Report no. 193. Uppsala, Sweden: Sveriges Lantbrukks-universitet.

Halloborg U, Bucht S, and Olaison S (1999) *A New Approach to Thinning: Integrated Off-ground Handling Reduces Damage and Increases Productivity*. Uppsala, Sweden: Skogsforsk results no. 23.

Hartsough B, Drews E, McNeel J, Durston T, and Stokes B (1997) Comparison of mechanized systems for thinning Ponderosa pine and mixed conifer stands. *Forest Products Journal* 47(11/12): 59–68.

Keane M and Kofman PD (1999) The thinning wood chain. In *Proceedings of a IUFRO Conference on Harvesting and Economics of Thinnings*. Dublin, Ireland: COFORD.

Kellogg L and Bettinger P (1994) Thinning productivity and cost for a mechanized cut-to-length system in the Northwest Pacific Coast Region of the USA. *Journal of Forest Engineering* 5: 43–53.

Lågeson H (1996) *Thinning from Below or Above? Implications on Operational Efficiency and Residual Stand*. Doctoral thesis. Umeå, Sweden: Swedish University of Agricultural Sciences.

McNeel J and Rutherford D (1994) Modeling harvester-forwarder system performance in a selection harvest. *Journal of Forest Engineering* 6: 7–14.

Puttock D and Richardson J (eds) (1998) *Wood Fuel from Early Thinning and Plantation Cleaning: An International Review*. Finnish Forest Research Institute. Research paper no. 667. Helsinki, Finland: Logging Industry Research Organization.

Raymond K and Moore T (1989) *Mechanized Processing and Extraction of Shortwood Thinning*. LIRO Reports, vol. 14, no. 5. Rotorua, New Zealand: TTS Institute.

Rieppo K and Pekkola P (2001) *Prospects for Using Harvester-Forwarders*. Työtehoseuran Metsätiedote no. 9.4 Helsinki, Finland: TTS Institute.

Siren M (1981) Stand damage in thinning operations. *Folia Forestalia* 474.

Sundberg U and Silversides CR (1988) *Operational Efficiency in Forestry*, vols I–II. Amsterdam, Holland: Kluwer Academic Publisher.

Roading and Transport Operations

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Introduction

Forest roads connect forested lands to primary roads to provide access for timber extraction and management, fish and wildlife habitat improvement, fire control, and recreational activities. Road location and design is a complex engineering problem involving economic and environmental requirements. Due to low traffic volumes, construction and maintenance costs are the largest components in the total cost of forest harvesting operations. Inadequate road construction and poor road maintenance have potential to cause more environmental damage than any other operation associated with forest management. Thus, forest roads must be located, designed, and constructed in such a way as to minimize construction and maintenance costs, satisfy geometric design specifications, and control environmental impacts.

Route Location

Road location is a cost optimization problem. The road location should achieve minimum total road cost, while protecting soil, water resources, and wildlife. The alignment should provide driver safety, reduce visual impacts, and improve the recreation potential of the forest. The systematic road location process consists of four phases: (1) office planning, (2) field reconnaissance, (3) selection of the final alignment, and (4) locating the alignment on the ground.

Office Planning

The first step involves study of the terrain using available data including topographical maps, air photo, orthophotos, digital elevation model (DEM), and soil and hydrologic reports. The designer studies the essential features of the land identifying the difficult places, such as swamps, rocky places, and steep or unstable slopes. The advantageous parts of the terrain, stream crossings suitable for bridges, saddles on ridges, suitable sites for curves, and gentle slopes, are also noted. If a logging plan is involved, the designer marks the suitable sites for log landings.

The road location must be economical for construction and feasible for hauling logs. The road should efficiently connect the main road to the secondary branches. At the end of this phase, the designer determines alternate feasible road corridors to be examined in the field reconnaissance. Office planning is the least expensive, yet the most important decisions of road design are made during this phase.

Field Reconnaissance

Each essential feature of the terrain (difficult and advantageous places) is examined in a detailed reconnaissance. To provide feedback for the earthwork operation, the designer should examine the terrain for limits of seasonal swamps, loose ground, rocky areas, and potential construction material. This phase is best done during the rainy season so that soil characteristics and the limits of wet places can be observed.

It is more convenient to start the fieldwork from the highest point of the road section to see the terrain easily by looking toward the bottom of the slope. In field reconnaissance, it is necessary to use appropriate survey instruments. At the end of field reconnaissance, one particular corridor is selected as the best corridor based on gradient, haul distance, ground condition, sources of road-building material, and stream crossing obstacles.

Selection of the Final Alignment

Following selection of the best corridor, the next step is to locate the final alignment. The party chief considers a number of strategies:

- On uniform terrain, building the road on a ridge minimizes the earthwork, provides good drainage, and reduces the number of culverts.
- On a side hill, keeping a constant gradient provides a balanced cut and fill section. If the side hill is steep, a full bench cross-section can be used to avoid overloading the slope below the road.
- In a valley, the route should be kept as low as possible, but above the floodplain. Proper choice of stream crossings and stream crossing angle minimizes bridge length.
- Cut bank heights should be kept low, because excessive earthwork increases construction and maintenance costs, increases potential for landslides, and requires special construction for drainage.

Laying Out the Alignment on the Ground

On uniform terrain the final location line is marked on the ground by centerline stakes with 15–20-m intervals. The road edges should be calculated on both sides from the centerline. On difficult and irregular terrain, the centerline and excavation and embankment limits should also be marked. The method for identifying the centerline and limits on a straight alignment varies with the method used for a horizontal curve.

On uniform terrain, a straight alignment is generally laid out by eye, using posts in three at a time. On uneven terrain, the grade line is carried forward in a series of incremental steps to preserve the gradient. The methods used for laying out a horizontal curve are aided using design tables. Several methods are used. The deflection angle method is described here. First, the deflection angle is defined, depending on the specified radius and a chord length (**Table 1**). Then, points on the curve are identified by turning chord deflections and pacing the chord distance (**Figure 1**). Several trials are generated from different starting points on the tangent, when a curve point of intersections is inaccessible.

