker setters, but this configuration has no lateral excursion capability. Where chokers are attached to a dropline they can be pulled laterally beyond the yarding corridor.

The weight of the logs, carriage, and cable causes the cable to sag towards the ground. The more it can be allowed to sag, the more weight it can carry. This *turn weight* can often be increased with a tall tower and often by elevating the skyline tail hold in a tree or up the opposite side of the valley. Concave topography provide near ideal conditions for skyline operations whereas convex topography are very difficult to log at any distance without intermediate supports. Skyline systems usually yard logs with one end off the ground (partial suspension), although full suspension (logs are lifted entirely off the ground) is also possible. The ability to provide partial or full suspension improves log control and reduces hang-ups, thus improving production and reducing ground disturbance.

Silvicultural systems that require a significant number of retained trees (e.g. thinnings, partial cuts) require a cable system that allows for both lateral reach and partial or full load suspension. Highlead systems, allowing neither, are appropriate only for clear-cut operations. Grapple yarding systems can provide partial or full load suspension but lack lateral reach capabilities, so they are suitable only for clear-cuts. Their lateral reach and load suspension make standing skyline the cable system of choice for thinning or high levels of tree retention.

Helicopter Yarding

Where soils, topography or other issues inhibit cable or ground-based yarding, the high cost of helicopter yarding can be justified. Helicopter operations usually have very high operating costs (US$16,000-28,000 per shift) and production rates (up to 1500 m^3/shift) compared to ground-based or cable-based systems. These costs necessitate running the helicopters at near-capacity payloads of 2,000-10,000 kg (Studier & Neal 1993). Helicopter logging also requires a large and highly skilled crew, and substantial planning and coordination to maintain efficiency. Fuel must be kept on site, logs must always be ready for lifting, log destination points kept clear, and fallers must ensure that log weights do not exceed the helicopter's payload capacity. Maximum yarding distances should not exceed 2000 meters (a flight time of 2 minutes), with level to downward flight paths so gravity can assist the loaded flight. Helicopters may use roadsides or water bodies as landings. Helicopters are more sensitive to wind and fog than are cable-based systems. Wind speeds above 50 km/hr will usually ground a helicopter operation.

Loading – The Interface between Primary and Secondary Transport

Operations at the landing can be just as varied as the yarding operations that moved the logs there. Logs are commonly loaded onto trucks with an excavator-type loader. It would be costly to have trucks waiting at the landing, so the landing also serves as a log storage site. Different log species and sizes are often used in different mills, so logs are often sorted by destination. Whole trees can be de-limbed and bucked at the landing by mechanized processors. Small pieces can be debarked and chipped at the landing.

The shape and size of a landing depends on whether logs/trees are yarded to a single landing by stationary towers or distributed along the road by mobile yarders or ground-based systems. Yarding and loading can be more flexible and efficient when the wood is not all yarded to a single location. In steep topography it can be difficult to find or create a horizontal space large enough for landing operations. Log storage space can fill quickly, necessitating a loader on-site during yarding. Log processing and storage is thus restricted in such confined landings (Schuh & Kellog 1988). Swing yarders that move from one yarding corridor to the next, can stack the small volume from each corridor at roadside. This wood can be loaded after the yarding has been completed.

The environmental impact of sediment eroded from landings depends largely on their location. It is more likely to reach vulnerable streams if roads and landings are located near streams. The excavated soils and logging debris from a cable landing on steep slopes can provide a significant source of subsequent landsliding. Helicopter yarding operations can require very large flat landings and the significant soil disturbance this entails.

Harvest Systems

With the variety of felling, processing, yarding, and loading options, the number of possible combinations of these components is very large. Topography, timber, and soils tend to favor some combinations over others however, and the requirements of each component tend to make it work better with some components than others. Where soils, topography, and log size permit, labor costs can be reduced using mechanized systems that drag (skidders), carry (forwarders), or swing (shovel yarders) the logs to the landing. When topography or soils inhibit ground operations, cables strung from towers can drag or fly the log to the landing. When neither ground nor cable systems will work effectively, more expensive helicopter systems can fly logs to the landing. When yarding distances are large, more time is spent driving to and from the woods, thus favoring the larger loads of forwarders and clambunks, and the vertical lift afforded by skyline systems. When the road density is high and yarding distances are short, inbound and outbound speed is less important than the time needed to pickup and drop a load (favoring skidders and shovel yarders) and change cable corridors (favoring highlead and grapple systems).

