THE STRUCTURAL GEOMETRY OF TURNS

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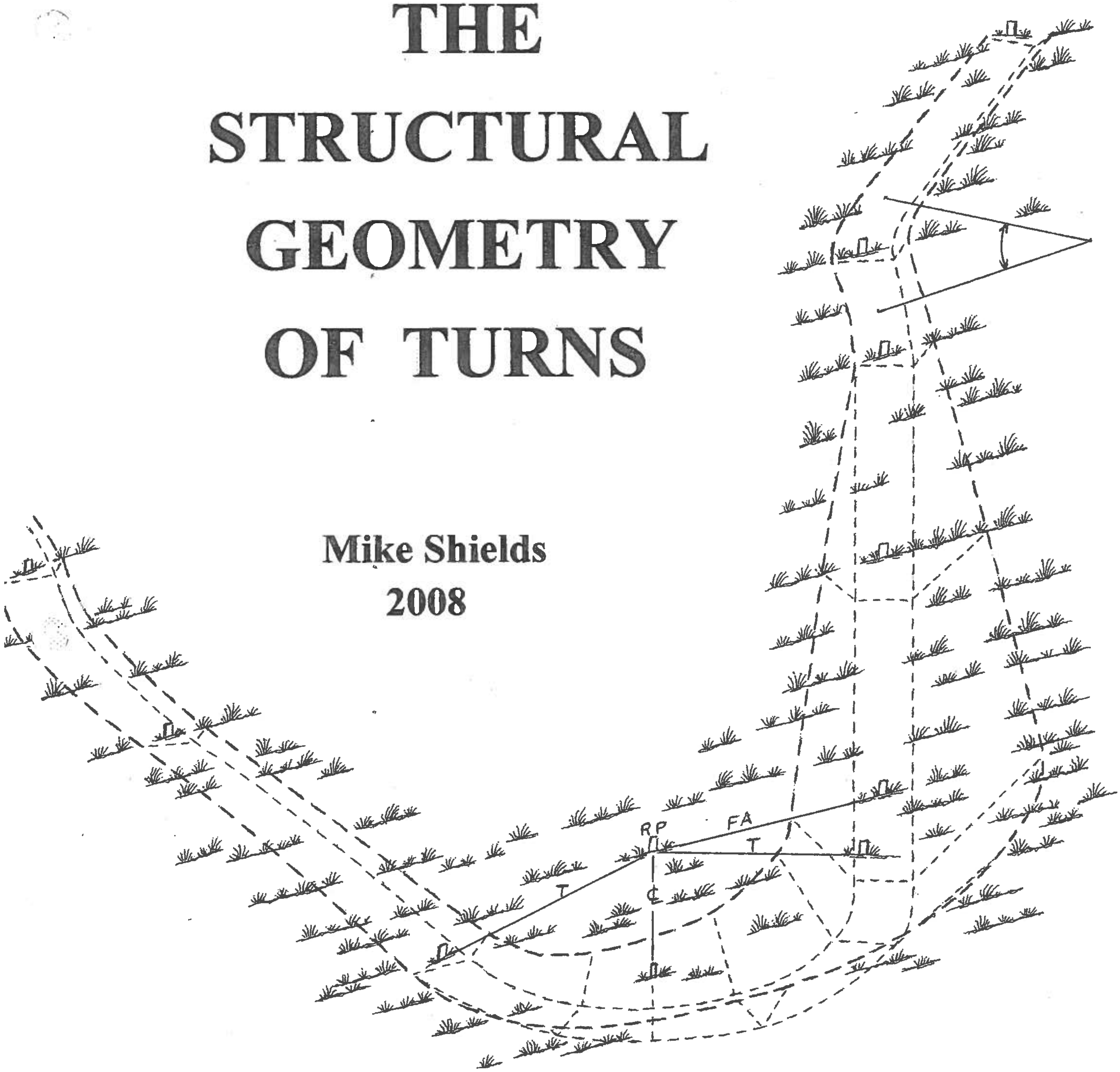

THE GEOMETRY OF TURNS
Design & Layout

COURSE CONTENTS

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INTRODUCTION

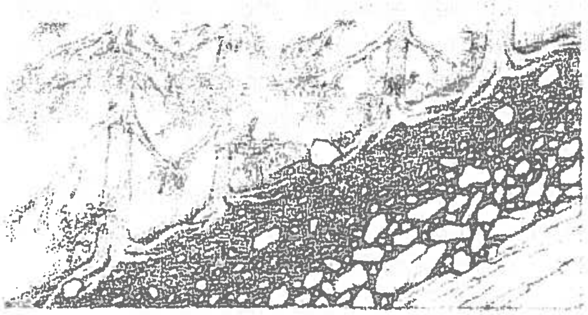
This course text deals with the geometry, design, and on-site layout of turns in trail alignments, with a focus on direction-reversing turns. While I have attempted to keep any "engineering" discussion and calculations to a minimum, you will better understand the reasons behind certain practices if you understand the physical limits which underlie the various designs and construction methods covered. Therefore more in-depth background material is included where appropriate, and appears in *italics*.

BASIC CONCEPTS – Remember these as you proceed:

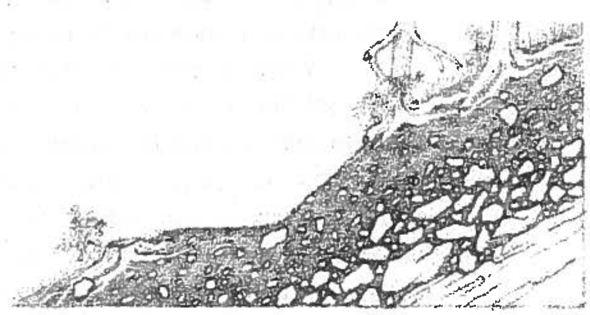
The ground is a Natural Structure, upon which a Man-made Structure (the trail) is imposed.
Unstable Ground means Unstable Trail; conversely --
Trail Stability preserves Ground Stability.
An Unstable Trail, by definition, cannot be a "Sustainable Trail".
We use Structures to improve Trail Stability (thus Ground Stability), AND to improve Ground Stability (thus Trail Stability).

THE GROUND AS A STRUCTURE

A trail is a man-made structure imposed on, and largely consisting of, the ground it crosses. It affects, and is itself affected by, that ground. Thus it is important that we understand the ground as a "Structural Element" itself, playing a central role in all our decisions about trail design, routing, and structural enhancements.



Ground Structure



with Trail Structure

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The ground (ie., soil) is a complex structure in which a number of elements work in combination to produce its structural character. That character is usually described in terms of the ground's stability on a slope (though even flat ground has stability issues), expressed as either:

Angle of Repose, being the slope angle at which a particular soil is inherently stable over time (decades or centuries); or

Angle of Immediate Instability, being the slope angle at which a particular soil is in balance between staying in place or collapsing by gravity, given a specific set of conditions; a minor change in any one of those conditions causes the Angle to change. Since this Instability Angle readily illustrates the role of each element of the ground structure, it is used in the following discussion.

Another measure of ground stability, with particular application to trail tread durability, is its **Bearing Capacity**, usually stated in pounds-per-square-inch (psi). A particular soil's <u>ultimate</u> Bearing Capacity is the amount of vertical load it can carry without the load overcoming that soil's shear strength (think internal friction), which would allow the soil to be forced laterally out from under the vertical load.

<u>Elements of Ground Structure</u>

Particle Size and Shape: How large (or small) are most of the soil particles, and are they angular, rounded, or plate-like?

Internal Particle Friction: How resistant is the soil to internal movement, called its Friction Coefficient? This is basically dictated by the Particle Size and Shape, but is readily changed by the other factors which follow.

Rock and Gravel Content: How much of the soil is made up of small rock (angular) and/or gravel (rounded), "small" meaning less than 4 inches in maximum dimension? Rock and, to a lesser extent, gravel content improves the soil's structural stability.

Organics Content: How much of the soil is made up of decaying organic matter, which decreases stability?

Density: How much of a cubic foot of a particular soil is solid matter (particles) versus air space (interparticle voids)? Higher density generally means better stability and, odd as it may seem, fine-grained soils are <u>less dense</u> than coarse-grained soils. When we dig up a soil and use it as backfill, we almost never achieve its original density no matter how we compact it – a fill slope is thus inherently less stable than the natural slope it is made from.

Soil Chemistry: Is the soil acidic (generally weaker) or alkaline (generally stronger)? (This is a gross over-simplification of a complex subject).

Soil Moisture: How much of the "air space" (interparticle voids) in a soil is occupied by water, often termed the "degree of saturation"? Soil moisture has profound effects on soil stability, ranging from highly positive at some levels to disasterously negative at others; we're normally most interested in what happens as a soil approaches or reaches 100% saturation, an always destabilizing condition.

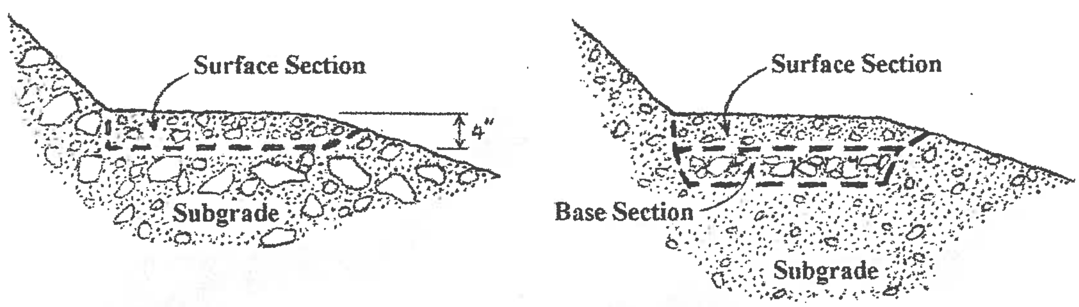
Underlying Bedrock: How far below the surface is bedrock? Is that bedrock at a steep or a gentle angle? Is the bedrock surface rough (holding the soil in place) or smooth (could allow the soil layer to slide on it)?

Vegetative Cover: What's the extent of vegetative cover, and type of vegetation (rooting depth and continuity)?

The TREAD STRUCTURE

The Trail Tread is considered to have a "structural section" extending from its surface down to a point at which surface traffic impacts are so disbursed that their effects are miniscule. While soil type obviously affects the depth, or thickness, of this **Surface Section**, long experience has led to the adoption of 4 inches as the standard, *and minimum*, thickness for pedestrian and stock trails (6 inches is more appropriate for wheeled traffic). Within this 4 inch layer all rocks and roots over 2 inches in size are removed. Leaving oversize rocks and roots in this section causes uneven response to surface impacts, and the surface tends to unravel over time.

Beneath the Surface Section is the **Subgrade**, being the native slope soil. If this Subgrade material is stable, then all trail construction and maintenance activities are confined to the Surface Section, the point being to *not* disturb the Subgrade. If the



Tread Structural Sections

Subgrade material is *not* reliably stable (eg., overly silty or sandy, overly moist, overly organic), it may be necessary to add a **Base Section**, usually composed of rocky or gravelly sandy soil, to provide enough structural rigidity to support the Surface Section and its traffic. (Base Sections may also be incorporated for subsurface drainage purposes). Base Sections can range from 2 to 6+ inches thick, and are best installed during initial trail construction rather than as a "maintenance fix"; they require the availability of a quantity of base material close to a place which obviously lacks it, most likely to be found during initial tread excavation. The Base Section must be laid and compacted in layers not more than 2 inches thick, after which the Surface Section is laid and compacted in 2-inch layers, obviously a fairly challenging process in practical terms. So try to locate your trail on stable ground where Base Sections are not needed.