Table 1 Deflection angles (in degree) for circular curves of various radii

Radius (m)	*Chord distance*		
	10 m	*15 m*	*20 m*
14	42	—	—
16	36	—	—
18	32	—	—
20	29	44	—
25	23	35	47
30	19	29	39
35	16	25	33
40	14	22	29
45	13	19	26
50	11	17	23
55	10	16	21
60	10	14	19
65	9	13	18
70	8	12	16
80	7	11	14
90	6	10	13
100	6	9	11
125	5	7	9
150	4	6	8
175	3	5	7
200	3	4	6

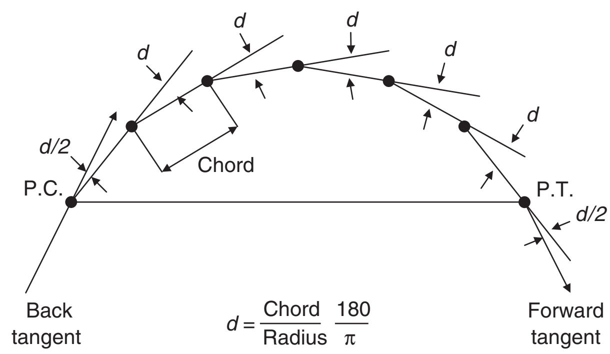

Figure 1 Curve location using deflection angle (*d*) method. P.C., beginning point of curve; P.T., ending point of curve.

Cost Control in Forest Road Design

The total cost of a road section consists of the construction cost, maintenance cost, and transportation cost.

Construction and Maintenance Costs

Road construction and maintenance costs are generally calculated using the 'engineer's' method. In this method, quantities of required material used are estimated and then multiplied by the unit costs for the items (i.e., cost per meter, square meter, or cubic meter). The road construction cost is the total cost of the road construction activities: construction staking, clearing and grubbing, earthwork, drainage, surfacing, and seeding and mulching. The maintenance activities involve rock replacement, grading, culvert and ditch maintenance, and brush clearing. Detailed information regarding formulae and tables to calculate the costs of these activities can be obtained from the references given in the Further Reading section.

Transportation Costs

Transportation costs depend upon the traffic, cost of vehicle operation, and vehicle speed. Traffic volumes should consider the immediate and longer-term road use. Vehicle speed is a function of road width, alignment, gradient, surface type, and traffic volume.

Selection of Most Economical Road Standard

Forest road design involves simultaneous consideration of and trade-offs between construction costs, road maintenance, vehicle performance, and environmental effects. The trade-offs are not always obvious and vary depending upon local availability of construction materials, road standards, and topography. Based on these factors, the designer should be able to select the best road standard. It is important to know as much as possible about the future performance of a selected road standard so that adequate roads can be designed and built at minimum expense. If forest roads are planned for use during spring thaw conditions, road designers should take extra care in constructing the roads to reduce the road deformation.

Geometric Design Specifications

In order to ensure driver safety, smooth traffic, and efficient and economic movement of the trucks, the road alignment must satisfy certain geometric design specifications. The main elements of geometric design specifications are stopping sight distance, middle ordinate distance, vehicle off-tracking requirements, road gradient, horizontal curves, and vertical curves.

Stopping Sight Distance

The objective in determining the stopping sight distance (SSD) is to provide a sufficient sight distance for the drivers to safely stop their vehicles before reaching objects obstructing their forward motion. The SSD (in meters) for two-lane roads is computed in eqn [1]:

$$\text{SSD} = \frac{V^2}{254(f \pm g)} + 0.278\,Vt_r \qquad (1)$$

where V is the design speed (km h^{-1}), t_r is perception/reaction time of the driver in seconds (generally 2.5 s), f is the coefficient of vehicle braking friction, and g is the road grade in decimal percent. On two-directional one-lane roads, the SSD is approximately twice the stopping distance for a two-lane road.

Middle Ordinate Distance

The middle ordinate distance must be visually clear, so that the available SSD is sufficient for the driver's line of sight (**Figure 2**). Experience has shown that a driver should be able to see from an eye height of 1070 mm and stop before hitting an object of 150 mm height at the mid-ordinate. On forest roads, 600 mm of object height at the middle ordinate point is generally used. Middle ordinate distance in meters is computed as follows:

$$M = R\left[1 - \cos\left(28.6\,\frac{\text{SSD}}{R}\right)\right] \qquad (2)$$

where R is the radius of horizontal curve (in meters). It is a straightforward task to compute M, once the R and SSD have been determined.

Off-tracking

When traveling around the horizontal curve, the rear wheels of the vehicles do not track in the same path as the front wheels, which is called off-tracking. To accommodate the off-tracking of the rear wheels,

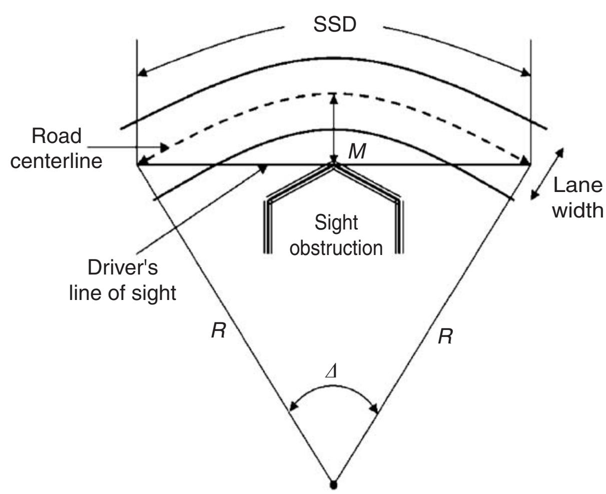

Figure 2 Middle ordinate distance (M) around a horizontal curve. SSD, stopping sight distance; R, radius; Δ, central angle of curve.