In retention harvests and thinnings, harvest systems are constrained both by what is cut and what is left. Harvested logs must be pulled out without causing excessive damage to the retained trees. Highlead and grapple yarder systems can not maneuver logs through the standing trees into the cable corridor. Ground-based and some cable systems (skylines with lateral reach) can move through the thinned stand, but have difficulties on side slopes, with logs swinging downhill and damaging the retained timber. The size and number of trees removed can further constrain the harvest. There is usually a negative relationship between harvested volume and harvest unit costs ($\$/m^3$). Lower timber volumes can render unprofitable all but the most efficient harvest system, necessitating careful consideration of where the conversion from tree to logs will take place.

In thinning operations, the small logs and narrowly spaced residual trees tend to favor *shortwood* methods, in which trees are felled, delimbed, and bucked in the harvest area then carried by forwarder to the landings. Tops and branches can be left scattered in the cutover area or be concentrated along skidding trails for equipment to travel over. The resulting pulpwood and sawlogs (usually 4-6 m) allow for better handling, resulting in less damage to residual trees and smaller landing sizes.

When not prohibited by landing and log size, yarding and processing costs can be reduced by yarding the *whole tree* (branches and tops attached) to the landing. Whole trees are processed at the landing, or transported as whole trees to a central processing yard or mill. Processing at the landing may involve bucking to logs and/or chipping of the tops or the whole tree (typical for early thinning material). Limbs, tops, and sometimes bark accumulate at the landing and may require disposal. The whole-tree approach reduces the slash left on the site which may reduce fire risks, but the removal of branches, needles and leaves from the site can reduce available nutrients. The additional processing equipment and residue accumulation necessitate a large landing. This whole-tree approach lends itself to highly mechanized operations, requiring high capital costs but few people, with a feller-buncher followed by grapple skidder or clam-bunk skidder, and processor equipment at the landing.

In mature large diameter timber stands, trees are felled, limbed, and bucked at the stump with a chainsaw to *log-lengths* (6-15 m) or topped to *tree-length* (top diameter of 7-10 cm). The large log lengths are yarded by cable systems or simple ground-based equipment such as grapple skidders. Tree-length methods may require additional processing at the landing (some delimbing and bucking) and have larger landing requirements than shortwood methods.

Roads and Haul – Secondary Transport

Forest roads exist to provide cost effective transportation of people and equipment to the forest, and forest products from the forest to mills. In this section we focus on haul traffic, but road use for forest administration and recreation follow similar patterns, with similar economic and environmental costs. The total cost of a road is the sum of the cost to build it, plus the costs to maintain it, plus the costs to drive on it.

total = construction + maintenance + traffic

For example, consider the costs for three alternate road options (Table 10.1). The total annual cost is the sum of the road construction cost (divided by the amortization period), the annual maintenance cost, and the annual trucking cost. Note that in this example, the low standard option has the lowest construction costs, the high standard has the lowest trucking costs, but the total cost is minimized by the moderate standard road. This approach can also be used to evaluate alternative routes, such as a longer route on a gentle favorable grade versus a shorter route with a steeper grade.

If the annual haul volume in Table 10.1 were larger, the haul costs would be proportionally higher for each option, and the total cost would be lowest for the high design standard. Similarly, if the haul volume were lower, then haul cost would be proportionally smaller, the construction costs begin to dominate and the low standard road would have the lowest total cost. Traffic volume on little-used roads does not justify high construction costs, since the resulting improvements in haul time (or transport cost savings) do not offset the increased construction costs.

Table 10.1 Costs* for three alternate road options

	Design Standard		
	High	**Moderate**	**Low**
Construction	$40,000	$22,000	$15,000
Depreciation	$1,600	$880	$600
Maintenance	$300	$400	$500
Traffic	$2,500	$3,000	$3,500
Total cost	**$4,400**	**$4,280**	**$4,600**

*The total annual cost of a kilometer of road is the sum of the 25 year depreciated construction costs, the annual maintenance, and the cost of hauling 10 million cubic meters of material over it. With increasing design standard, construction costs increase but maintenance and traffic costs drop, yielding a total cost that is minimized by the moderate road standard for this moderate haul volume.