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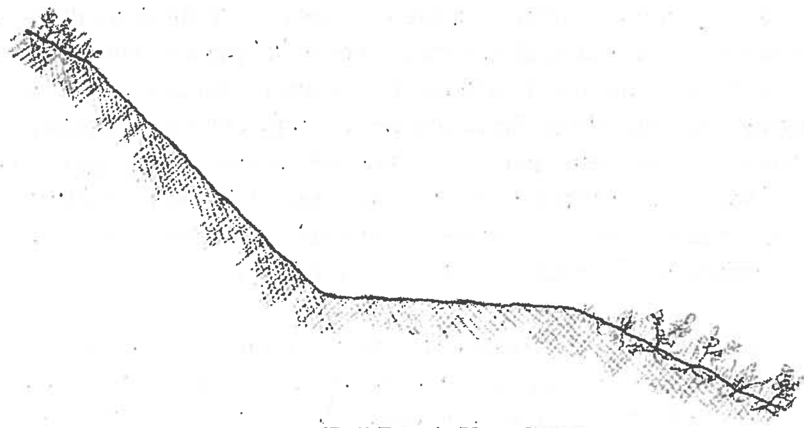
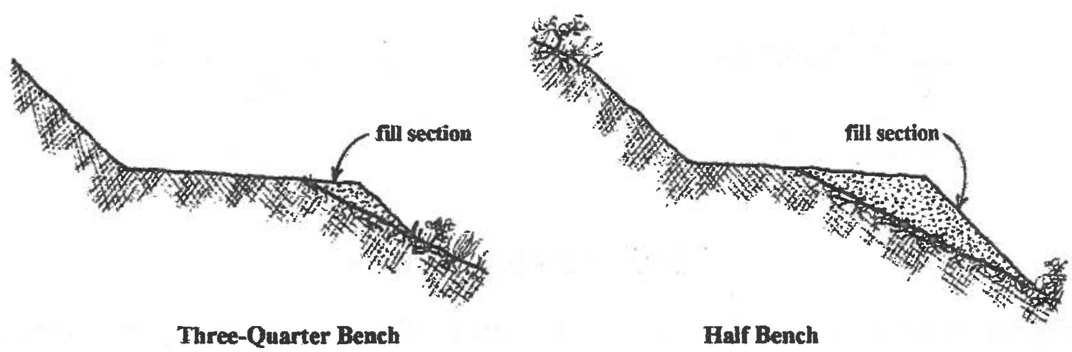
The TREAD BENCH

The **Tread Bench** is the excavated platform on which the trail, and its traffic, rests. In good soil the Surface Section is simply the top 4 inches of the Bench soil. **Full Bench** construction (ie., the entire width of the tread is excavated into the slope) is strongly preferred due to its structural continuity. **Partial Bench** ("cut-and-fill") construction (ie., ½ to ¾ of the tread width is excavated, the remainder resting on a backfill section made from the excavated material) is strongly discouraged, since it presents long-term structural stability problems:



Full Bench Treadway



Partial Bench Treadway

The Fill Section, despite our best efforts at compaction, will be less dense than the soil underlying the excavated bench. That means it will settle farther and more quickly under traffic compaction, and be less resistant to surface wear, during the 2 or more years it will take to finally approach its "natural density". It will also have a lower Friction Coefficient than the undisturbed slope soil, so (at least initially) its stable angle will be less than that of the natural slope, yet by its very nature it must have a *steeper angle* than the natural slope. Thus the Fill Section is inherently less stable than either the excavated bench it adjoins or the slope on which it rests. Almost invariably the Fill Section is placed on top of ground-level vegetation down-slope from the excavated bench, which leaves an organic-layer break in soil continuity between the fill and excavated portions of the tread. It's easy to see why Fill Sections routinely settle and shear away from the rest of the tread, making Partial-Bench construction a poor idea.

By design, the outer face of a Fill Section must have a steeper angle than the natural slope; to make it the same would require extending the fill down slope until the natural slope gentled enough to provide a footing, a distance which could be several hundred feet. The ideal fill face slope would be 2:1, or 50%, but since there is almost never enough soil volume available from the excavated area to achieve that, the face slope usually ends up between 70% and 100%. The steeper the face angle, the harder it is to adequately compact the fill. On steeper ground (usually over 50%), it's also possible to induce sectional downslope failure by using Partial-Bench construction – if the natural slope is very near its Instability Angle, the weight of the fill may be sufficient to cause the underlying slope to creep or slide.

SWEEP TURNS and SWITCHBACKS

Curve Radius: There are curvature limits for trails, just as there are for roads, usually expressed as the Minimum Radius for *any* turn. These limits are based on the type and speed of the traffic that will be traveling through the curve, and while they are most noticeable in direction-reversing turns they also apply to the linear curves employed in contouring, weaving past obstacles, dropping in and out of gullies and streams, etc.

The trail tread material also plays a role in establishing the Minimum Radius for any particular curve, since it must resist the higher lateral displacement forces generated by turning traffic. These lateral forces increase dramatically as the Radius decreases and/or the traffic speed increases, and are generally higher for wheeled traffic than for foot or hoof traffic. The given Minimum Radii routinely assume a tight sandy gravel soil with good bearing capacity and wear (shear) resistance; if the actual tread soil is a looser sand or a mud-prone silt, the Radius needs to be increased 10% to 25%. However the presence of a *more* wear-resistant soil does NOT mean the Radius can be decreased – the Radius is based on the curve-negotiating capability of the particular traffic type, and anything less is no longer adequately functional for that traffic.

In general, the Minimum Radius for common trail traffic types is:

Traffic type	Minimum Radius	
Hikers	8 ft	
Horses, Bicycles	10 ft	
OHVs*, Skiers	15 ft	*(includes ATVs and Motorbikes)
Snowmachines, Skijourers	20 ft	
Dog Mushers, Groomers	30 ft	

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NOTE that OHV's pulling trailers need a Minimum 25-ft Radius; snowmachines pulling sleds need a 30-ft Radius; long dog teams, such as are used in racing or heavy freight hauling, may need a 50 to 100-ft Radius.

Direction-Reversing Turns: When reversing direction, the desire is to allow traffic to flow through the turn with as little impedance (abrupt loss of speed) as reasonably possible. By design, Sweep Turns allow more Radius flexibility and better traffic flow than do Switchbacks, which by design actually *do* impede traffic. But the steepness of the slope is a major limiting factor in the location of Sweep Turns, sometimes forcing us to use Switchbacks, and can also limit the reasonably-constructable Radius so much that some traffic types cannot use them. Let's look at the geometry of these turn types and the limits placed on them by the terrain, keeping in mind that they are by function **Control Point structures**.

SWEEP TURN GEOMETRY

A Sweep Turn ("Climbing Turn") is a means of reversing trail direction while avoiding the design and construction difficulties, and the traffic flow restriction, of Switchbacks. Ideally a Sweep Turn would reverse the trail direction while gaining enough elevation within the turn to preclude any "entrenchment", and thus the possible need for a drainage ditch within the turn. "Entrenchment" means the difference in elevation between the trail tread outer margin and the natural slope at that same point (how much lower is the tread from the slope surface). As the trail leaves the upper arc of the turn, it must quickly climb out of the trench in what's called "Runout (to daylight)". See the PLAN VIEWS on the next page.

To truly understand the function and limits of Sweep Turns, several factors must be considered:

(1) The maximum trail grade allowed within the turn.
(2) The sideslope at the turn location.
(3) The tread-centerline radius of the turn.
(4) The tangent angle where the trail enters (and "on paper" leaves) the turn.
(5) The "Full Arc" angle at which the trail actually leaves the turn.
(6) The Runout length and across-slope grade.
(5) Drainage through the turn.

Maximum In-Turn Grade:
In order to limit or preclude entrenchment, the trail in the turn must gain enough elevation to nearly match the elevation gain of the sideslope between the two turn tangent points. But the factors controlling the grade are the *type of use* and the *wear resistance* of the tread material, rather than the desire to gain elevation. A maximum in-turn grade of 10% works for most soils and traffic types. If the soil is particularly wear resistant, *and the traffic exerts little lateral pressure in the turn* (eg., hikers and livestock), grades up to 15% may work. Obviously, on poorer soils grades under 10% may be necessary, which will increase the depth of entrenchment.

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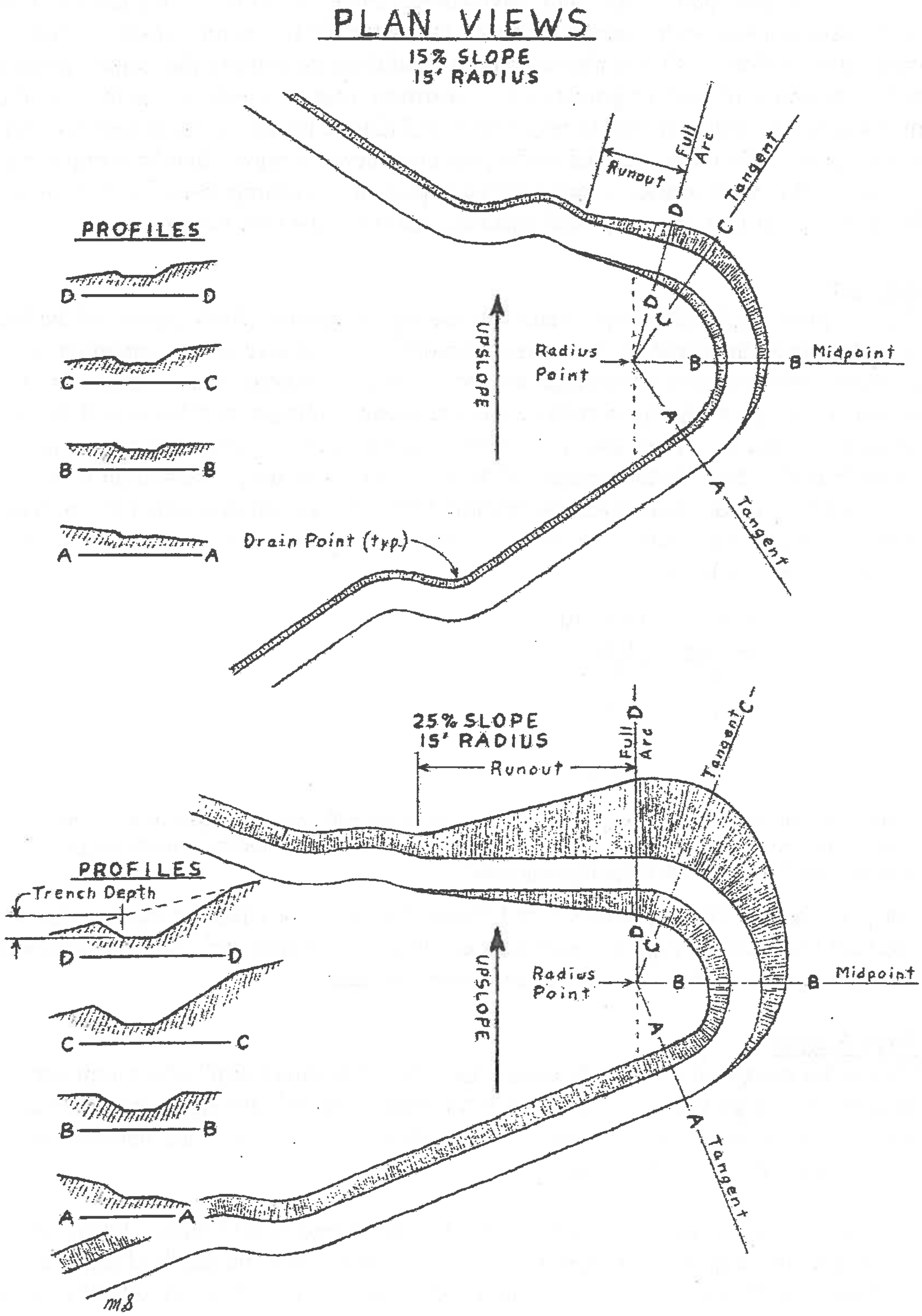

Note that a higher grade value may have already been identified for the particular trail as its "Maximum Allowable Grade". Use of this value for the in-turn grade is subject to two important cautions: (1) The physical tread conditions permitting that higher grade (eg., a high percentage of rock or gravel in the substrate) must be *confirmed* at the site of the turn and not simply *assumed* to be present; and (2) the lateral displacement forces in turns, particularly from wheeled traffic, are considerably higher than in straight runs. Therefore it is wise to take a conservative approach to pushing in-turn grades unless frequent (ie., at least annual) tread maintenance is planned for the trail.

Sideslope:

The steepness of the sideslope relative to the rate of in-turn climb (grade) of the trail directly affects the depth of trail entrenchment(1). To achieve *no* entrenchment at a 10% in-curve grade requires a sideslope around 11%; at 12% grade the sideslope limit is around 14%. So a certain amount of entrenchment is almost inevitable, and the real question should be "when does the sideslope drive us away from sweep turns and toward switchbacks", based on the amount of excavation and drainage construction required. My personal "guide" is to question the suitability of a sweep turn when the entrenchment depth exceeds 2 feet and/or the runout length exceeds 20 feet at 10%. That results in the following general limits:

Curve Radius	Sideslope Limit
8'	25%
10'	22%
15'	20%
20'	18%

(1) Note that Entrenchment depth is the difference between tread level and slope surface *at the outer tread margin*. This difference is greater at the trail centerline, and even greater at the inner margin, but it is the outer margin difference that forms the trench wall.

These limits are "recommended", and Sweep Turns are possible on steeper slopes, but you will find that the rapidly increasing excavation volumes and drainage complications will make 30% a "practical maximum" sideslope angle.

Turn Radius:

This is the measured distance between the staked "Radius Point" of the turn and the tread centerline through the turn. The size of the radius controls the tightness of the turn (a radius under 8 feet usually becomes a Switchback in actual use) and needs to be matched to the intended trail user group(s).