extra road width is required on the inside of the curve (**Figure 3**). The required curve widening depends on various factors such as vehicle dimensions, curve radius, and the central angle of the curve (Δ). To predict off-tracking (OT), an empirical method, providing the designers with quick, easy, and relatively accurate results, is generally employed.

$$\mathrm{OT} = (R - \sqrt{R^2 - L^2})[1 - e^{(-0.015\Delta\frac{R}{L}+0.216)}] \quad (3)$$

where L is computed for a stinger-steered trailer as:

$$L = \sqrt{L_1^2 - L_2^2 + L_3^2} \quad (4)$$

where L_1 is wheelbase of the tractor, L_2 is the length of the stinger measured from the middle of the tractor rear duals to the end of the stinger, and L_3 is bunk-to-bunk distance minus the length of the stinger. For a low boy or conventional trailer:

$$L = \sqrt{L_1^2 + L_2^2 + L_3^2} \quad (5)$$

where L_1 is wheelbase of the tractor, L_2 is the distance from the fifth wheel to the middle of the rear duals for the first trailer, and L_3 is the distance from the fifth wheel to the middle of the rear duals for the second trailer.

Road Gradient

Road gradient (%) is calculated in units of vertical rise divided by the horizontal distance. The minimum road gradient is limited by the minimum acceptable road grade to provide proper drainage. Having minimum 1–2% longitudinal gradient along the road section helps avoiding the ponding of water on the surface. The maximum road gradient is determined based on the design vehicle. A list of recommended truck gradients for low light trucks is shown in **Table 2**. Since trucks lose speed rapidly when climbing a grade, and ultimately reach an equilibrium speed, the vehicle performance should be taken into account to minimize overall transportation cost. In current vehicle performance models, the road alignment and surface type are taken as inputs, and alignment-specific results (ground speed, engine speed, gear shifting requirements, fuel consumption, and roundtrip time) are determined. Detailed information on these models can be obtained from the references in the Further Reading section.

Horizontal Curves

On low-volume forest roads, a circular horizontal curve is generally used to provide a transition between two tangents (**Figure 4**). To design a feasible horizontal curve, the designer considers the minimum curve radius, acceptable road grade on the horizontal curve, and minimum safe stopping distance.

Having high centers of gravity and narrow track width (the distance between the outside faces of the wheels at opposite ends of an axle), logging trucks may overturn due to an inadequate radius. Design

Table 2 Maximum road gradient (%) for various design speed and topography (Transportation Association of Canada)

Speed ($km\,h^{-1}$)	*Rolling topography*	*Mountainous topography*
30	11	16
40	11	15
50	10	14
60	10	13
70	9	12
80	8	10

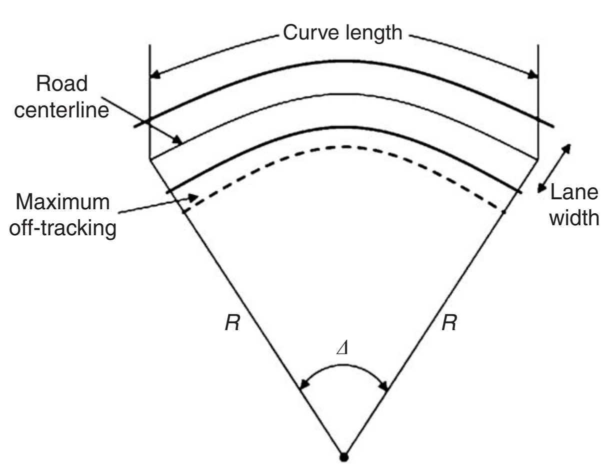

Figure 3 Maximum off-tracking on a horizontal curve. R, radius; Δ, central angle of curve.

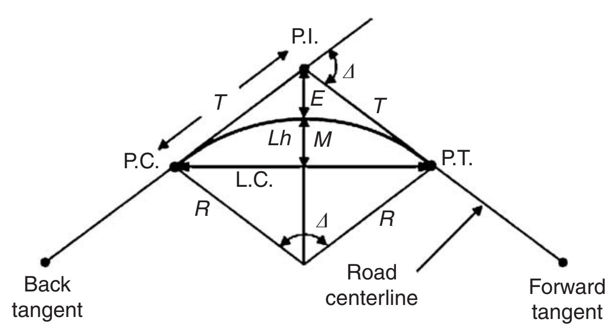

Figure 4 Geometry of a circular horizontal curve. P.I., point of intersection; P.C., beginning point of the curve; P.T., ending point of the curve; Lh, curve length; Δ, central angle; M, middle ordinate; R, radius; T, tangent distance; L.C., long chord; E, external distance. Equations: $Lh = \frac{\Delta\pi R}{180^\circ}$ $T = R\tan\frac{\Delta}{2}$ $L.C. = 2R\sin\frac{\Delta}{2}$ $E = T\tan\frac{\Delta}{4}$.

Table 3 Minimum radius for various vehicle speeds ($f_s = 0.15$, $e = 0$)

Speed (km h^{-1})	*Minimum radius (m)*
30	47
40	84
50	131
60	189
70	257
80	336

speed, lateral acceleration, and vehicle weight must be considered (**Table 3**).

The maximum gradient permitted on the horizontal curve should be kept lower than that on a tangent because: (1) off-tracking of the vehicle creates a higher 'effective' grade for both the truck and the trailer, (2) the truck incurs additional forces required to turn the tandem axles around the curve, and (3) the powered wheels may have unbalanced normal loads due to a combination of centrifugal force, super elevation, and angle of the trailer. The effects of these factors are increased as the radius decreases.