While the road network covers the entire landscape being accessed, the traffic is concentrated on just a few roads (Figure 10.4). Most of the roads in a road network carry little traffic, but most of the traffic to and from the woods is concentrated along a few heavily-used roads. Traffic volume on the many, little used roads does not warrant high construction costs since the resulting improvements in haul time (transport cost) do not offse the increased construction costs. In order to minimize the total cost of a road network, high transport costs are allowed along less used roads so as to minimize the

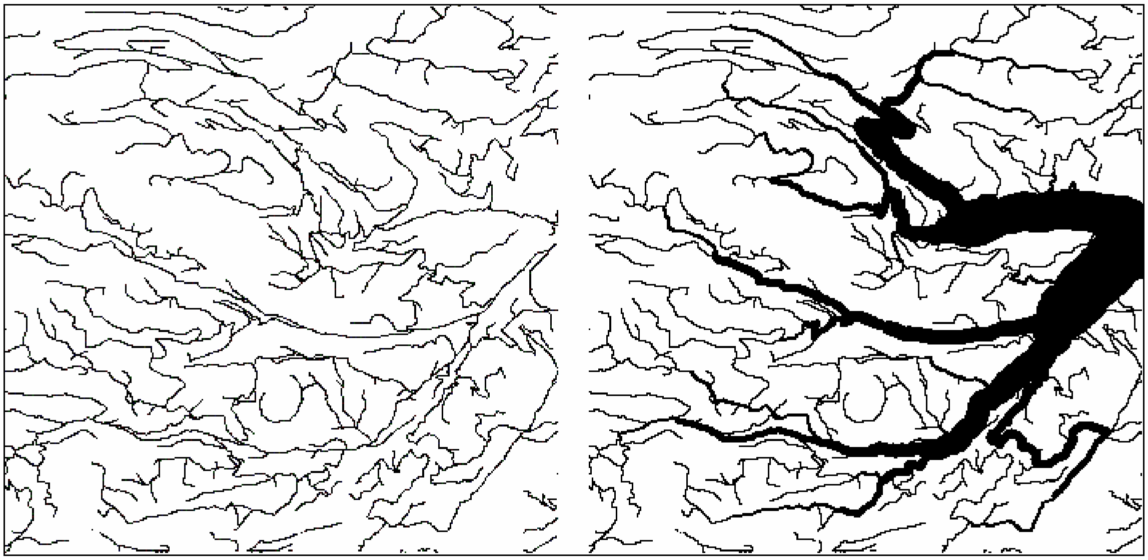

Figure 10.4 The road network (left) is spread across a landscape (in central Washington State), but haul traffic (right) is concentrated on a relatively small fraction of these roads. Haul traffic (line thickness) determines potential environmental impact and optimal construction and maintenance levels.

construction costs, while high construction costs are allowed along the heavily used roads so as to minimize traffic costs. In general, the heavily traveled roads will tend to be straight, flat, and wide, with good surfacing, while the less traveled roads are narrower, steeper and less straight, with little or no surfacing. The various tradeoffs are summarized according to traffic service level in Table 10.2.

Trucking Costs

When moving to and from the woods, time is money, and forest roads exist to reduce this transportation cost. Travel time is the inverse of travel speed, so increasing speed reduces costs. For example, at US $70/hour (the typical cost for truck and driver), increasing travel speed from 10 to 20 kilometer per hour on a half-kilometer segment of road reduces haul costs by $3.50 per round trip. Much like non-forest roads, travel speed is reduced by sharp turns, steep grades, and limited sight distances. Along narrow forest roads, travel speed can be further limited by road width, turnout spacing, and road surface roughness.

The environmental costs of forest road traffic are similar to the economic costs. Steep grades, sharp turns, rutted and potholed road surface not only slow traffic, but also increase the erosion of road surface materials. For example a road segment with asphalt surfacing provides a smooth running surface allowing for higher haul speeds and little or no sediment generation. A native surfaced road (with no surface improvement) is less expensive to build but will generate more sediment, reduce haul speeds, and increase trucking costs.