Once the sideslope steepness rises above the "no entrenchment value" for the given in-turn grade, the turn radius begins to have an effect on both the depth of Entrenchment and the length of the Runout. The Entrenchment effect is illustrated in the following table for a 10% in-turn trail grade:

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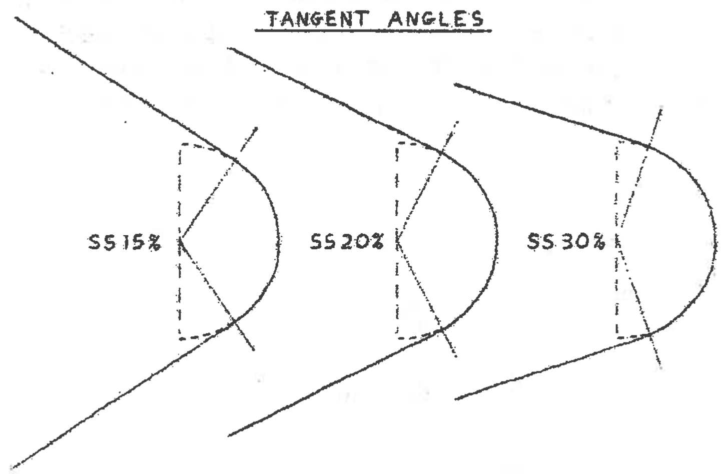
	Entrenchment at Upper Tangent*				
Radius:	**8'**	**10'**	**15'**	**20'**	**30'**
SS%					
30	2.6'	3.2'	4.8'	6.4'	9.6'
25	1.8'	2.3'	3.4'	4.5'	6.8'
20	1.1'	1.4'	2.1'	2.7'	3.7'
15	0.4'	0.5'	0.8'	1.1'	1.6'

*(For Entrenchment at 12% grade, multiply by 0.26 for 15% SS, 0.68 for 20% SS, 0.79 for 25% SS, 0.84 for 30% SS; at 15% grade, 0.18 for 20% SS, 0.47 for 25% SS, 0.61 for 30% SS).

Tangent Angle:
Since the linear trail is tangential to the curve, the amount of curve available for the turn to climb in is less than a full half-circle. As the sideslope gentles, the tangent angle widens and the length of curve nominally available decreases (see drawing below). If the grade and sideslope are matched so there is no Entrenchment, the trail enters and leaves the turn at the Tangent points.



Full Arc Angle:
Once Entrenchment becomes a factor, things get more complicated at the Upper Tangent point. If the trail simply proceeds across the slope at its "normal" angle and grade, it will never rise out of its trench, so some realignment is necessary to preclude that. On sideslopes of 17% or more, this means continuing the turn beyond the Upper Tangent to the full half-circle point (call it the **Full Arc** point), and entering the Runout from there. On sideslopes *under* roughly 17% this presents another alignment problem – the tangent angle is so wide on gentle slopes that the transition from Runout to normal trail alignment becomes a sharp turn at less than the minimum turn radius. The Full Arc must end *before* the half-circle point to prevent that. To further complicate matters on gentle slopes, the turn Radius itself influences where the Full Arc must end to accommodate both alignment and reasonable Runout length. The following table, showing both Tangent-to-Tangent and Full Arc angles, illustrates the point (also see the PLAN VIEWS drawing).

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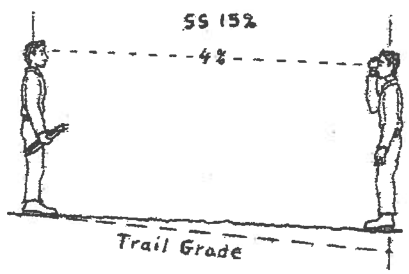
Side-slope	between Tangents angle	Full Arc angle
20%	127°	153°
25%	136°	158°
30%	143°	162°

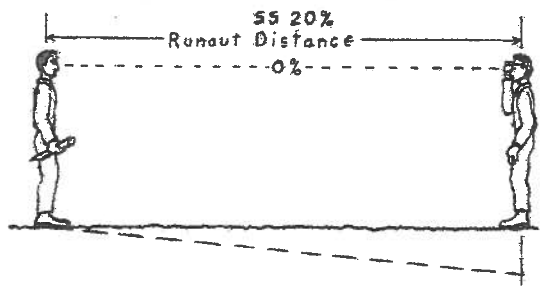
Side-slope	between Tangents angle	Full Arc angle
15% at		
R = 8'	112°	123°
10'	"	125°
15'	"	130°
20'	"	131°*
25'	"	132°*
30'	"	133°*

* (In the field, use 132° for R of 20' to 30')

Runout:

We want to get out of the trench as quickly as possible, but without violating grade limits. This means running the trail from the Full Arc point *across* the slope for the distance necessary (the **Runout**) for the trail's grade to bring it up to the slope surface. When the Full Arc point is the same as the half-circle point (sideslope 17+%), shoot a 0% clinometer reading across the Runout distance (see drawing and Runout table below). When the Full Arc is less than the half-circle point (sideslope under 17%), use the clinometer reading shown in the table for 15% sideslope; it will get you in the ballpark.





Side-Slope: R =	RUNOUT @ clinometer reading 15%	20%	25%	30%
8'	9.5' @ 6%	8.5' @ 0%	16' @ 0%	24' @ 0%
10'	12' @ 5%	10.5' @ 0%	20' @ 0%	30' @ 0%
15'	12' @ 4%	16' @ 0%	30' @ 0%	45' @ 0%
20'	15' @ 3%	22' @ 0%	41' @ 0%	60' @ 0%
25'	17' @ 3%	27' @ 0%	51' @ 0%	75' @ 0%
30'	19' @ 3%	33' @ 0%	62' @ 0%	91' @ 0%

NOTE: For Runout distance at 12% trail grade, multiply by 0.83, at 15% trail grade, multiply by 0.67.

This will all seem like a lot of referencing tables and shooting angles for what is really a pretty simple turn, and you'll find that the "pro's" at this game often simply "eyeball" the layout. But accurate eyeballing takes experience; using the tables, clinometer and compass will gain you that experience much quicker than if you rely solely on hit-or-miss layouts in the field.

Turn Drainage:
In the ideal situation where there is no entrenchment, Grade Reversal drain points are incorporated into the trail legs, usually some 30 feet before entering the low end of the curve and within 20 feet of leaving the upper end of the curve. Where entrenchment is included, the upper leg drain is placed within 10 feet of the end of the Runout, and the lower leg drain is placed to catch and divert any down-slope flow from the upper drain.

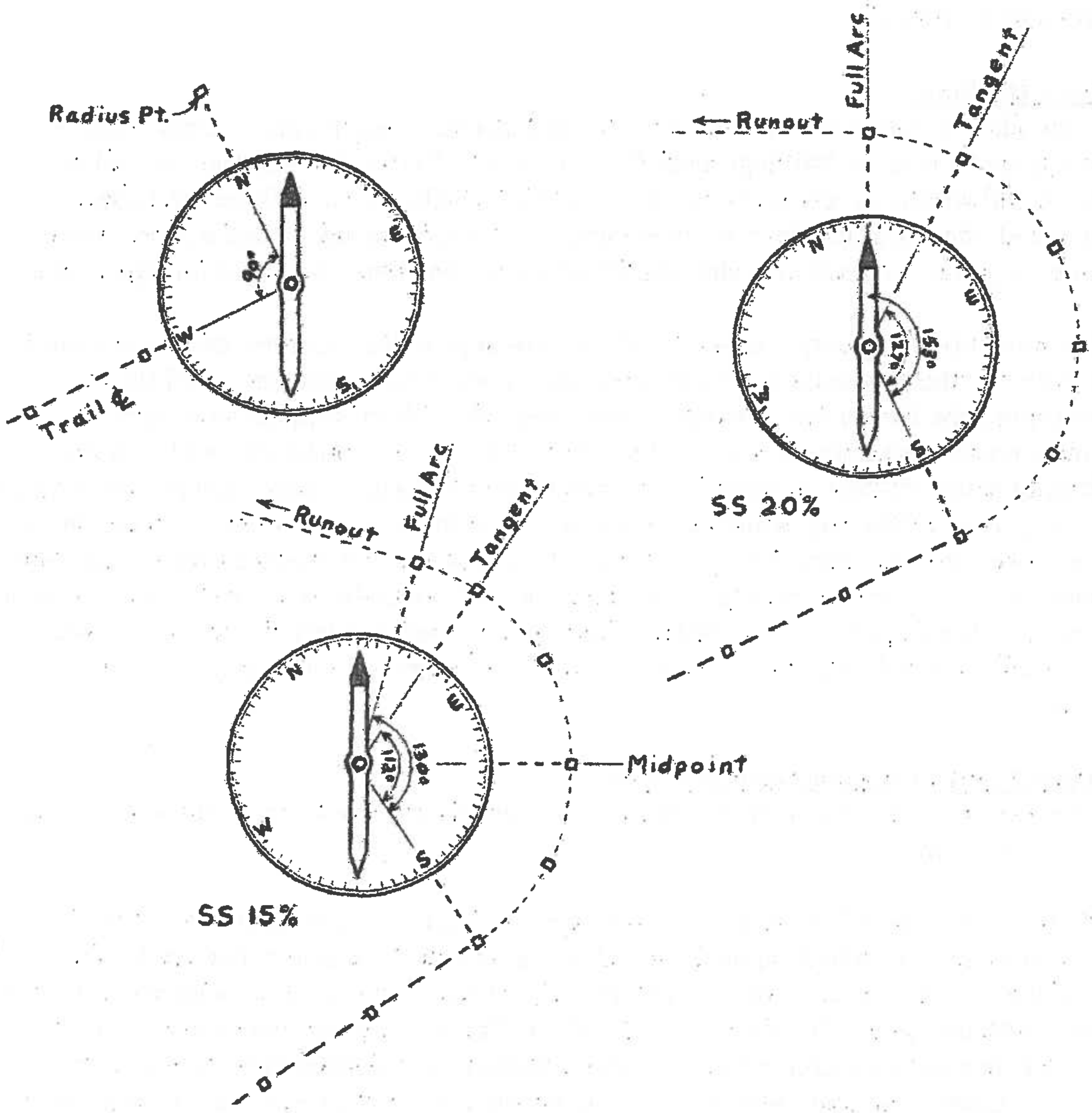
The more critical question is what to do for drainage *within the turn,* and the answer is dictated by the particular combination of use, tread erosion resistance, and surface moisture flow for the site. On tight-radius turns with short Runouts there may be no undue erosion, so nothing need be done, but when the combined length of turn plus Runout means 50 feet or more of in-trench water flow a ditch may be necessary along the inner margin of the turn which carries water to the lower leg drain point. Note that this will widen the excavation through the turn by 2 to 4 feet. In extreme cases it may also be necessary to move the upper leg drain to a point *within* the Runout trench, and construct it as a 20-feet-long Grade Dip with the drain outlet punched through the outer trench wall; unfortunately that will also increase the total length of the Runout section by at least 10 feet.

Turn Layout Problems and Solutions:
There are a few questions to be answered in Sweep Turn layout that cause a good deal of head-scratching:

(1) How do I know what angle to use between the Lower Tangent and Full Arc points (ie., how much of a half-circle is available), and how do I measure that angle in the field? Use the Full Arc table on page 11 for the angle (take it into the field with you); it's based on a 10% trail grade, but will put you in the ballpark for grades between 8% and 12%. **NOTE** that tables useful in the field are reproduced as an **Appendix** for easy copying.

Carry a compass with you – it can be used like a protractor (see drawing on next page). Standing at the point on the trail centerline where you want to start the turn, align the East-West axis with the trail, and place the Radius Point stake along the North-South axis (it takes 2 people to do this accurately). Then stand at the Radius Point, align the North-South axis with the radius line, and place the Full Arc point stake at the appropriate angle (for example, 130°). You can also locate the Upper Tangent point in the same manner. See drawing on next page.

(2) How do I know what Runout length is needed, and what clinometer reading to use for it? As with the angles, take the Runout table from the previous page into the field with you. Wrapping copies of the tables in clear plastic packaging tape for use as field references sure beats doing trig calculations in the skeeters and rain!



(3) Do I need to find the mid-point of the Tangent-to-Tangent arc, and if so, how do I do that? It's nice, but not critical, to locate that point. Stand at the Radius point and shoot a level line (0%) to the turn centerline.

(4) The centerline excavation depth and the Entrenchment depth are different, and the centerline depth varies with the width of the tread while Entrenchment depth does not. As a construction control it would be good to mark the start-of-Runout (Full Arc) stake with one or the other, or perhaps both – so how do I calculate those depths? The simple answer is "Don't", because it's too much math to fiddle with in the field. Instead, use the table below (take it with you). If you use only a centerline stake, mark it with "CL exc." and the depth. *It is poor practice to only use an outer-tread-margin stake marked with Entrenchment depth*; the better method is to centerline stake and also set an outer-tread-margin stake, and mark it with "Trench depth" and the depth.