The safe stopping distance is computed using eqn [1] in which the limiting speed of the vehicle around the horizontal curve, V (in km h^{-1}), can be formulated considering vehicle weight, side friction force, centrifugal force, curve radius, side friction coefficient, and super elevation.

$$V = 11.27\sqrt{R(f_s + e)} \qquad (6)$$

where f_s is the coefficient of side friction, R is the radius of horizontal curve in meters, and e (%) is the super elevation of the horizontal curve if it exists.

Vertical Curves

Forest road engineers customarily use parabolic vertical curves (**Figure 5**) with a constant rate of change of gradient, because: (1) they result in alignments comfortable to drive, (2) they are easy to lay out, and (3) the SSD is constant along the curve. The vertical curves should have a sufficient curve length to permit a log truck to pass a curve without bottoming out in the sag or breeching the crest and provides SSD.

In determining a feasible curve length, crest and sag vertical curves are considered separately based on the assumption that whether the curve length is greater or less than the SSD. Equations [7] and [8] indicate the formulation for length of the crest vertical curve in meters. If SSD is greater than the curve length (**Figure 6**):

$$Lv = 2SSD - \frac{200(\sqrt{h_1} + \sqrt{h_2})^2}{A^2} \qquad (7)$$

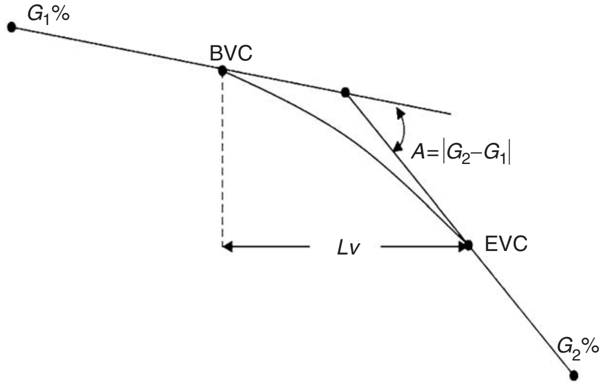

Figure 5 Geometry of a crest vertical curve (symmetrical). BVC, beginning point of the curve; EVC, ending point of the curve; *Lv*, curve length; G_1, initial tangent grade; G_2, final tangent grade; *A*, absolute difference between grades.

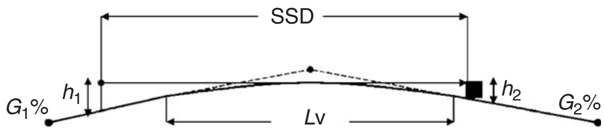

Figure 6 Stopping sight distance (SSD) is greater than the length of a vertical curve. G_1, initial tangent grade; G_2, final tangent grade; *Lv*, curve length; h_1, distance from road surface to level of driver's eye; h_2, height of object on road.

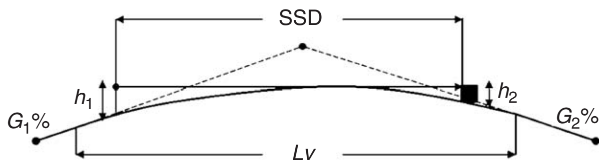

Figure 7 Stopping sight distance (SSD) is less than the length of a vertical curve. G_1, initial tangent grade; G_2, final tangent grade; *Lv*, curve length; h_1, distance from road surface to level of driver's eye; h_2, height of object on road.

where h_1 is the distance from road surface to level of the driver's eye, h_2 is the height of the object on road, and A is absolute value of the difference between gradients. If SSD is less than the curve length (**Figure 7**):

$$Lv = \frac{SSD^2 A}{200(\sqrt{h_1} + \sqrt{h_2})^2} \qquad (8)$$

The length of a sag curve, for a required SSD, is formulated in eqns [9] and [10]. If SSD is greater than the curve length:

$$Lv = 2SSD - \frac{200(h_3 + SSD \tan \alpha)}{A} \qquad (9)$$

where h_3 is the distance from road surface to level of the vehicle headlights and α is angle of the headlight beam above axis of the vehicle. If SSD is less than the curve length:

$$Lv = \frac{SSD^2 A}{200(h_3 + SSD \tan \alpha)} \qquad (10)$$

Forest Road Construction

Clearing and Grubbing

The road centerline, the cut and fill limits, and the clearing limit should be marked on the ground prior to clearing. The clearing limit is the width that the trees, stumps, and organic debris are to be cleared across the future roadway. The terminology of a forest road on a cut and fill type cross-section, which generally applies to most road types, is indicated in **Figure 8**.

The methods used for the clearing and grubbing should be consistent with good safety and environmental practices while keeping construction costs to a minimum. The hazardous snags and unsafe trees adjacent to the clearing limit should be felled and removed from within the road prism. Merchantable timber should be piled on the decking areas so as to not interfere with the construction of the road or turnouts. Unmerchantable material and stumps should be disposed of with care to prevent any hazard during the logging operation.

Earthwork

On gentle terrain, the bulldozer proceeds from both sides of the road to construct an embankment that will keep the road structure dry. In difficult terrain hydraulic excavators combined with advanced drilling and blasting technology are the best solutions both environmentally and economically. The features of the hydraulic excavator and advanced drilling and blasting technique in road construction are:

- The excavator operates by digging, swinging, and dumping of excavation.
- The excavator works from the fixed position and does not require additional road width for maneuvering.
- Using buckets and attachments increases the excavator's versatility to do ripping, trenching, loading, compacting, and hydraulic hammering.
- The high breakout force of the excavator reduces the need for blasting.
- The hydraulic drilling units attached to the excavator optimize blasting by performing vertical as well as horizontal drilling.
- Soft blasting techniques avoid loosening of fractured rock, and control the rock size.