This haul cost and road erosion is not evenly or randomly distributed across the landscape, but instead is concentrated onto a few heavily used roads (Figure 10.4). Economic and environmental costs can be minimized by building these few heavily-used roads to a high standard. The many little-used roads contribute comparatively little to total trucking costs and road erosion. Trucks travel only a short distance on these low volume roads before entering higher volume roads which make up most of their trip to the mill. These many little-used roads can thus be built to low standards (Tables 10.1 and 10.2) with relatively little increase in haul cost and sediment impacts.

Construction

The construction of a road involves converting the natural topography into a road structure with specific design elements (Figure 10.5), each serving a particular function in maintaining the road and the access it provides to the forest. In constructing a forest road, the trees, organic material and topsoil are removed first. The topography must then be excavated and moved to match the intended road alignment. Drainage structures and surfacing layers may then be added to minimize future road damage and thus reduce future maintenance and environmental costs.

The organic material is sometimes incorporated into the road structure. Over time this material will decay, weakening the road structure and sometimes causing landsliding. These problems can be avoided by first removing any vegetation (clearing) and scraping away the remaining organic materials such as stumps and duff layer (grubbing). Depending on vegetation and side slopes, clearing and grubbing can comprise 10-20% of the total road construction cost

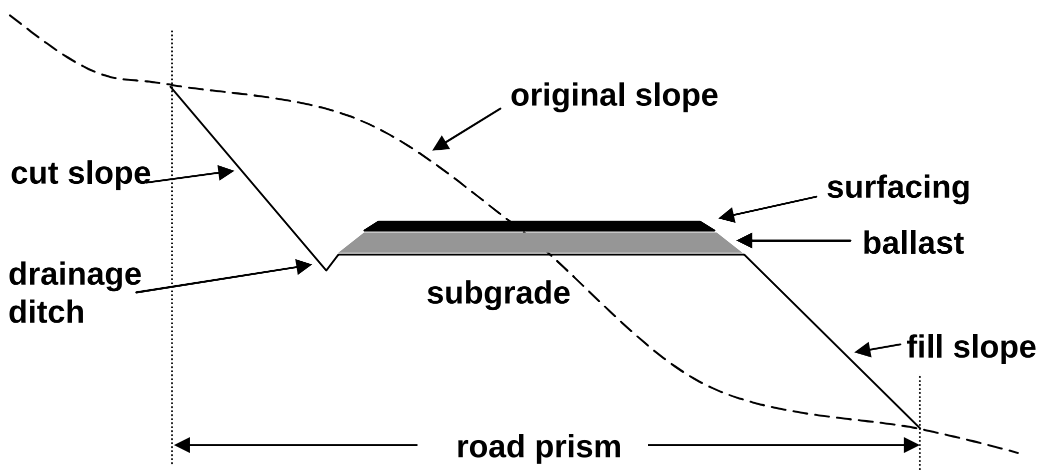

Figure 10.5 Road structural terms

A level surface is constructed by excavating, moving, and sometimes compacting soil. This earthwork can be done either by multiple passes of a bulldozer or by hydraulic excavator (Figure 10.6). Several earthwork strategies have been developed to minimize these economic

Table 10.2 Traffic service levels control the design, construction, and use of forest roads (USDA Forest Service 1982).