Entrenchment & Centerline Excavation Depth at 15% SS

Tread width: R	trench margin	2'	2.5'	3'	4'	5'	6'	8'
		at tread centerline						
8'	0.4	0.5	0.5	0.6	na	na	na	na
10'	0.4	0.6	0.6	0.7	0.7	na	na	na
15'	0.6	0.7	0.8	0.8	0.9	1.0	1.0	1.2
20'	0.8	0.9	1.0	1.0	1.1	1.2	1.3	1.4
25'	1.0	1.1	1.2	1.2	1.3	1.3	1.4	1.6
30'	1.1	1.2	1.3	1.3	1.4	1.5	1.6	1.7

Entrenchment & Centerline Excavation Depth at 20% SS

Tread width: R	trench margin	2'	2.5'	3'	4'	5'	6'	8'
		at tread centerline						
8'	0.9	1.1	1.1	1.2	na	na	na	na
10'	1.1	1.3	1.3	1.4	1.5	na	na	na
15'	1.6	1.8	1.9	1.9	2.0	2.1	2.2	2.4
20'	2.2	2.4	2.4	2.5	2.6	2.7	2.8	3.0
25'	2.7	2.9	3.0	3.0	3.1	3.2	3.3	3.5
30'	3.3	3.5	3.6	3.6	3.7	3.8	3.9	4.1

Entrenchment & Centerline Excavation Depth at 25% SS

Tread width: R	trench margin	2'	2.5'	3'	4'	5'	6'	8'
		at tread centerline						
8'	1.6	1.9	1.9	2.0	na	na	na	na
10'	2.0	2.3	2.3	2.4	2.5	na	na	na
15'	3.0	3.3	3.4	3.4	3.6	3.7	3.8	4.1
20'	4.1	4.4	4.4	4.5	4.6	4.7	4.9	5.1
25'	5.1	5.4	5.4	5.5	5.6	5.7	5.9	6.1
30'	6.2	6.4	6.5	6.6	6.7	6.8	6.9	7.2

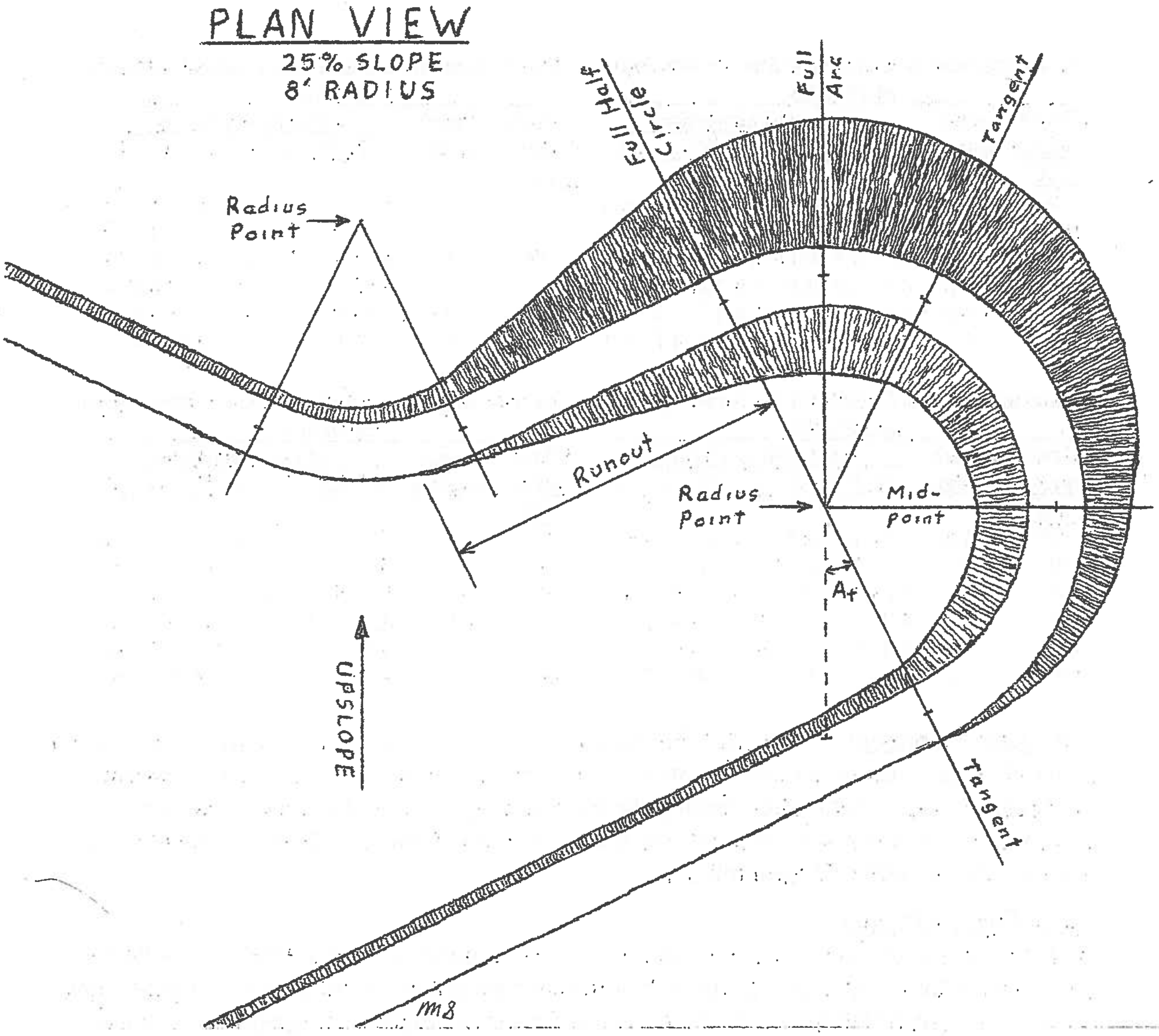
Entrenchment & Centerline Excavation Depth at 30% SS

Tread width: R	trench margin	2'	2.5'	3'	4'	5'	6'	8'
		at tread centerline						
8'	2.4	2.7	2.8	2.8	na	na	na	na
10'	3.0	3.3	3.4	3.4	3.6	na	na	na
15'	4.5	4.8	4.9	5.0	5.1	5.3	5.4	5.7
20'	6.0	6.3	6.4	6.5	6.6	6.8	6.9	7.2
25'	7.5	7.8	7.9	8.0	8.1	8.3	8.4	8.7
30'	9.1	9.4	9.4	9.5	9.7	9.8	10.0	10.3

(5) And the big one: Why can't I continue the turn to a full 180° from the lower Tangent line, thus gaining more tread rise within the turn and, by pointing the tread alignment toward the slope surface, shortening the Runout length and reducing the excavation volume? The answer is "you can, but there are complications and risks to consider" in what is often called a **Fishhook Turn**.

The Fishhook Turn:
By continuing the in-Turn arc beyond the Full Arc point to the Full Half-Circle (180°) point from the lower tangent line, the length of turn climb lost to the lower tangent angle is restored (see Drawing on next page, where the lost tangential segment is shown as angle A_t). At the same time, this aligns the Runout parallel with the lower trail leg, thus pointing it toward the slope surface and reducing its length to daylight by 50% to 60%. Note that the added arc length is in the deep-excavation zone, which will affect the total Turn excavation volume to be dealt with. At the daylighting end of the Runout a reverse curve, at the Turn radius, is added to realign the trail across the slope; the length of this curve will be roughly twice the A_t segment length. One drawback to the Fishhook is that its geometry creates a significant "invitation to short-cut" for descending traffic as it enters the reverse curve, and the placement of physical barriers between the upper and lower trail legs may prove to be essential.

Caution: Do not carry the Turn arc beyond the Half-Circle point. That would require you to either lose tread elevation in the reverse curve, thus negating part of the desired elevation gain, or would require the curve to occur at significantly less than the Turn radius, abruptly impeding the traffic flow. In either case, the invitation to short-cutting would be increased.



Another Caution: The double curve in the upper Turn-plus-Runout is already more challenging for traffic than the standard Sweep Turn, and if we construct the upper-leg drain either within or immediately beyond the reverse curve, both the vertical and horizontal aligment get very complicated (like a writhing snake in fact). Go at least 6 feet up-trail from the end of the reverse curve, or 10 feet on trails with wheeled traffic, before starting that upper-leg drain.

So what have we accomplished with the Fishhook Turn? Depending on sideslope steepness, the in-Turn arc length has increased by 12% to 45%, allowing more in-Turn tread elevation gain (see Table on next page), and the Runout length has been reduced by half or more. The resulting total Turn+Runout length has been reduced roughly 25%, *but the total excavation volume has gone up by 10% to 12%.* The Fishhook has its place, particularly where the terrain either allows or forces wrapping the Turn around a physical and/or visual barrier which minimizes the invitation to short-cutting, but it is not a "quick and easy" solution to any perceived difficulty with the standard Sweep Turn.

Tangential Segment Length
at 10% trail grade

Side-Slope	Angle A_t	length % of Half Circle[1]	length increase over Full Arc
12%	56°	31.1	1.452
15%	42°	23.3	1.304
20%	30°	16.7	1.20
25%	24°	13.3	1.154
30%	19°	10.6	1.118

[1] To determine additional trail elevation gain, multiply Turn radius by 3.14 and the Half Circle percent. That result times the in-Turn trail grade will be the vertical rise in feet.

Walls and Barriers:
Sweep Turns have the advantage over Switchbacks that the trail legs entering and leaving the turn are fairly well separated, somewhat reducing the temptation to short-cut the turn. But as the turn radius decreases below 20 feet this advantage wanes, and placing physical barriers like boulders or logs between the legs may be necessary. On very short-radius turns in less stable soils it may even be necessary to construct a rock or timber retaining wall in the lower turn backslope to support the upper turn tread margin and further discourage short-cutting; such walls can also be used in the upper turn backslope to reduce the up-slope reach of the backslope cut on steeper sideslopes.

The "SLOPE-GRADE SWEEP TURN"

For those of you now feeling seriously challenged by all the angles, entrenchment and runout of properly constructed Sweep Turns, there is an alternative, which is shown as "the way" to build these turns by some trail handbooks. It's too often an **Oversteep Turn** in which the slope angle is simply accepted as the trail grade in the turn – there is no entrenchment, though you still need to abide by the Tangent Angles to make the turn work for traffic flow. So, for example, a trail at a 10% grade on a 20% sideslope would make its turn arc across the slope, its grade rising from 10% at the lower Tangent Point to 20% at the turn mid-point, then declining back to 10% at the upper Tangent Point. This trail will thus be "oversteep" for some 22 feet in a 10-foot radius turn, or 67 feet in a 30-foot radius turn (push the sideslope up to 25% and the oversteep lengths rise to 24 feet and 71 feet).

This approach may work on sideslopes up to perhaps 25%, but there are several factors working against its success, not the least being a requirement that the tread soil be *exceptionally* stable and wear-resistant. Torque loading and lateral displacement forces are maximized in the turn as traffic "powers up" in climbing, or brakes in descending, through it. It abruptly slows the normal flow of uphill traffic, and encourages overly high speed by downhill traffic, so the turn can rapidly become banked (insloped) whether you want it to or not. The trail must also be near or at the fall-line of the slope through most of the turn, inviting water erosion which, if the turn becomes banked, will be further channelized and destructive. Also note that it has a chance of working successfully only with smaller radii (limiting the trail length at or near fall-line), and only on gentler side-slopes which are in the same range that is easiest for proper Sweep Turn construction. So while it is possible to use the Slope-Grade approach in certain limited circumstances (sideslopes up to around 15%), it is inherently risky on steeper ground where you should expect such turns to require frequent high-intensity maintenance or even reconstruction.

SWITCHBACK GEOMETRY

On any sideslope of 30% or more, Sweep Turns require so much entrenchment, trench-entrapped drainage, and backslope-plus-runout excavation, that they are routinely replaced by Switchbacks. A Switchback allows the two trail legs to actually meet, and replaces the Sweep Turn arc with a "Turning Table" -- traffic moves from one trail leg onto the Table, where it reverses direction and then leaves the table on the other trail leg.

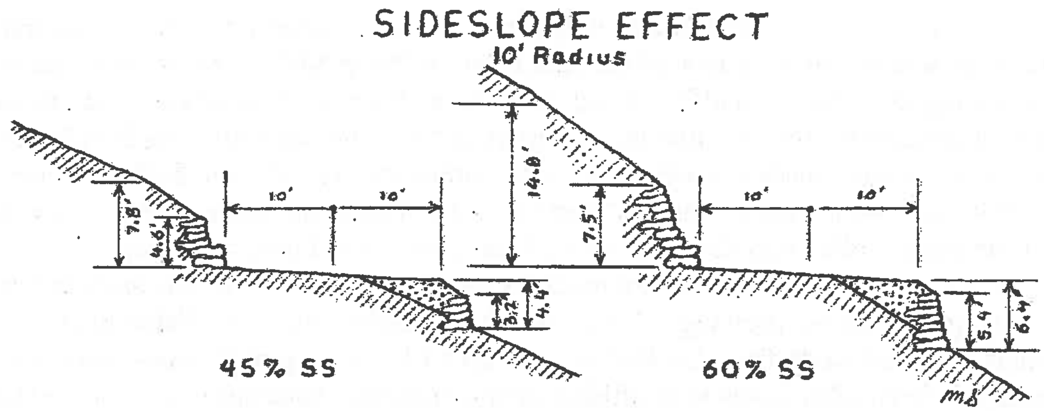
Note that the given Minimum Radius used for Sweep Turns is also used for the Turning Table, and that roughly three-quarters of a full circle is used to make the Table. There is one *major* difference: In Switchbacks the Radius is an outer-perimeter measurement, not a centerline measurement, so the Switchback turn is tighter and assumes that traffic must move much more slowly through the turn.