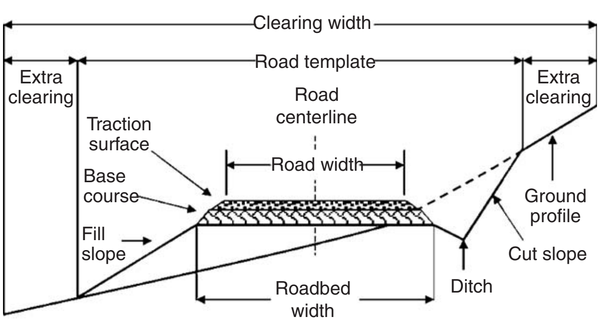

Figure 8 Road elements on the cross-section.

Building the desired cut and fill slope steepness is critical during the earthwork operation. If the operator constructs a steeper cut slope, this will require further excavation, increase construction cost, and may cause slope failure. Therefore, road cut and fill banks should be constructed to the slope angles that minimize slope failure and erosion. Cut and fill slopes are constructed depending on the available soil and rock types (**Table 4**).

Embankments are commonly used on stream drainages, swamps, flat ground, and are used as waste areas. The common methods used for embankment are: (1) end haul dumping where cut material is hauled to a fill area, and (2) side casting where cut material is pushed from a road cut to a close fill location. In both methods, material should be layer-placed and compacted to minimize future maintenance, soil erosion, and road failure. On deep fills and roads with heavy traffic, a mechanical roller can be used for effective compaction.

The economic distribution of cut and fill quantities in forest roads is traditionally determined using the mass diagram method. However, its capability is limited where soil characteristics vary along the roadway. To overcome the limitation of the mass diagram, linear programming has been used to plan the movement of earthwork during road construction.

Surfacing

Native-soil surfacing can be used when harvest operations are conducted during the dry season. However, road operations in the wet season require aggregate surfacing (crushed rock) to increase the strength of the

Table 4 Cut and fill slope types for various soil and rock types

Soil type	*Cut*	*Fill*
Common soil	1 : 1	1.5 : 1
Clayey soil	2 : 1–3 : 1	Not used
Solid rock	0.5 : 1	Not used
Fractured rock	0.75 : 1	1.25 : 1

forest road surface to support vehicle traffic (**Figure 8**). Aggregate surfacing also provides increased wheel traction and relatively smooth traveling surface that reduces the subsequent road maintenance, and extends the life of the subgrade by reducing road surface ruts and erosion. The rock size and the depth of the aggregate surfacing are determined based on the type of the subgrade soil along the roadway, road gradient, traffic density, season of road use, availability of the aggregate, and cost. A traction surface can be placed over the base rock to increase traction and to provide a smooth durable traveling surface.

The hardness, durability, wearability, and shape of the aggregate affect the quality of the road surfacing. The surfacing rock should be tested in the field in terms of its hardness, shape, and durability. If there is doubt regarding its compatibility, it should be directed to laboratory tests. The Los Angeles Abrasion Test is one of the standard laboratory tests that is used to examine the wearability of the rock.

On wet ground or soils that do not compact well, geotextile material is added on top of the subgrade to provide additional strength to the subgrade, keep soil moisture from surfacing, and prevent intermixing of soil and surface aggregate layer (**Figure 9**). This also reduces the depth of surface rock. The road engineer should determine the trade-off in terms of cost and effectiveness between reducing the rock depth and extra cost of laying down the geotextile. The best practice for using geotextiles involves:

- Spreading out the geotextile in short stages to allow rock placement to follow closely.
- Securing the top of the geotextile to avoid slippage.
- Placing the geotextile free of tears and wrinkles and join the rolls with overlapped joints.

Drainage

When constructing a road, the road surface must be sloped to eliminate the tendency of surface runoff water to break up the road under heavy loads. There are three basic types of roadway templates (**Figure 10**):

- Crowned: half of the water is carried to the ditch and half to the outside shoulder.
- Insloped: water is carried to the ditch and ditch relief pipe culverts to the streams.
- Outsloped: road surface sheds runoff to the outside.

Ditched roads (crowned and insloped) require more excavation cost for the ditch and additional cost for relief culverts. Ditch water runoff should be intercepted periodically by relief culverts to carry roadway runoff from the ditch, transport it beneath the road, and discharge the water from the road (**Figure 11**). A catch basin is built in the ditch to channel the water from the ditch to the culvert inlet. Plastic relief culvert is widely used in forest roads because one person can handle plastic culvert installation and it is easy to cut to length for fabrication. The determination of culvert size depends on conditions of the precipitation, topography, soil, and vegetation types. Smaller diameter culverts

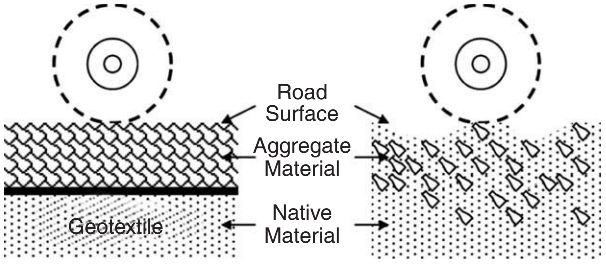

Figure 9 Geotextile material provides support and separation.

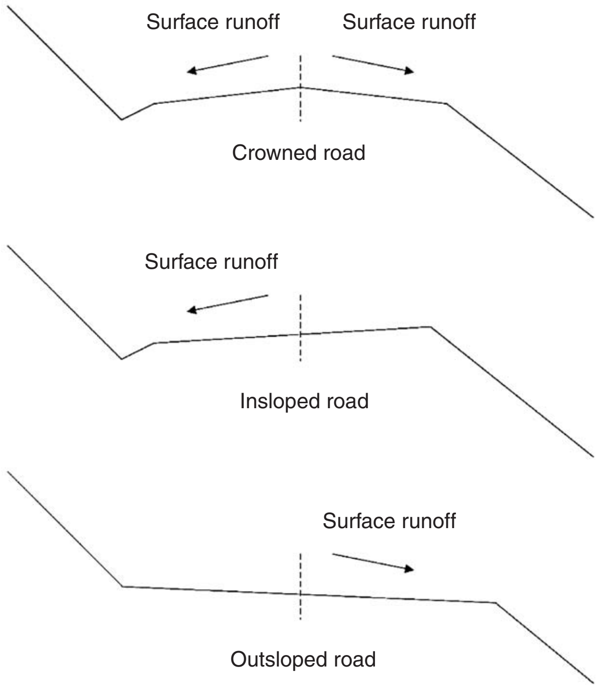

Figure 10 Ditched and outsloped roadway templates.