	A	B	C	D
FLOW	Free flowing with adequate parking facilities.	Congested during heavy traffic such as during peak logging or recreation	Interrupted by limited passing facilities, or slowed by the road condition.	Flow is slow or may be blocked by an activity. Two way traffic is difficult and may require backing to pass.
VOLUMES	Uncontrolled; will accommodate the expected traffic volumes.	Occasionally controlled during heavy use periods.	Erratic; frequently controlled as the capacity is reached.	Intermittent and usually controlled. Volume is limited to that associated with the single purpose.
VEHICLE TYPES	Mixed; includes the critical vehicle and all vehicles normally found on public roads.	Mixed; includes the critical vehicle and all vehicles normally found on public roads.	Controlled mix; accommodates all vehicle types including the critical vehicle. Some use may be controlled to vehicle types.	Single ue; not designed for mixed traffic. Some vehicles may not be able to negotiate. Concurrent use traffic is restricted.
CRITICAL VEHICLE	Clearances are adequate to allow free travel. Overload permits are required.	Traffic controls needed where clearances are marginal. Overload Permits are required.	Special provisions may be needed. Some vehicles will have difficulty negotiating some segments.	Some vehicles may not be able to negotiate. Loads may have to be off-loaded and walked in.
SAFETY	Safety features are a part of the design.	High priority in design. Some protection is accomplished by traffic management.	Most protection is provided by management.	The need for protection is minimized by low speeds and strict traffic controls.
TRAFFIC MANAGE MENT	Normally limited to regulatory, warning, and guide signs and permits	Employed to reduce traffic volume and conflicts.	Traffic controls are frequently needed during periods of high use by the dominant resource activity.	Used to discourage or prohibit traffic other than that associated with the single purpose.
USER COSTS	Minimize; transport-ation efficiency is important.	Generally higher than "A" because of slower speeds and increased delays.	Not important; efficiency of travel may be traded for lower construction cost.	Not considered.
ALIGNME NT	Design speeds is the predominant factor within feasible topographic limitations.	Influenced more strongly by topography than by speed and efficiency.	Generally dictated by topographic features and environmental factors. Design speeds are generally low.	Dictated by topography, environmental factors, and the design and critical vehicle limitations. Speed is not important.
ROAD SURFACE	Stable and smooth with little or no dust, considering the normal season of use.	Stable for the predominant traffic for the normal use season. Periodic dust control for heavy use or environmental reasons. Smoothness is commensurate with the design speed.	May not be stable under all traffic or weather conditions during the normal use season. Surface rutting, roughness, and dust may be present, but controlled for environmental or investment protection.	Rough and irregular. Travel with low clearance vehicle is difficult. Stable during dry conditions. Rutting and dusting controlled only for soil and water protection.

and environmental costs. Excavated material can rapidly be pushed downslope with a bulldozer blade, but this uncompacted *side cast* material, resting on organic material can become saturated with water and unstable. Excavating down to a level surface (full bench) and hauling away the excavated material (end haul) can become expensive if there are no stable dumping locations nearby. On steeper slopes, excavators allow the precise placement of material, reducing excavation requirements, improving fill construction and generally superior to bulldozer in both cost and quality of construction (FAO 1989).

The width that must be cleared and the volume that must be excavated increase with the gradient of the pre-existing side slope. This additional earthwork increases both the construction cost and the potential for environmental impacts. The resulting cut and fill slopes are steeper than the pre-existing topography. The more soil that is side-cast and the more the uphill soil is undercut, the greater the risk of future landsliding. The cut and fill slopes, devoid of a protective organic layer will also erode much more rapidly than the natural forest soils. Some of this erosion can be reduced if the cut and fill slopes can be revegetated after the road has been completed.