As with Sweep Turns, there is a "practical constructability" limit to the size of the Turning Table, primarily dictated by the sideslope steepness; in other words, the larger Tables can require such massive fill sections, and such extensive retaining walls in both downslope fill and backslope cut, that they become impractical to construct. As a general guide, the maximum sideslope on which a given radius Table can be reasonably constructed is as follows:

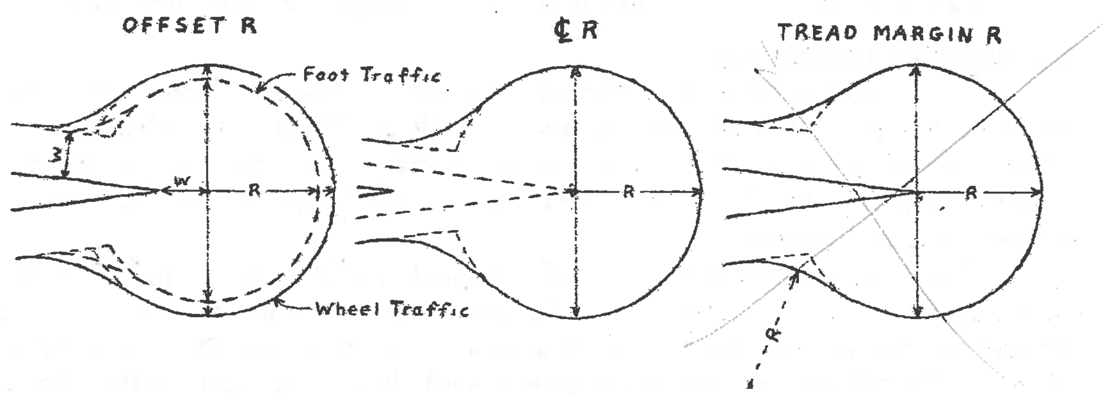
Table Radius	max. Sideslope	Table Radius	max. Sideslope
8 ft.	48%	20 ft.	38%
10 ft.	45%	25 ft.	36%
12 ft.	42%	30 ft.	34%
15 ft.	40%		

Note that these are practical rather than absolute limits. Switchbacks with a Radius of 10 feet or less can be built on *stable* sideslopes as steep as 60%, but they do require high massive retaining walls to support both the fill slope and the backslope, and should be avoided if at all possible. The drawing on page 18 shows the difference between 45% and 60% sideslope for a 10-foot-Radius Switchback, with a near doubling in the amount of rock retaining walls.

The **Turning Table** is the crucial item in Switchback layout. There are 3 methods of selecting and marking the Radius Point: (1) Tread Margin Junction (the "old time method"); (2) Offset (from tread margin junction); and (3) Centerline Junction. See the



drawing below. A common novice's mistake, because it's easy when centerline marking the trail route, is to use the Centerline Junction method, which is the only one that *does not work*: It places the Radius Point so far ahead of the physical junction of the trail legs that it essentially isolates the Table. Foot and single-horse traffic in particular will "cut the corner" behind the Radius Point and never enter the Table; other traffic types may be forced to use the Table, but we've created a narrow high-wear area at the Table entry/exit point which can eventually destroy the junction and even make the Table unuseable.



So use one of the two Tread Margin methods. The "old time method" on the right locates the Radius Point where the outer tread margin of the uphill trail leg meets the inner tread margin of the downhill trail leg. This incorporates the Table, with the disadvantage that it's hard to maintain the legs junction (and discourage short-cutting) when it is so far within the Table itself. That disadvantage is largely overcome in the Offset method, where the Radius Point is placed one tread-width out from the tread margins junction. Another advantage to the Offset method where hikers and single horses (not pack-strings) are the *only* users is that the Minimum Radius can be somewhat reduced, the amount of reduction being related to tread width (no reduction is possible for wheeled traffic). Use the following for guidance:

Tread width	min. R	Tread width	min. R
2'	6'	5'	10'
3'	7'	6'	12'
4'	8'		

Use this table for pedestrian-only trails.

In either case, layout marking consists of placing a centerline stake in the trail leg at the point where you want to start the turn (mark it "Start SB"); place another stake at 90° to the leg axis and one-half the tread width away from the first stake, which marks the margins junction (for the old time method mark it "RP", for the Offset method leave it blank); place a third stake at roughly 90° to the other leg axis and one-half the tread width away from the second stake (mark it "End SB"); for the Offset method, place a fourth stake one tread width away from the second stake, on a level line, and mark it "RP". The transitions from trail leg to Table are made by a reverse curve having the same radius as the Table (see previous drawing). If you wish to centerline mark the Table itself, deduct one-half the tread width from the Radius, though such marking of Switch-backs is not normally done (it often leads to confusion in construction, particularly on steeper slopes).

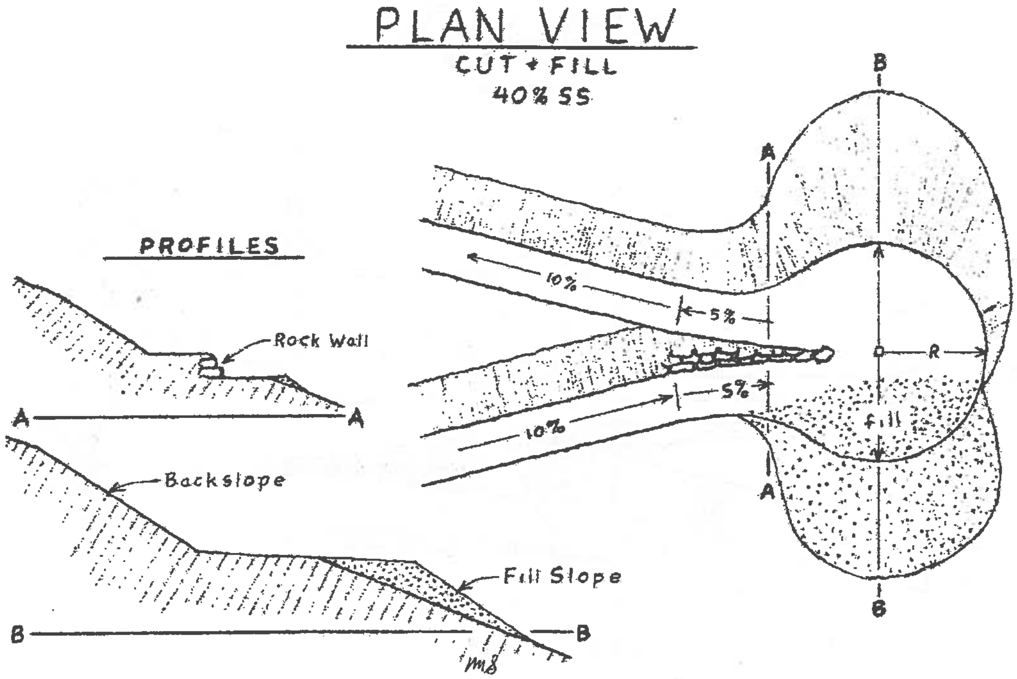
<u>Speed Control for Switchbacks</u>: As the trail approaches and leaves the Table, it's helpful to provide a "deceleration section" at roughly 5% grade, rather than abruptly dump traffic at 10% or more onto and off from a nearly flat surface. Allowing for deceleration benefits both the traveler and the trail, and the length of the section is based on the normal speed of the traffic type. A good Rule of Thumb is 10 feet for hikers and horses, 20 feet for bicyclers and skiers, and 25 feet for any motorized traffic. On sideslopes over 45% this can place the trail legs so close together that the upper leg is unstable even with a supporting wall, and you may have to shorten or forego deceleration sections.

Cut-and-Fill Construction:

An advantage commonly assumed for Switchbacks over Sweep Turns is that they avoid the entrenchment routinely encountered in Sweep Turns. This advantage is achievable only if the construction method is cut-and-fill, and the grade through the Table turn is roughly 5% (the U.S. Forest Service specifies a 2% maximum grade, which assures some entrenchment).

The Turning Table creates a "bulb" in the trail alignment, the inslope portion of which increases the excavation and backslope required while the outer portion extends beyond the ground level, requiring a fill section to support it (see Plan View drawing on page 20). The fill portion, which constitutes nearly half of the Table, suffers from the same structural problems that affect any cut-and-fill construction: lack of native-ground compaction density, subsidence along the cut/fill line, a fill face necessarily steeper than the natural slope, and potential overloading of that slope. In other words, these things can be tough to build well!

The fill material comes from the Table and backslope excavation (assuming it's of good enough quality), and is laid and thoroughly compacted in 2-inch-thick lifts to achieve a fill-slope face no steeper than 1.5:1 (34°, or 67%). A face angle of 2:1 (27°, or 50%) is preferred, but there is seldom enough excavated material produced to achieve that. Rock or log-crib retaining walls are routinely needed to support the upper trail leg as it reaches the Switchback, and the same wall requirement can occur to retain the fill section below the Table and/or lessen the backslope cut above it. Drainage of this Switchback is often accomplished solely by tread out-sloping in the trail legs and the slight downslope pitch of the Table surface, since no part of the Switchback is entrenched.



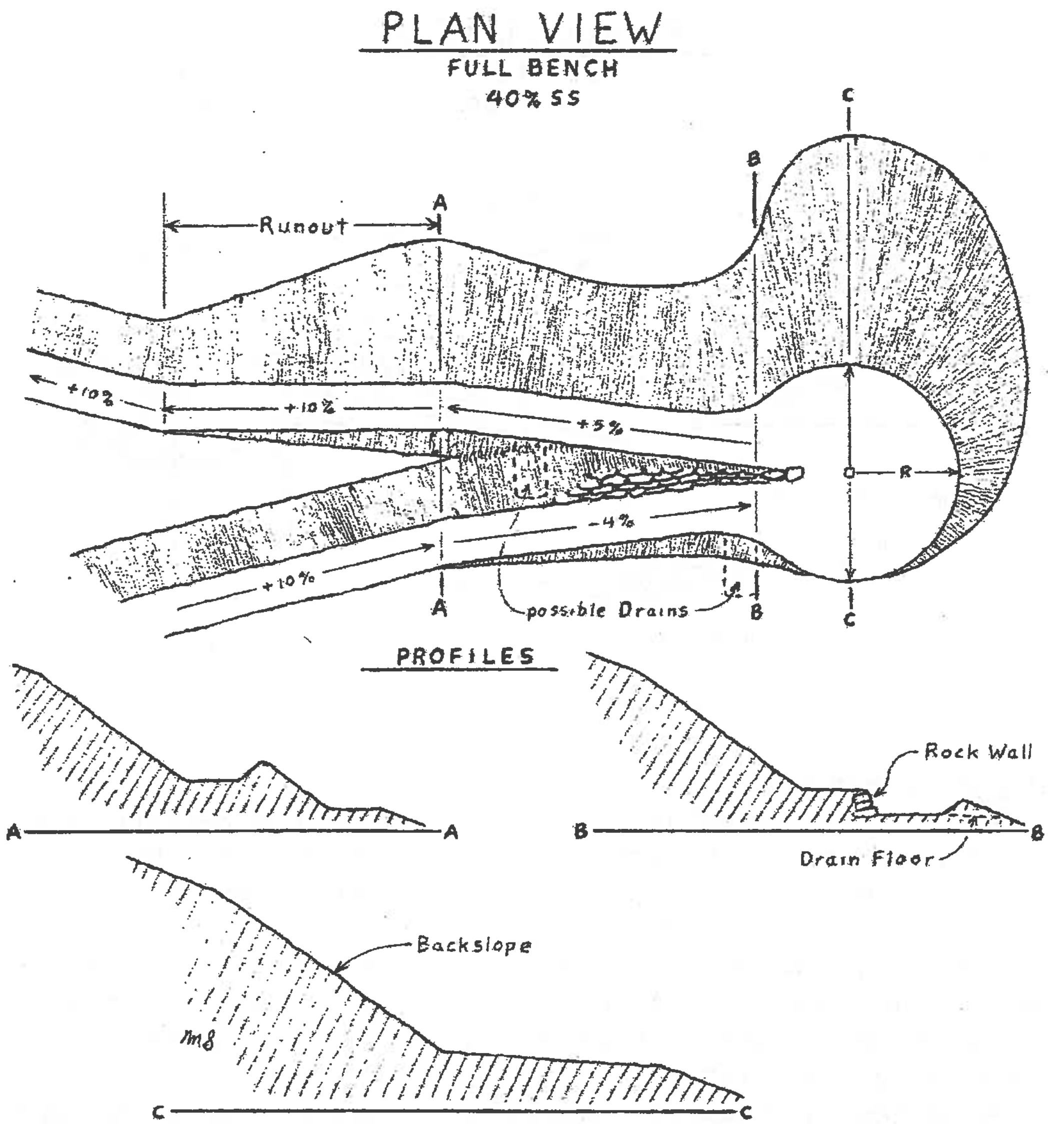
Full-Bench Construction:

It is possible to construct the Turning Table as a full-bench excavation, and in poorer soils this method may be essential to its survival, but trail entrenchment both above and below the Table is required, and the layout geometry becomes much more complicated (see Plan View on page 21).

The lower trail leg "deceleration section" is given a reverse grade of roughly 4%, so that it *descends* to the lower Table entry/exit point. The only way to do this without seriously misaligning the trail is to entrench this section. A climbing grade of 5% is maintained through the Table turn.

At the upper Table exit/entry point the trail is now entrenched, and as with the entrenchment in Sweep Turns a "Runout" section is needed to allow the trail to climb out of its trench. But with Switchbacks the trail legs are so close together as they approach the Table that promptly constructing the Runout would require a fairly massive and extensive retaining wall to support the upper leg Instead, the normal deceleration section is constructed as entrenched trail and the Runout section follows it.