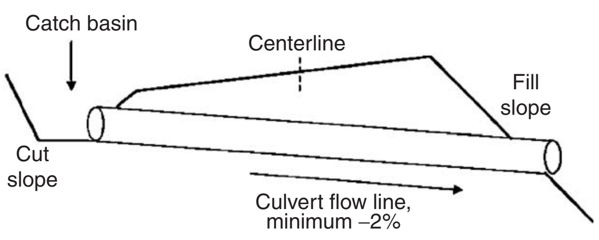

Figure 11 Geometry of a ditch relief culvert.

are inexpensive and easy to install. However, they are difficult to clean out and carry less water. Culvert spacing is generally determined based on its location on the hill, local rainfall intensity, soil erosion classes, road grade, and culvert size. Open-top culverts are also effective in controlling surface water. They offer land managers an alternative to crowning and ditching roadbeds for water control. The cost is comparable to that of a gravel broad-based dip. Installation of the culvert can be done manually or with the use of a small dozer. Open-top culverts must be cleaned regularly to remove sediment, gravel, and logging debris to allow normal function of structure.

Outsloped roads have reduced construction and maintenance costs and lessened environmental impacts due to their type of drainage. They also yield less erosion than a ditched road on the same location. Outsloped roads are not ideal for every condition. On wet or frozen surfaces, trucks slide to the outside of the roadway on steep grades. This lowers vehicle speed and in some conditions is unsafe. To enhance the effectiveness of outsloped roads, drain dips and water bars are used. Drain dips should be built considering adequate truck passage and road grade (2–8%). On road grades greater that 8%, water bars are often constructed to catch runoff water.

Seeding and Mulching

Bare cut and fill slopes, resulting from road construction on sloping terrain, increase soil erosion and stream sedimentation. Seeding and mulching can provide quick stabilization and enhance the beauty of the area. The best time for seeding is usually spring or autumn, but results will depend on local weather conditions. The seed mixture should be easy to plant, readily available, and adaptable to soil conditions (drainage, soil depth, aspect, drought tolerance, and climate conditions).

The use of mulch is considered to prevent erosion, keep seed on steeper slopes, reduce seedling mortality, and preserve soil moisture. Straw is the most commonly used mulch material. To increase the effectiveness of mulch, straw can be used in combination with other bank erosion control measures.

Forest Road Maintenance

Road maintenance protects the road investment, provides for safe and reliable vehicle operation, and controls environmental impacts. Road maintenance generally consists of road surface maintenance, roadway drainage maintenance, and ditch and culverts maintenance. Removing brush from both cut and upper fill slopes is also considered to maintain visibility.

Road Surface Maintenance

The forest road surface deforms under vehicle wheel loads and develops ruts over time if the subgrade is not constructed adequately. If the wheel load is excessive for the existing road surface conditions, shear failure occurs. Failure can also occur where the subgrade becomes saturated from standing water and the wheel load on this saturated subgrade causes damage. Ditches should be kept free of obstruction and ruts should be removed to avoid this type of damage. The forward and downward motion of wheels on the surface causes a corrugation called washboarding. To correct this, the surface rock should be reshaped to restore the camber of the road.

To decrease the road construction and maintenance costs, variable tire inflation technology is increasingly being considered for low speed operation. Central tire inflation (CTI) systems enable the driver to change and monitor the vehicle's individual tire pressures while driving. As tire pressure decreases, the tire footprint increases, primarily in the longitudinal direction. This reduces the stress applied to the road surface through a greater contact area and lower dynamic loads. Traction capability, related to tire contact length is also increased. Test studies have shown that reduction in stress reduces surface maintenance, sediment production, tire damage, and improves vehicle mobility, the ride quality, and traction on snow, ice, and loose sand.

Roadway Drainage Maintenance

Maintenance of the drainage system is also one of the key factors to preserve structural integrity and travel quality. Poor drainage can cause deterioration and weaken the road structure. To prevent this, rain and snowmelt must be quickly removed from the road surface before moisture soaks through the surface into the subgrade.

Ditch and Culvert Maintenance

Culvert maintenance involves removing debris, leaves, mud, and gravel from the culvert, the inlet, the outlet, and the catch basin. Plugged culverts cause significant ditch and roadbed erosion into the subgrade. To prevent catastrophic damage on the road, inspection and hand cleaning of culverts should be done during wet weather. Ditches should be kept free of obstructions with a shovel, a backhoe, motor grader, or loader. To stabilize the soil in ditches and to reduce the force of water, the ditch can be armored with rock, grass can be grown in the ditch bottom, and culverts should be installed at more frequent intervals.

Crossings Wetlands and Streams

Some of the planning and design considerations on wetland and stream crossings are:

- Limit the number, length and width of roads and skid trails.
- Locate roads outside riparian management zones except at stream crossings.
- Road fill must be bridged, culverted, or otherwise designed to prevent restriction of expected flood flows.
- Properly maintain road fill during and after road construction to prevent erosion.
- Correctly design, construct and maintain wetland road crossings to avoid disrupting the migration or movement of fish and other aquatic life.