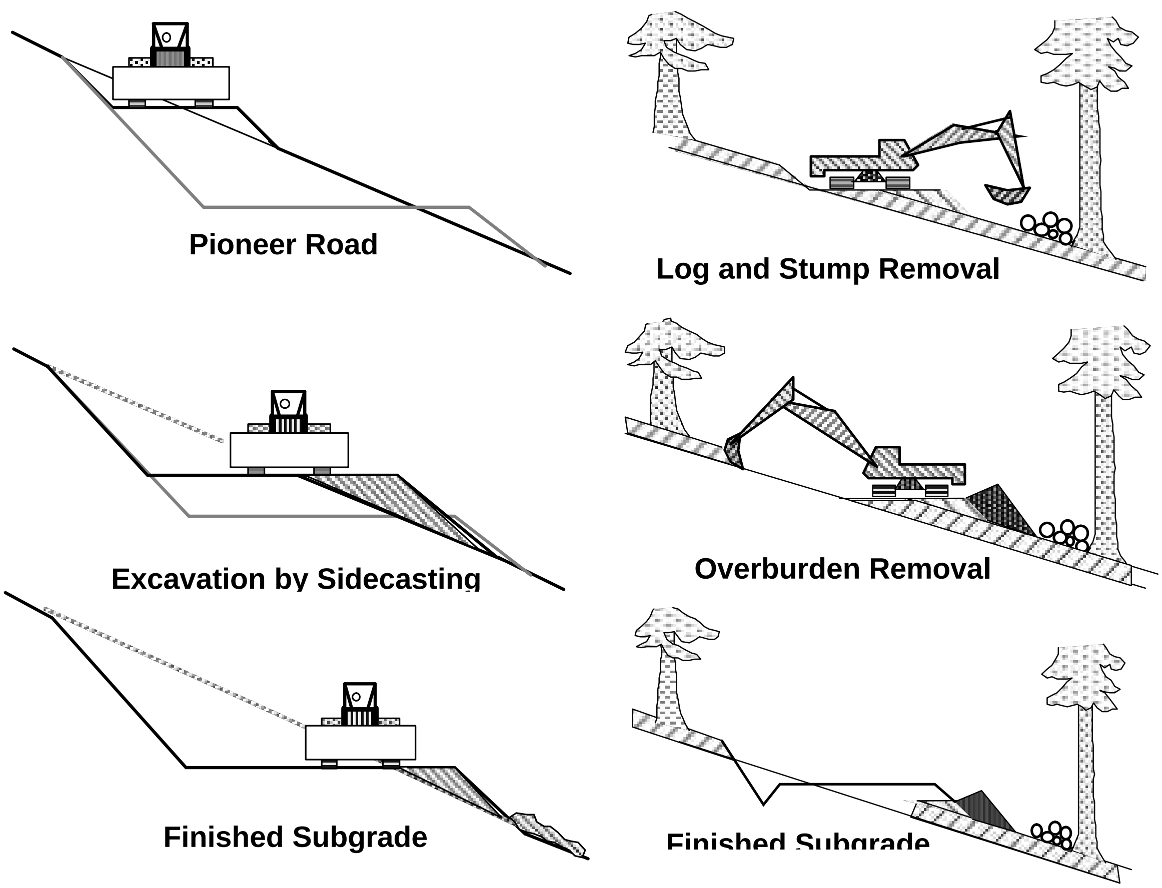

Figure 10.6 A bulldozer (left) can rapidly construct a road prism by repeated passes in which soil is pushed (sidecast) downhill. Excavators (right) proceed more slowly, but their greater control of placed material can dramatically reduce the earthwork and environmental impacts on steeper slopes

In some cases, the cleared and flattened soil can serve as the running surface of the road. Such *native surface* roads are common when traffic is to be restricted to the dry season. When these roads are wet, they tend to be vulnerable to traffic damage, such as deep ruts and high erosion rates. Adding an armoring layer of rock or gravel (ballast or base course) over the native soil can dramatically reduce traffic damage and sediment production (Kochenderfer & Helvey 1984) and maintenance requirements. Over time, traffic will push this armoring layer into the underlying soil (subgrade) which is then exposed to erosion and rutting. The rate at which the rock (ballast) layer is pushed into the subgrade is a function of traffic volume, the vehicle weight, the area over which this load is spread, and the strength of the underlying soil (subgrade). Local pressure can be reduced by increasing the number of axles on each truck and/or decreasing tire pressure, but the most common way to spread load is thicken the ballast layer. The strength of the subgrade can be increased by compaction, but subgrade soil will rapidly loose strength if it gets saturated. A surfacing layer of finer materials can be laid atop the ballast and graded outwards to shed rainwater and reduce infiltration to the subgrade. The ballast and surfacing is typically the major cost item of a road and can range from 30% to 60% of the total road construction cost.

The subgrade can also become saturated by surface and subsurface water from the surrounding forest. This water can be routed away from the road through a network of ditches and culverts. Unfortunately, this network can deliver sediment-laden runoff from the road surface and cut slope wherever it crosses the stream network. Sediment delivery to the stream network can be reduced by the judicious placement of cross drains and culverts to divert ditch water onto the forest floor where it can get filtered and trapped by the organic layer before it reaches a stream (Wiest 1998.)

The surest way to avoid road-stream interactions however, is to not build roads near streams. This may at first seem difficult because stream networks (like road networks) cross the entire landscape, seemingly necessitating numerous road-stream crossings. Valley bottoms are frequently the flattest and lowest gradient parts of the landscape, and many existing road alignments run parallel to or even directly up stream channels. Ridges form another low gradient network however, which covers the entire landscape, never crossing streams, and being midway between streams maximize road-stream separation. Locating roads along this ridge network can minimize road-stream crossings, and the resulting landings will concentrate their soil disturbance away from the stream network.