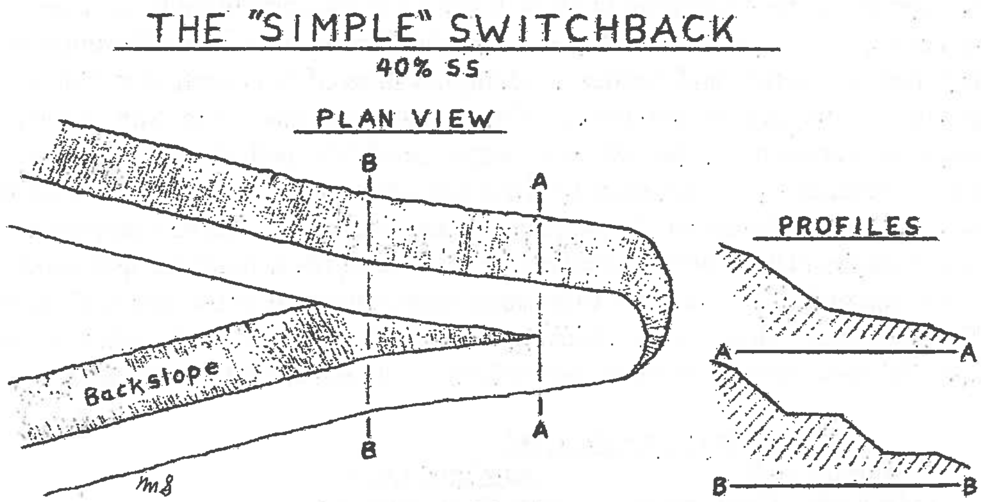
With all this entrenchment, simple outsloped drainage is no longer possible, and specific drainage points must be constructed. These are usually simple drainways which breach the outer trench wall, rather than true Drain Dips which would vastly complicate the trail-grade/runout-length layout and construction challenges. There are 2 locations to consider for drainways: (1) The upper deceleration-plus-Runout trench is fairly long (30 to 50 feet, depending on sideslope steepness), and a wall-breaching drain some 15 to 20 feet beyond the Table is recommended. (2) Where the lower deceleration section, on a descending grade, meets the Table and its ascending grade, a pond point is created which almost always needs a drain. The only instances where these breaching drains are not necessary are where vertical drainage (percolation) through the tread soil is so rapid and



consistent that water never ponds or runs on the tread surface, a real rarity!

The complexity of full-bench construction is the reason why over 90% of the Switchbacks constructed in the past were cut-and-fill, and that will undoubtedly continue to be the case. However, cut-and-fill, with its inherent structural stability problems, means that the larger-radius Switchbacks are often not reliable on steeper slopes. Thus if the terrain dictates that only small-radius Switchbacks are reasonable, that will also mean that the traffic types that require a larger radius may be precluded from using the trail – more on that subject later.

The "Simple Switchback": By now some of you have asked yourself, "Why not simply bring the trail legs together and skip the Turn Table?", making what old-timers called a "Simple Switchback". Obviously that could only work for traffic types capable of making very tight turns: Hikers, and burros and llamas (if *not* in pack-strings). There is also a problem with tread cross-slope at the turn; without a Table, there is no turn arc to provide the turn length necessary to compensate for sideslope steepness, so the tread at the turn will outslope at roughly 20% (see drawing). That's far too steep a surface for normal tread soils to resist turning traffic wear, so it rapidly becomes a steep-sided, berm-walled "cup" or an eroded gully extending downslope. However, there is one place



where the Simple Switchback *can* work *for hiker-only trails*, and may in fact be preferred: Talus fields. Void-chinked angular talus tread can withstand the traffic wear on a 20+% turn cross-slope, and it can be very difficult to build a full Turn Table on steep large-block talus slopes. For foot traffic in talus the deceleration sections can be reduced or eliminated if they overly complicate the routing of the trail legs.

BANKED TURNS

As traffic travels through a turn it exerts lateral pressure against the tread soil, causing it to displace toward the outer perimeter of the turn where it accumulates as a soil berm. Regrading this berm back onto the full turn surface and compacting it is the most critical, and the most labor-intensive, task in turn maintenance. While the amount and speed of such tread displacement increase in poorer soils, they are more affected by the speed of traffic and tightness of the turn, and are often more noticeable in Switchbacks than in Sweep Turns. One way to reduce displacement is to purposely "bank the turn" (construct it with a surface inslope toward its Radius Point). In effect, this tips the tread surface upward against the direction of the traffic's lateral pressure, thus reducing its soil-displacement force.

Turning traffic, be it a hiker's boot or a 4-wheeler's tires, delivers its impact to the tread surface in 3 directions: Vertically, Axially, and Laterally. The majority of the impact is delivered vertically, as a compressive force, and unless it exceeds the soil's bearing and/or shear strength it causes little damage. The smaller but still significant axial portion of the impact is a shear force (seen as torque), delivered backward from the boot/tire when it is at constant travel speed or accelerating, or forward when it is slowing or stopping. The lateral (and smallest) portion of the impact is also a shear force (seen as centrifugal), delivered sideways from the boot/tire toward the outer turn margin. Both the axial and lateral forces are affected by the speed of travel, and the rate of *acceleration or deceleration. The axial force also increases as trail grade increases, while the lateral force increases as turn Radius decreases.*

While foot and livestock traffic do exert lateral pressures that can lead to outer perimeter berming, their speed is so slow that actually constructing a Banked Turn for them is almost never done; the exception is trails designed to accommodate foot-racers or high numbers of joggers. Wheeled traffic, particularly if motorized, is a different story, being generally heavier, faster, and having much higher rates of acceleration and deceleration through turns. The appropriate degree of tread inslope is thus a function of the traffic type (wheeled versus non-wheeled), its normal speed of travel, the radius of the turn, the presence or absence of deceleration sections approaching the turn, *and the structural integrity of the tread material*. In practical terms that means a certain amount of estimating (called "Guesswork") comes into play, with the truly most appropriate inslope being revealed under use – expect to do some turn reshaping in the first year or two of use. The following will provide a starting point for the inslope grade, with the caution that it should *never* exceed 10% for non-wheeled traffic, or 20% for wheeled traffic.

BANKED TURN INSLOPE

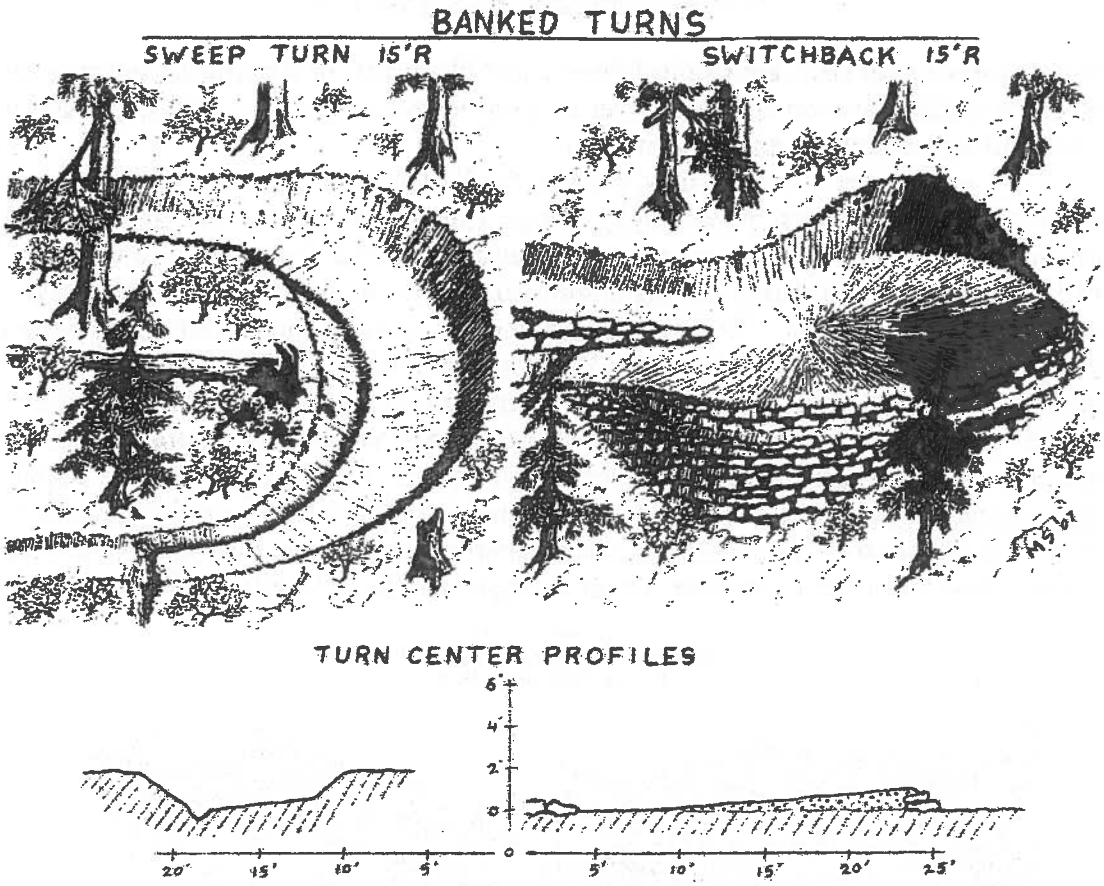
	wheeled traffic		**non-wheeled traffic**	
Radius	**Sweep Turns**	**Switchbacks**	**Sweep Turns**	**Switchbacks**
8 ft	12%*	18%*	6%	8%
10 ft	10%	16%	5%	6%
15 ft	8%	12%	NA	5%
20 ft	6%	10%	NA	NA
25 ft	5%	8%	NA	NA
30 ft	NA	6%	NA	NA

*(for Bicycles)

The tricky part is deciding what to do where there's a mix of traffic types. Inslopes over 6% will tend to force hikers and horses toward the inner turn margin, which can lead to rutting and eventually destroy any constructed drain ditch. For mixed wheeled and other traffic it may be necessary to widen the tread surface by 50% to 100% through Sweep Turns, giving the inner portion of the tread a gentler slope than the outer portion. In Switchbacks, which already use the entire Radius width as a travel surface, widening is not necessary to accomplish this.

Insloping occurs smoothly, starting at the upper trail-to-turn (Full Arc) point, and ends in a transition beyond the lower trail-to-turn point. It should achieve the full inslope angle within the upper quarter of the turn arc, and begin to lessen only after the directly down-slope point of the turn is passed.

The outer perimeter of the more steeply banked turns usually requires some structural reinforcement to maintain their physical integrity, particularly in cut-and-fill Switchbacks. This can be accomplished by adding angular rock fragments (assuming they're available) to the subgrade soil underlying the outer turn surface, or by placing a course of laid stone under the outer surface. Do *not* use logs or timbers instead of stone; their shapes and light weight work against structural stability in this application, and they are too easily displaced or misaligned by the trail traffic.



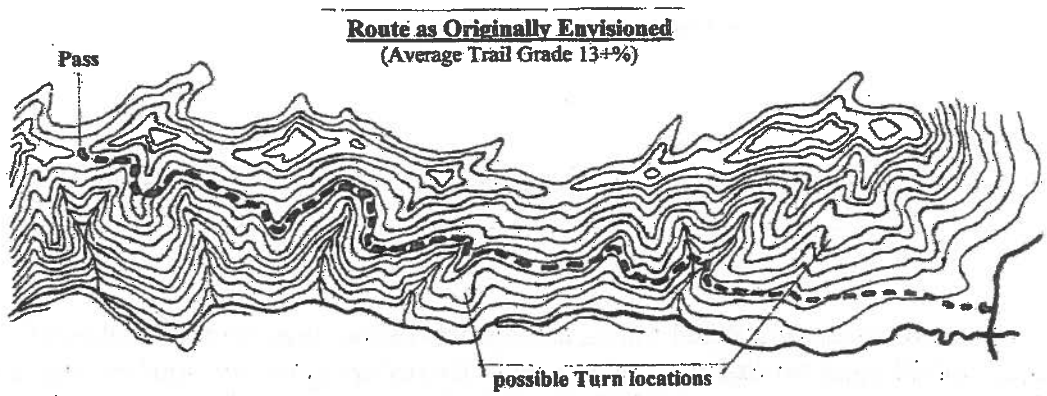
Now to the downside of Banked Turns, aside from the fact they're more technically difficult to build and maintain: (A) Drainage – By insloping the turn surface, any hope for drainage by sheet runoff is abandoned. All surface runoff is accumulated at the inner turn margin, where it becomes channeled (more erosive) runoff; the construction of an inner-perimeter ditch is usually required, particularly in Sweep Turns, and it must extend down-trail from the turn to the first good drain point. (B) Tread Slope Transition – The upper trail leg easily transitions from its normal outslope to a steeper tread slope as it enters the turn, since both trail leg and turn are sloped in the same direction. But at the lower end of the turn the tread must transition from insloped to outsloped as it becomes the lower trail leg. This change in tread slope direction cannot occur before the full turn is completed (a common mistake is to end the turn inslope too soon, leading to rollovers or traffic running off the trail), and it cannot be abrupt (make it occur over a trail distance of at least 8 to 10 feet). (C) Switchback Enlargement – The lower portion of cut-and-fill Switchbacks is already tightly constrained and, resting entirely on fill, of somewhat less than optimum stability. Adding embankment for the turn (which *should include* structural reinforcement in this case) requires adding a foot or more to the width (Radius) of this fill section to provide sufficient space to safely accommodate the reinforcement and the traffic load it must carry.