Wetland Crossings

Wetland crossing methods include wood mats, wood panels, wood pallets, expanded metal grating, plastic roads, corduroy, and wood aggregate. Geotextiles can be also used to solve drainage problems in wetlands. Wood mats are individual cants or logs cabled together to make a single-layer crossing. Wood panels are constructed by nailing parallel wood planks to several perpendicular wood planks where the vehicle's tires will pass. Wood pallets are three-layered pallets similar to those used for shipping and storage, specifically designed to support traffic. They are easy to install, replace, and interconnect. Machine weight can be distributed over a broader area by placing a metal grating on top of a geotextile.

The grating is relatively light, inexpensive, and also it provides sufficient traction. Plastic roads, made of PVC and HDPE pipe mats, are portable, reusable, and provide lightweight corduroy type crossing. Using pipes generate a conduit for water to move through the crossing without further wetting the area. One method of building temporary roads across wetlands is the use of corduroy where brush and small logs are laid perpendicular or parallel to direction of travel. Nonwoven geotextile is recommended to separate the brush, logs, or mill slabs from the underlying soil. Wood aggregate (wood particles ranging in size from chips to chunks) can also be used as a fill material for crossing soft soils. Important advantages of using wood particles are they are relatively light and biodegradable. Geotextiles are used to provide subgrade restraint over areas of low bearing pressure. They are occasionally placed over buried corduroy to cross wet holes.

Stream Crossings

When the streams are shallow, inexpensive stream crossings can be constructed using drifts or fords (**Figure 12**). On shallow sandy rivers, stone-surfaced drifts are used when the fall is gentle. A higher-elevated concrete drift is used when the water flow is strong. Culvert drifts are also built in small rivers with heavy currents.

Open-bottom structures such as open-bottom arches and box culverts are also used for stream

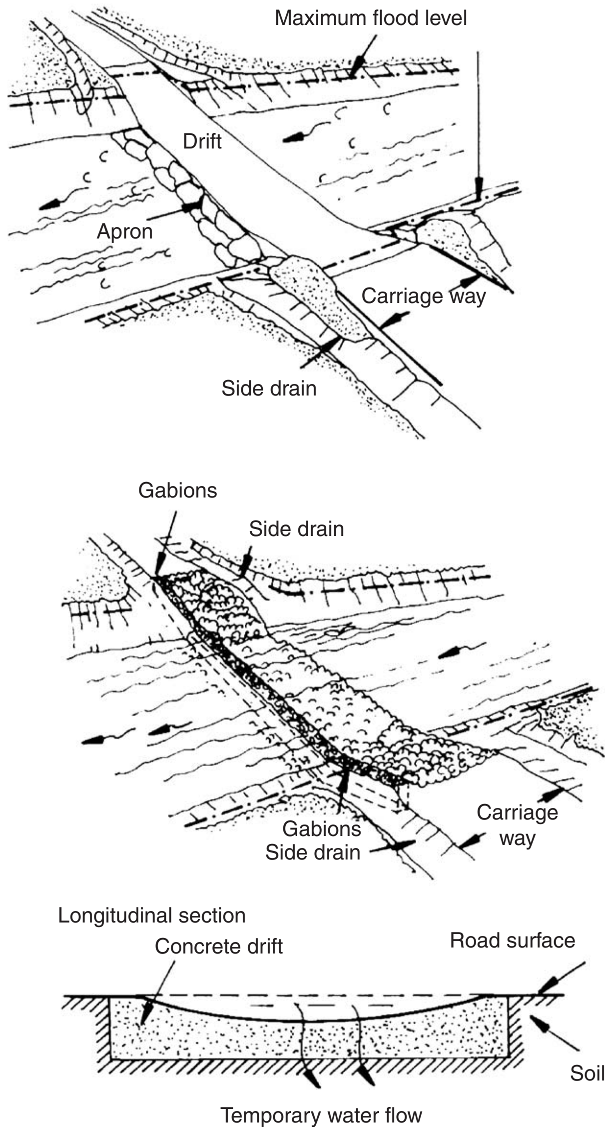

Figure 12 Examples of drifts. Reproduced with permission from Kantola M and Harstella P (1986) *Forest Harvesting Handbook on Appropriate Technology for Forest Operations in Developing Countries.* FTP Publication 19(2) pp. 79–81, National Board of Vocation Education of Finland.

Figure 13 Open-bottom Box Culvert. Courtesy of Big R Manufacturing.

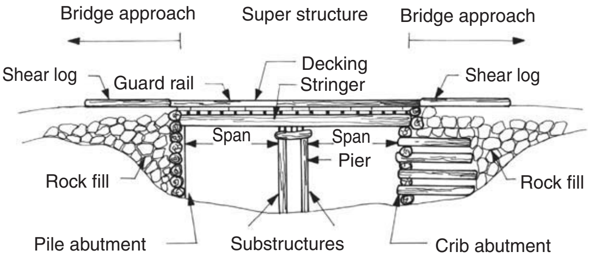

Figure 14 Log stringer bridge. Reproduced with permission from Kantola M and Harstella P (1986) *Forest Harvesting Handbook on Appropriate Technology for Forest Operations in Developing Countries*. FTP Publication 19(2) pp. 79–81, National Board of Vocation Education of Finland.

crossings. Their footings are installed on bedrock to prevent scouring (**Figure 13**). If they installed on an erodible foundation, the entire area should be ripraped between the footings. The size of the riprap material depends on water depth and flow velocity. Open-bottom culverts provide more natural conditions for fish passage than culverts.

Bridges must be built for deeper crossings. Construction cost of the bridges is high because they should be elevated sufficiently above maximum flood level, and be strong enough to carry the heavy traffic. When crossing a stream is inevitable, selecting the right structure is critical to ensure suitable and cost effective crossing, and minimum pollution of the stream.