Maintenance

Once built, a road will begin to be damaged by traffic and other causes. Vehicles traveling over the surface, impose both compressive and shearing forces that can rut and otherwise damage the road, slowing traffic and eroding sediment. This road damage can be reduced by periodic maintenance. Potholes, rutting and wash-boarding can be eliminated by minor grading. The drainage network and cross-drains must also be periodically cleared of vegetation, sediment, and debris, which can slow or divert runoff and cause saturation and instability of the road prism. Maintenance costs can add up over time but they are often not considered in the initial planning of a road. While reducing erosion from road damage, maintenance is itself a source of soil disturbance and erosion, which must be weighed against its environmental benefits.

If a road will not be used for several years maintenance might be discontinued, but if the road is not blocked, traffic can continue to cause damage. Even if it is blocked, natural hydrologic, geomorphic, and vegetative processes will continue, leaving the drainage network vulnerable to sediment and debris accumulation, and the erosion, saturation, and landsliding they can cause. The economically cheapest approach might be to ignore this road damage and repair it only when reactivating the road, but the sediment delivered to the stream from the resulting drainage failures and landsliding may be environmentally unacceptable.

It may be cheaper to deconstruct much of the road instead of maintaining the drainage network during years of road inactivity. Deconstruction usually involves removal of cross drains and stream culverts that might plug and fail. Water bars can also be built across the road to route water off the road and dissipate its erosive force. Such alterations can be easily reversed when the road is reopened.

Instead of this partially deconstruction and then reconstruction, it may turn out to be better to totally eliminate the existing road, and build a replacement in a better location. Existing roads were built with technologies and management objectives that may no longer be valid. Stream-proximate road alignments and unstable fill slopes can be difficult and costly to ‘fix’. The cost of ballast/surfacing and drainage requirements may account for up to 80% of a new road construction, but a road following a ridge alignment may have so little chance of delivering sediment to the stream that no ballast is needed to prevent environmental impacts. This approach of building a whole new road is commonly overlooked in favor of repairing and upgrading existing or even overgrown road alignments.

If a road will only be used for a single dry season (and immediately deconstructed), then it need not be constructed to the drainage and slope stability standards of a permanent road. This approach can reduce both construction costs and environmental impact. If cut and fill slopes do not need to withstand wet season saturation, then they can be made steeper, reducing earthwork and clearing requirements. Logs and stumps can be used to stabilize and steepen the toe of the fill (a practice that should not be used in the construction of permanent roads). The subgrade is unlikely to become saturated during the dry season, so the road surface can be out-sloped to eliminate a roadside ditch and to further reduce road width. Where the native soil is strong enough, the use of ballasting and surfacing material can also be avoided, eliminating the cost of acquiring, hauling, and placing it, and the environmental costs of leaving or removing it. Where soils are soft and/or saturated, a good surfacing can be made by chipping the unmerchantable wood and debris, which can then be spread across the site when the road is eliminated. If on the other hand, the temporary road is built to the standards of a permanent road, it will be wider, and more costly, with much more exposed soil. It will take longer to build and un-build, so it will be more likely to deliver sediment during the wet season, assuming it is removed.

Road and Harvest Planning – Bringing It All Together

Harvest operations are about getting timber from the stump to the mill at the lowest economic and environmental cost (Table 10.3). As outlined in the previous sections, selection of the appropriate system is based on a number of variables, including:

- topography (slope steepness and variability);
- soil (saturation, composition, sensitivity to disturbance);
- silvicultural system (clear-cut, thinning, retention level/pattern);
- timber characteristics (tree size, volume, density);
- potential road access constraints;
- equipment characteristics and performance (production and cost);
- processing (limbing and bucking) location;
- stream and wetland distribution;
- mill and market requirements

In the preceding sections, harvest systems and roads were discussed in isolation. However, the design of seemingly unrelated operations, such as a road segment from point A to point B, or the delineation of a particular harvest setting should not be considered separately. The fact that harvesting costs tend to increase with increasing yarding distance, might suggest a goal of reducing yarding distances so as to reduce harvest costs (stump-to-truck). On the other hand, shorter yarding distances usually require more roads, increasing road costs. This contradiction suggest that it is not the harvest or road costs that must be minimized, but rather their sum. The task is to find the
optimal yarding distance (the point at which the total road/harvest cost is minimized) for a given system and use it as a guideline in planning harvest boundaries and road access options. The planning process involves finding the optimal mix of harvest system and road network for an area and timeframe beyond any single operation (Cullen & Schiess 1992).