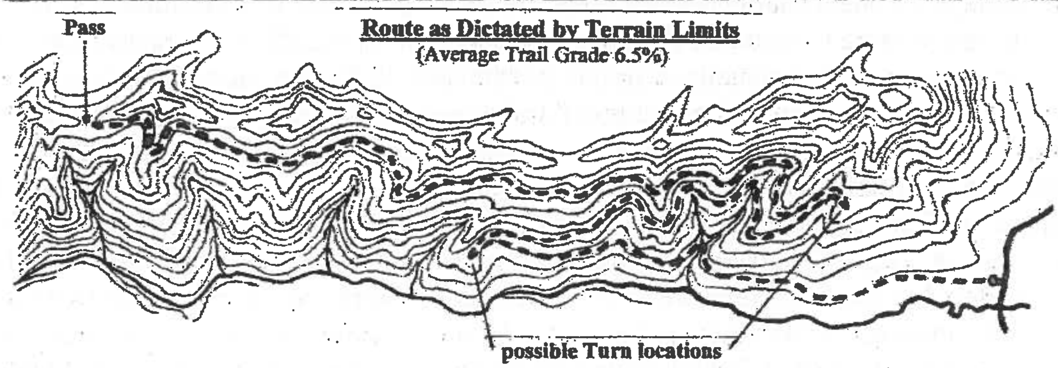
THE GEOMETRY OF TURNS
Design & Layout

TURNS as CONTROL POINTS

Direction-reversing turns are Control Points, just like a cliff or a trailhead, because they influence traffic flow and are themselves influenced by topography. This is perhaps best illustrated by a couple of example situations.

#1 – We want to build a new, roughly 5 mile long, hiker/horse trail from a valley bottom trailhead to a pass, traversing up along a ridgeside to do so. A straight route as originally envisioned will require an average trail grade well above 13%, so we know we'll need at least 2 direction-reversing turns to gain enough trail distance to keep the average grade at or below 10%. The ridgeside slope *averages* nearly 50%, but there are two spurs with short crest slopes under 30%, one within a mile of the trailhead but high on the ridge, the other halfway up the valley but lower on the ridge (see drawing below). At a 30% slope Sweep Turns are not a good option, but Switchbacks certainly are, particularly given the 10-foot Radius needed for horses. So the crests of those 2 spurs are Route Control Points, and the trail must be routed to place the turns on them. Notice that because these Control Points are over a mile apart we're going to gain much more trail distance than is necessary, and the *actual* average trail grade is going to be around 6.5%.





#2 – The trail above got built 8 years ago, with a 5-feet-wide tread to allow passing of horses, and now the Area Manager wants to allow winter use on it by skiers and snowmachines. The tread width is fine for skiers, though pretty marginal for snow-machines on a 50% slope, but the existing Switchbacks have only half the *minimum* Radius needed for snowmachines. So the question becomes "Can these turns be at least doubled in size without compromising the stability of either the turn or the slope on which it rests?" A corollary question is whether the larger Switchback will still function for the summer hiker/horse traffic without being seriously degraded by their inevitable "short-cutting" of the larger full Radius. This is an example of where terrain limitations on turn type and size can preclude some traffic types on a given route. While another more cirquitous route, with no turns required, might be found, it is entirely possible to face the situation where the terrain simply will not accommodate the type of use desired; don't expect that to be an easy sell to either the user group or the Area Manager.

Maintenance and Other Considerations

Whether it's a Sweep Turn or a Switchback, the maintenance needed is essentially the same: Regrading to pull berm and sluff material, and the inevitable down-the-turn migration of tread soil, back onto the turn surface where it is compacted. If the turn includes a drainage ditch, that must be cleaned and reshaped as necessary. If this is a Banked Turn, the regrading is a bit more difficult since it must also re-establish the design inslope. All direction-reversing turns are points of maximized traffic wear, and annual maintenance is the minimum frequency you should plan for.

Sweep Turns and Switchbacks tend to accumulate and hold snow more than does linear trail, particularly if there is any entrenchment in the turn or its approaches. Aspect obviously affects this phenomenon, so when it's possible to place a turn on a south or west-facing slope (rather than a north or east-facing slope) that should be considered. Another trick, where practical, is to cut the Backslopes at a gentler angle, like 2:1, which allows slightly more sun exposure in the turn. But keep in mind that turns are often the last places on a trail to fully melt out, thaw, drain and stabilize in spring, and thus may also be "season of use" control points.

IN CONCLUSION

Neither Sweep Turns nor Switchbacks are "simple" structures, and though Sweep Turns are preferred there are places where they don't work as well as Switchbacks. Both turn types are constrained by the terrain, to the extent that they may preclude use by some types of trail traffic. Both turn types are a lot of work to build correctly, but that work pays off in the long-term durability and useability of the structure. Turns are perhaps the most noticeable feature which demonstrates that ***"Cheap Design and Construction equals Very Expensive Maintenance"***.

APPENDIX

TURN ANGLES

use Tangent for slope-grade turns, Full Arc for controlled-grade turns

Side-slope	between Tangents angle	Full Arc angle
20%	127°	153°
25%	136°	158°
30%	143°	162°

Side-slope	between Tangents angle	Full Arc angle
15% at		
R = 8'	112°	123°
10'	"	125°
15'	"	130°
20'	"	131°*
25'	"	132°*
30'	"	133°*

* (In the field, use 132° for R of 20' to 30')

SWEEP TURN RUNOUT

Side-Slope: R =	RUNOUT @ clinometer reading 15%	20%	25%	30%
8'	9.5' @ 6%	8.5' @ 0%	16' @ 0%	24' @ 0%
10'	12' @ 5%	10.5' @ 0%	20' @ 0%	30' @ 0%
15'	12' @ 4%	16' @ 0%	30' @ 0%	45' @ 0%
20'	15' @ 3%	22' @ 0%	41' @ 0%	60' @ 0%
25'	17' @ 3%	27' @ 0%	51' @ 0%	75' @ 0%
30'	19' @ 3%	33' @ 0%	62' @ 0%	91' @ 0%

NOTE: For Runout distance at 12% trail grade, multiply by 0.83, at 15% trail grade, multiply by 0.67.

SWEEP TURN ENTRENCHMENT

Entrenchment & Centerline Excavation Depth at 15% SS

Tread width: R	trench margin	at tread centerline 2'	2.5'	3'	4'	5'	6'	8'
8'	0.4	0.5	0.5	0.6	na	na	na	na
10'	0.4	0.6	0.6	0.7	0.7	na	na	na
15'	0.6	0.7	0.8	0.8	0.9	1.0	1.0	1.2
20'	0.8	0.9	1.0	1.0	1.1	1.2	1.3	1.4
25'	1.0	1.1	1.2	1.2	1.3	1.3	1.4	1.6
30'	1.1	1.2	1.3	1.3	1.4	1.5	1.6	1.7

Entrenchment & Centerline Excavation Depth at 20% SS

Tread width: R	trench margin	at tread centerline 2'	2.5'	3'	4'	5'	6'	8'
8'	0.9	1.1	1.1	1.2	na	na	na	na
10'	1.1	1.3	1.3	1.4	1.5	na	na	na
15'	1.6	1.8	1.9	1.9	2.0	2.1	2.2	2.4
20'	2.2	2.4	2.4	2.5	2.6	2.7	2.8	3.0
25'	2.7	2.9	3.0	3.0	3.1	3.2	3.3	3.5
30'	3.3	3.5	3.6	3.6	3.7	3.8	3.9	4.1

Entrenchment & Centerline Excavation Depth at 25% SS

Tread width: R	trench margin	at tread centerline 2'	2.5'	3'	4'	5'	6'	8'
8'	1.6	1.9	1.9	2.0	na	na	na	na
10'	2.0	2.3	2.3	2.4	2.5	na	na	na
15'	3.0	3.3	3.4	3.4	3.6	3.7	3.8	4.1
20'	4.1	4.4	4.4	4.5	4.6	4.7	4.9	5.1
25'	5.1	5.4	5.4	5.5	5.6	5.7	5.9	6.1
30'	6.2	6.4	6.5	6.6	6.7	6.8	6.9	7.2

Entrenchment & Centerline Excavation Depth at 30% SS

Tread width: R	trench margin	at tread centerline 2'	2.5'	3'	4'	5'	6'	8'
8'	2.4	2.7	2.8	2.8	na	na	na	na
10'	3.0	3.3	3.4	3.4	3.6	na	na	na
15'	4.5	4.8	4.9	5.0	5.1	5.3	5.4	5.7
20'	6.0	6.3	6.4	6.5	6.6	6.8	6.9	7.2
25'	7.5	7.8	7.9	8.0	8.1	8.3	8.4	8.7
30'	9.1	9.4	9.4	9.5	9.7	9.8	10.0	10.3

BACKSLOPE CUTLINE

slope distance from tread centerline

Sideslope at 20%

Tread Width	Backslope cut at 1:1	1.5:1	2:1
2'	1.5	1.8	2.3
4'	3.0	3.7	4.6
6'	4.5	5.5	7.0
8'	6.0	7.5	9.3
Incr*	(1.3)	(2.1)	(3.3)

Sideslope at 25%

Tread Width	Backslope cut at 1:1	1.5:1	2:1
2'	1.7	2.2	3.1
4'	3.4	4.5	6.2
6'	5.1	6.7	9.3
8'	6.9	8.9	12.4
Incr*	(1.4)	(2.4)	(4.1)

*(per ft of exc depth)

Sideslope at 30%

Tread Width	Backslope cut at 1:1	1.5:1	2:1
2'	2.0	2.8	4.4
4'	3.9	5.5	8.7
6'	5.9	8.3	13.1
8'	7.9	11.1	17.4
Incr*	(1.5)	(2.8)	(5.4)

Sideslope at 35%

Tread Width	Backslope cut at 1:1	1.5:1	2:1
2'	2.2	3.4	6.3
4'	4.4	6.8	12.5
6'	6.7	10.5	19.2
8'	8.9	13.6	25.0
Incr*	(1.6)	(3.3)	(7.3)

Sideslope at 40%

Tread Width	Backslope cut at 1:1	1.5:1	2:1
2'	2.5	4.3	10.3
4'	5.1	8.8	20.6
6'	7.6	12.9	na
8'	10.2	17.2	na
Incr*	(1.8)	(4.0)	(11.4)

Sideslope at 50%

Tread Width	Backslope cut at 1:1	1.5:1	2:1
2'	3.3	7.5	15.1
4'	6.7	14.9	na
6'	10.0	22.4	na
8'	13.4	na	na
Incr*	(2.2)	(6.3)	(14.0)

Sideslope at 60%

Tread Width	Backslope cut at 1:1	1.5:1	2:1
2'	4.7	20.2	na
4'	9.4	na	na
6'	14.0	na	na
8'	18.7	na	na
Incr*	(2.9)	(15.9)	--

Sideslope at 70%

Tread Width	Backslope cut at 1:1	1.5:1	2:1
2'	6.9	na	na
4'	13.8	na	na
6'	20.8	na	na
8'	27.7	na	na
Incr*	(4.1)	--	--

DOWNSLOPE CUTLINE

slope distance from tread centerline at 1 ft exc depth

Sideslope at 20%

Tread Width	Downslope cut at 1:1	1.5:1	2:1
2'	1.9	2.2	2.5
4'	2.9	3.2	3.5
6'	3.9	4.2	4.5
8'	4.9	5.2	5.6
Incr*	(0.9)	(1.2)	(1.5)

Sideslope at 25%

Tread Width	Downslope cut at 1:1	1.5:1	2:1
2'	1.9	2.2	2.4
4'	2.9	3.2	3.4
6'	3.9	4.2	4.5
8'	5.0	5.2	5.5
Incr*	(0.8)	(1.1)	(1.4)

*(per additional ft of exc depth)

Sideslope at 30%

Tread Width	Downslope cut at 1:1	1.5:1	2:1
2'	1.9	2.1	2.4
4'	2.9	3.2	3.4
6'	3.9	4.2	4.4
8'	5.0	5.3	5.5
Incr*	(0.8)	(1.1)	(1.3)

Sideslope at 35%

Tread Width	Downslope cut at 1:1	1.5:1	2:1
2'	1.9	2.1	2.3
4'	2.9	3.1	3.4
6'	4.0	4.2	4.4
8'	5.0	5.3	5.5
Incr*	(0.8)	(1.0)	(1.2)

Sideslope at 40%

Tread Width	Downslope cut at 1:1	1.5:1	2:1
2'	1.9	2.1	2.3
4'	2.9	3.2	3.4
6'	4.0	4.2	4.4
8'	5.1	5.3	5.5
Incr*	(0.8)	(1.0)	(1.2)