Permanent bridges The most common type of permanent bridge is the stringer bridge where a deck is placed on top of the stringers to support the vehicle loads. Stringers can be logs, sawn timbers, and steel beams. Decking is placed perpendicular to the stringers and can consist of sawn lumber planks, timber deck panels, or concrete panels. Basic components of a log stringer bridge are indicated in **Figure 14**. The size of the stringer depends on the unsupported length of the span and loading. Stringers should be debarked, mortised, and anchored by wooden poles in the ground. The deck logs should be placed on the stringers perpendicularly, transversely, or diagonally.

Portable bridges When permanent access to a site is not needed, portable bridges are used and then removed after operations are finished. They have been used in military applications for many years, but use in forestry applications is more recent. In the past, the lower cost approaches to temporary stream crossings (log crossings, fords, and culverts) were used over portable bridges due to high initial cost of the bridges. However, these low-cost approaches frequently involve the use of large amount of fill in the stream crossing and may result in excessive erosion and sedimentation of the stream. Portable bridges cause less impact on water quality. Portable bridges can be made of steel or concrete panels and timber mats. A relatively new type of engineered design is the glulam bridge that can be moved from site to site relatively quickly and easily. To simplify the installation, the glulam panels are not connected to each other instead; they are set in place on site. Abutments to support the bridge ends are not required since the panels can be placed on a mud sill. The use of a portable bridge has been shown to be an environmentally sensitive method since it minimizes site disturbance and sedimentation in the stream.

Environmental Considerations

There are a number of actions that can be done during road construction and maintenance to protect the environment. Some of them are listed below:

- Earthwork operations should be scheduled for dry seasons.
- Steep grades should be avoided through soils that erode easily.
- Ditches and culverts should be constructed properly.
- Stream crossings should be located where minimum soil disturbance may occur.
- Stream crossing angles should be close to perpendicular.
- Seeding should be applied on cut banks and fill slopes to reduce erosion.
- Bridges and culverts should be constructed to handle the maximum water flow, and they should allow appropriate fish passage.
- Aggregate should be replaced to preserve structural integrity of the road.

- Grading and other maintenance activities, cleaning culverts and cleaning ditches, should be performed regularly.
- Excessive sediment delivered to streams has a dramatic effect on water quality and aquatic life; therefore, roads must be designed to minimize sediment production.
- The road segments with a high potential for delivering sediment can be identified using sediment prediction models.

See also: **Harvesting**: Forest Operations in the Tropics, Reduced Impact Logging; Forest Operations under Mountainous Conditions; Wood Delivery. **Operations**: Forest Operations Management.

Further Reading

AASHTO (1990) *A Policy on Geometric Design of Highways and Streets*. Washington, DC: American Association of State Highway and Transportation Officials.

Akay AE (2003) *Minimizing Total Cost of Construction, Maintenance, and Transportation Costs with Computer-Aided Forest Road Design*. Thesis, Forest Engineering Department, Oregon State University, Corvallis, OR.

Douglas RA (1999) *Delivery, the Transportation of Raw Natural Products from Roadside to Mill*. Fredericton, Canada: University of New Brunswick.

FAO (1998) *A Manual for the Planning, Design, and Construction of Forest Roads in Steep Terrain*. Rome: Food and Agriculture Organization of the United Nations. Available online at http://www.fao.org/docrep/W8297E/W8297E00.htm

Hickerson T (1964) *Route Location and Design*. New York: McGraw-Hill.

Holmes D (1982) *Manual for Roads and Transportation*. Burnaby, Canada: British Columbia Institute of Technology.

Kantola M and Harstella P (1988) *Handbook on Appropriate Technology for Forestry Operations in Developing Countries*, Part 2, *Wood Transport and Construction*. Forestry Training Program Publication no. 19. Helsinki: National Board of Vocation Education of the Government of Finland.

Kramer BW (1993) *A Road Design Process for Low Volume Recreation and Resource Development Roads*. Corvallis, OR: Oregon State University.

Kramer BW (2001) *Forest Road Contracting, Construction, and Maintenance for Small Forest Woodland Owners*. Corvallis, OR: Oregon State University.

Pancel L (ed.) (1993) *Tropical Forestry Handbook*, vol. 2. Hamburg, Germany: Springer-Verlag.

Ritter M (1990) *Timber Bridges: Design, Construction, Inspection, and Maintenance*. Washington, DC: US Department of Agriculture.

Smith DM (1993) *Effects of Variable Tire Pressure on Road Surfacing*, vol. 2, *Analysis of Test Results*. US Army Corps of Engineers, Waterways Experiment Station. Prepared for the USDA Forest Service. Vicksburg, MI. Technical Report no. GL-93-20, p. 84.

Watts S (ed.) (1983) *Forestry Handbook for British Columbia*, 4th edn. Vancouver, Canada: University of British Columbia.

Wenger K (ed.) (1984) *Forestry Handbook*. New York: Society of American Foresters.

Wood Delivery

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Introduction

Cost-efficient forest harvesting operations are key to economic timber production and overall competitiveness of the global wood production sector. Consequently, efforts have been made towards the enhancement of operational efficiency through:

1. Rationalization of forest harvesting techniques and work methods, including stand establishment, harvesting operations, wood delivery, ergonomic concerns, automation of machine functions, and the control of environmental impacts.
2. Improved wood supply logistics, including supply chain and information chain management, and harvesting and transport planning.
3. Maximization of raw material utilization including log value optimization, and use of unmerchantable material and forest residues as alternative fuel sources.
4. Development of the forest industry through customer focused production, quality control in the delivered wood, and work safety.

The efforts outlined above are aimed at the optimization of forest production on a sustainable basis. The rationalization of forest harvesting techniques and improvement of wood supply logistics can be implemented relatively quickly (i.e., over a short time span), hence wood delivery is a crucial issue in optimization of the entire wood supply chain. Wood delivery in the context of this article refers to the chain of operations related to the extraction and transport of different categories of timber and by-products of forest harvesting, including wood chips and forest residue materials that are used for energy. The forest residue is transported as compacted residue or slash logs.