When determining an optimal yarding distance, all costs must be considered. Unfortunately, yarding distances are often optimized to minimize just yarding and road construction alone, without consideration of maintenance and environmental costs. This has commonly resulted in high road densities serving cost-efficient short yarding systems. Over time the environmental costs (landslides and other erosion) of these high road densities have necessitated economically costly maintenance and/or decommissioning activities. If these costs had been included in the original planning, then a longer optimal yarding distance would have been selected, with a less dense road network

Table 10.3 Total system costs, stump-to-truck (US$), production rates (truck loads) and production costs (US$/m^3) for six harvest systems. Silvicultural system, tree size and yarding distance affect production rates and costs

Type of System and System Crew	**Total Monthly Owning & Operating Costs (1000 US$)**	**Economical External Yarding Distance Limit**	**Daily Production Range (Truck Loads) [1)]**	**Production Cost**
Ground-based, mechanized system 1 feller-buncher 1 Shovel/log loader 1 delimber-processor 1 log loader, 4-man crew	40-44	100-160m 30-450ft	15-20 [3)]	8-12$/m^3 23-33$/cunit 17-24$/MBGF
Ground-based, semi-mechanized system 2 wheeled skidders, 1 log loader, 3-man crew + 3 fallers	38-44	250-300m 700-900ft	11-16 [2)] 5-8 [4)]	11-15$/m^3 30-42$/cunit 22-30$/MBF 21-40$/m^3 60-110$/cunit 43-80$/MBF
Cut-to-Length System 1 harvester, 1 forwarder 2-man crew	35-40	250-300m 700-900ft	4-7 [4)]	20-36$/ m^3 460-100$/cunit 42-72$/MBF
Standing Skyline – small tower 1 log loader 5-man crew, +3 fallers	42-48	250-300m 700-900ft	2-5 [4)]	32-100$/ m^3 100-290$/cunit 72-210$/MBF
Live Skyline - large tower 1 log loader 7-man crew +3-4 fallers	64-67	400-600m 1200-1800ft	12-15 [2)] 7-12 [3)]	13-20$/m^3 40-70$/cunit 29-51$/mbf 25-40$/m^3 75-110 $/cunit 55-80$/MBF
Helicopter medium size 2 log loaders 14-man crew +6-8 fallers	370-420	1500-2000m 4500-6000ft	20-24 [2)] 11-15 [3)]	56-64$/m^3 160-180$/cunit 116-130$/MBF 105-133$/ m^3 295-370$/cunit 214-268$/MBF

[1)] A truckload is based on 22 tonnes or about 23-25 m^3 based on wood density, or ~50-55,000lbs, or about 4.5-5 MBF
[2)] Production rates based on clear cut operations, average tree size 3 m^3, or ~ 900 BF
[3)] Production rates based on clear cut operations, average tree size 1 m^3 , or ~250BF
[4)] Production based on thinning operations, average tree size 0.5 m^3 , or ~ 120BF

For any given system, road-stream separation may be the most effective tool for reducing sediment delivery to the streams. Sediment is produced on almost all forest roads, landings, and yarding operations, but its delivery to streams is a function of the distance and routing to a stream. The further the sediment has to flow across the forest floor, the more it can be filtered, and the less likely it is to be delivered to the stream network. Roadside ditches and culverts (that deliver to stream crossings) short-circuit this filtering, so road alignment should avoid streams wherever possible. Road-stream proximity can be avoided by noting that the stream network is the topographic opposite of the ridge network; never crossing ridges and always maximizing its distance from the ridge network. A network of primary and secondary roads following ridge networks (and crossing the stream network only rarely) would minimize sediment delivery to the stream network (Krogstad & Schiess 2000). Shifting from a riparian-based road network to a ridge-based road network will necessitate building new roads and might even increase road density. In shifting to a ridge-base network however, new road construction may actually improve water quality by routing traffic over roads that deliver less sediment to the stream. Such a solution is only possible in the context of comprehensive harvest and transportation planning at the landscape or watershed level.

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