Sideslope at 50%

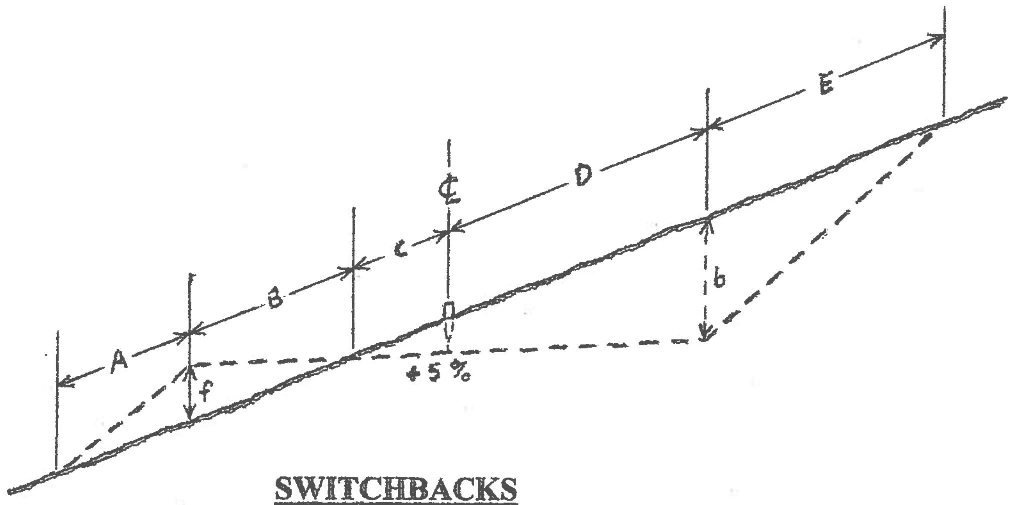
Tread Width	Downslope cut at 1:1	1.5:1	2:1
2'	1.9	2.1	2.2
4'	3.0	3.2	3.4
6'	4.1	4.3	4.5
8'	5.2	5.4	5.6
Incr*	(0.7)	(1.0)	(1.1)

Sideslope at 60%

Tread Width	Downslope cut at 1:1	1.5:1	2:1
2'	1.9	2.1	na
4'	3.1	3.3	na
6'	4.2	4.4	na
8'	5.4	5.6	na
Incr*	(0.7)	(0.9)	--

Sideslope at 70%

Tread Width	Downslope cut at 1:1	1.5:1	2:1
2'	1.9	2.1	na
4'	3.2	3.3	na
6'	4.4	4.6	na
8'	5.6	5.8	na
Incr*	(0.7)	(0.9)	--



SWITCHBACKS

slope distance between points

multiply Radius by factor

SS %	A @1.5:1	B	C	D	E @ 1:1	E @ 1.5:1	E @ 2:1	approximate cut b	approximate fill f
30	0.5	0.7	0.4	1.0	0.5	1.0	1.9	0.35	0.18
40	0.9	0.7	0.4	1.1	0.9	1.9	5.5	0.48	0.23
50	1.6	0.7	0.4	1.1	1.2	3.4	na	0.54	0.26
	@1.25:1								
60	2.1	0.8	0.4	1.2	2.2	11.9	na	0.75	0.35
70	5.0	0.8	0.5	1.2	3.6	na	na	0.89	0.42

References

Most of the material presented in this text comes from 50+ years' experience, much of it involving correcting poorly built turns that were failing. The following references provide a general coverage of the subject.

Trail Construction and Maintenance Notebook, Hasselbarth & Vachowski, U.S. Forest Service, 1999.

Trail Handbook, Griswold, Sequoia & Kings Canyon National Park, 1989.

Lightly on the Land, Birkby, Student Conservation Assn., 1996.

Trail Solutions, Int'l Mountain Bicycling Assn., 2004.

DOWNSLOPE CUTLINE

slope distance from tread centerline at 1 ft exc depth

Sideslope at 20%

Tread Width	Downslope cut at 1:1	1.5:1	2:1
2'	1.9	2.2	2.5
4'	2.9	3.2	3.5
6'	3.9	4.2	4.5
8'	4.9	5.2	5.6
Incr*	(0.9)	(1.2)	(1.5)

Sideslope at 25%

Tread Width	Downslope cut at 1:1	1.5:1	2:1
2'	1.9	2.2	2.4
4'	2.9	3.2	3.4
6'	3.9	4.2	4.5
8'	5.0	5.2	5.5
Incr*	(0.8)	(1.1)	(1.4)

*(per additional ft of exc depth)

Sideslope at 30%

Tread Width	Downslope cut at 1:1	1.5:1	2:1
2'	1.9	2.1	2.4
4'	2.9	3.2	3.4
6'	3.9	4.2	4.4
8'	5.0	5.3	5.5
Incr*	(0.8)	(1.1)	(1.3)

Sideslope at 35%

Tread Width	Downslope cut at 1:1	1.5:1	2:1
2'	1.9	2.1	2.3
4'	2.9	3.1	3.4
6'	4.0	4.2	4.4
8'	5.0	5.3	5.5
Incr*	(0.8)	(1.0)	(1.2)

Sideslope at 40%

Tread Width	Downslope cut at 1:1	1.5:1	2:1
2'	1.9	2.1	2.3
4'	2.9	3.2	3.4
6'	4.0	4.2	4.4
8'	5.1	5.3	5.5
Incr*	(0.8)	(1.0)	(1.2)

Sideslope at 50%

Tread Width	Downslope cut at 1:1	1.5:1	2:1
2'	1.9	2.1	2.2
4'	3.0	3.2	3.4
6'	4.1	4.3	4.5
8'	5.2	5.4	5.6
Incr*	(0.7)	(1.0)	(1.1)

Sideslope at 60%

Tread Width	Downslope cut at 1:1	1.5:1	2:1
2'	1.9	2.1	na
4'	3.1	3.3	na
6'	4.2	4.4	na
8'	5.4	5.6	na
Incr*	(0.7)	(0.9)	--

Sideslope at 70%

Tread Width	Downslope cut at 1:1	1.5:1	2:1
2'	1.9	2.1	na
4'	3.2	3.3	na
6'	4.4	4.6	na
8'	5.6	5.8	na
Incr*	(0.7)	(0.9)	--

TURN ANGLES

use Tangent for slope-grade turns, Full Arc for controlled-grade turns

Side-slope	between Tangents angle	Full Arc angle
20%	127°	153°
25%	136°	158°
30%	143°	162°

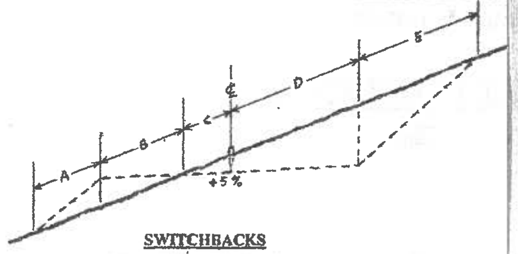
Side-slope	between Tangents angle	Full Arc angle
15% at R = 8'	112°	123°
10'	"	125°
15'	"	130°
20'	"	131°*
25'	"	132°*
30'	"	133°*

* (In the field, use 132° for R of 20' to 30')

SWEEP TURN RUNOUT

Side-Slope: R =	RUNOUT @ clinometer reading 15%	20%	25%	30%
8'	9.5' @ 6%	8.5' @ 0%	16' @ 0%	24' @ 0%
10'	12' @ 5%	10.5' @ 0%	20' @ 0%	30' @ 0%
15'	12' @ 4%	16' @ 0%	30' @ 0%	45' @ 0%
20'	15' @ 3%	22' @ 0%	41' @ 0%	60' @ 0%
25'	17' @ 3%	27' @ 0%	51' @ 0%	75' @ 0%
30'	19' @ 3%	33' @ 0%	62' @ 0%	91' @ 0%

NOTE: For Runout distance at 12% trail grade, multiply by 0.83, at 15% trail grade, multiply by 0.67.



SWITCHBACKS

slope distance between points
multiply Radius by factor

SS %	A @1.5:1	B	C	D	E @ 1:1	E @ 1.5:1	E @ 2:1
30	0.5	0.7	0.4	1.0	0.5	1.0	1.9
40	0.9	0.7	0.4	1.1	0.9	1.9	5.5
50	1.6	0.7	0.4	1.1	1.2	3.4	na
	@1.25:1						
60	2.1	0.8	0.4	1.2	2.2	11.9	na
70	5.0	0.8	0.5	1.2	3.6	na	na

BACKSLOPE CUTLINE

slope distance from tread centerline

Sideslope at 20%

Tread Width	Backslope cut at 1:1	1.5:1	2:1
2'	1.5	1.8	2.3
4'	3.0	3.7	4.6
6'	4.5	5.5	7.0
8'	6.0	7.5	9.3
Incr*	(1.3)	(2.1)	(3.3)

Sideslope at 25%

Tread Width	Backslope cut at 1:1	1.5:1	2:1
2'	1.7	2.2	3.1
4'	3.4	4.5	6.2
6'	5.1	6.7	9.3
8'	6.9	8.9	12.4
Incr*	(1.4)	(2.4)	(4.1)

*(per ft of exc depth)

Sideslope at 30%

Tread Width	Backslope cut at 1:1	1.5:1	2:1
2'	2.0	2.8	4.4
4'	3.9	5.5	8.7
6'	5.9	8.3	13.1
8'	7.9	11.1	17.4
Incr*	(1.5)	(2.8)	(5.4)

Sideslope at 35%

Tread Width	Backslope cut at 1:1	1.5:1	2:1
2'	2.2	3.4	6.3
4'	4.4	6.8	12.5
6'	6.7	10.5	19.2
8'	8.9	13.6	25.0
Incr*	(1.6)	(3.3)	(7.3)

Sideslope at 40%

Tread Width	Backslope cut at 1:1	1.5:1	2:1
2'	2.5	4.3	10.3
4'	5.1	8.8	20.6
6'	7.6	12.9	na
8'	10.2	17.2	na
Incr*	(1.8)	(4.0)	(11.4)

Sideslope at 50%

Tread Width	Backslope cut at 1:1	1.5:1	2:1
2'	3.3	7.5	15.1
4'	6.7	14.9	na
6'	10.0	22.4	na
8'	13.4	na	na
Incr*	(2.2)	(6.3)	(14.0)

Sideslope at 60%

Tread Width	Backslope cut at 1:1	1.5:1	2:1
2'	4.7	20.2	na
4'	9.4	na	na
6'	14.0	na	na
8'	18.7	na	na
Incr*	(2.9)	(15.9)	–

Sideslope at 70%

Tread Width	Backslope cut at 1:1	1.5:1	2:1
2'	6.9	na	na
4'	13.8	na	na
6'	20.8	na	na
8'	27.7	na	na
Incr*	(4.1)	–	–

SWEEP TURN ENTRENCHMENT

Entrenchment & Centerline Excavation Depth at 15% SS

Tread width: R	trench margin	at tread centerline 2'	2.5'	3'	4'	5'	6'	8'
8'	0.4	0.5	0.5	0.6	na	na	na	na
10'	0.4	0.6	0.6	0.7	0.7	na	na	na
15'	0.6	0.7	0.8	0.8	0.9	1.0	1.0	1.2
20'	0.8	0.9	1.0	1.0	1.1	1.2	1.3	1.4
25'	1.0	1.1	1.2	1.2	1.3	1.3	1.4	1.6
30'	1.1	1.2	1.3	1.3	1.4	1.5	1.6	1.7

Entrenchment & Centerline Excavation Depth at 20% SS

Tread width: R	trench margin	at tread centerline 2'	2.5'	3'	4'	5'	6'	8'
8'	0.9	1.1	1.1	1.2	na	na	na	na
10'	1.1	1.3	1.3	1.4	1.5	na	na	na
15'	1.6	1.8	1.9	1.9	2.0	2.1	2.2	2.4
20'	2.2	2.4	2.4	2.5	2.6	2.7	2.8	3.0
25'	2.7	2.9	3.0	3.0	3.1	3.2	3.3	3.5
30'	3.3	3.5	3.6	3.6	3.7	3.8	3.9	4.1

Entrenchment & Centerline Excavation Depth at 25% SS

Tread width: R	trench margin	at tread centerline 2'	2.5'	3'	4'	5'	6'	8'
8'	1.6	1.9	1.9	2.0	na	na	na	na
10'	2.0	2.3	2.3	2.4	2.5	na	na	na
15'	3.0	3.3	3.4	3.4	3.6	3.7	3.8	4.1
20'	4.1	4.4	4.4	4.5	4.6	4.7	4.9	5.1
25'	5.1	5.4	5.4	5.5	5.6	5.7	5.9	6.1
30'	6.2	6.4	6.5	6.6	6.7	6.8	6.9	7.2

Entrenchment & Centerline Excavation Depth at 30% SS

Tread width: R	trench margin	at tread centerline 2'	2.5'	3'	4'	5'	6'	8'
8'	2.4	2.7	2.8	2.8	na	na	na	na
10'	3.0	3.3	3.4	3.4	3.6	na	na	na
15'	4.5	4.8	4.9	5.0	5.1	5.3	5.4	5.7
20'	6.0	6.3	6.4	6.5	6.6	6.8	6.9	7.2
25'	7.5	7.8	7.9	8.0	8.1	8.3	8.4	8.7
30'	9.1	9.4	9.4	9.5	9.7	9.8	10.0	10.3

THE GEOMETRY OF TURNS
Design & Layout

COURSE CONTENTS