TimberTransportForum
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Draft for consultation

The
Timber Transport Toolkit:
Hauling timber on the public highway

Annex

The design and use of the
structural pavement of
unsealed roads

Foreword

Xxx

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Introduction

Many millions of tonnes of timber are hauled each year in the UK. Hauling timber is an essential part of sustainable forest management, which delivers major economic, social and environmental benefits, including, employment, climate change mitigation, improved biodiversity, renewable fuel, enhanced air quality, flood mitigation, recreation and public health opportunities. The UK's forest industries directly support over 160,000 jobs and home-grown timber is especially valuable in terms of reducing "timber miles", by substituting for imports from around the world.

In some cases, timber haulage involves using roads that were not designed for traffic of this nature. The historical legacy of our road infrastructure is compounded by the fact that councils have faced major pressure on roads' budgets over the two last decades, with under-funding in highway maintenance a significant long-term issue. Councils have many competing demands on these diminished funds.

The timber supply chain functions on small margins. As with most other raw materials, the value in timber products is added much further down the chain. From harvesting to retailing the finished product, timber can increase in value 100-fold, or more. Timber haulage is an essential part of this process, delivering the raw material to this economic activity.

Experience has shown that, by working in partnership, the forest industry and the roads authorities can maintain an effective relationship and ensure that the needs of both are accommodated. A great deal of work has been done in building these partnerships and in developing tools to ensure that they are effective.

This Annex to the "Timber Transport Toolkit" deals with the design and use of the structural pavement of unsealed roads. It does not cover the financial appraisal, planning, consultation, construction and maintenance of the road. Neither does it cover road layout, however, for reference purposes, the Forestry Commission *Road specification summary* is attached at Appendix 1.

Principles of road design

Introduction

This document deals with the design and use of the structural pavement of unsealed roads.

It does not cover the financial appraisal, planning, consultation, construction and maintenance of the road. Neither does it cover road layout, however, for reference purposes, the Forestry Commission *Road specification summary* is attached at Appendix 1.

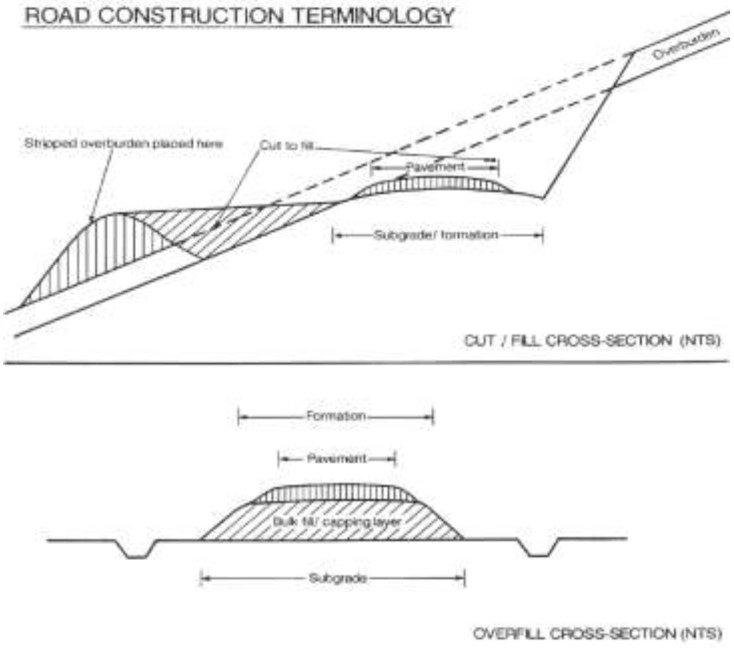
The principles are mainly directed towards low-volume forest roads but can be applied to unsealed public roads.

The ideal structural pavement for such roads:

- Can be constructed and maintained at minimum cost.
- Carry a range of vehicles from light vans to 44T lorries in addition to recreational users and in-forest machines.
- Provide a reasonably smooth surface to optimise vehicle wear, fuel consumption and driver comfort.
- Minimises pollution from dust or slurry.
- Provides sufficient friction for safe braking and traction.

These objectives are achieved by providing a smooth, durable surface that transmits the wheel loads to the ground below (sub-grade) without damaging the surface materials or the sub-grade.

The following diagrams explain the terminology used:



In looking at the principles of road construction, the following are examined:

1. Sub-grade strength.
2. Pavement design.
3. Selecting pavement materials.
4. Aggregate specification.
5. Transmitting the wheel load through the pavement.
6. Avoiding damage.
7. Vehicle selection.
8. Best practice for usage.

1. Sub-grade strength

The sub-grade can be the original ground in an overfill road or the ground surface that is left after preparing the basic shape and alignment of the road. In the case of soft ground, or peat, this could be the surface that is left after excavating the weak materials. In either case the sub-grade is the surface that will have to bear the load from the pavement itself and the applied vehicle loads.

Assessing the strength of the sub-grade is one of the most important, but also most difficult, aspects of road construction. Most low-cost roads cannot bear the cost of doing a comprehensive soil survey so the assessment is largely down to the experience of the engineer. Local knowledge and a visual inspection is a good start. This can identify ground conditions from indicative vegetation and from surface evidence of rock, peat etc.

It is likely in the poor ground usually associated with upland forests that the soils will be variable and inaccessible to vehicles in the early stages of the design process. There are no real alternatives to hand probing for weak soils and peat, CBR probes for sound soils and rock sampling for hard materials.

The CBR probe is a device which measures the California Bearing Ratio (CBR) of the ground. This is a measure of the sub-grade strength against a standard and is empirically linked to the depth of surfacing required for different loading.

In-situ CBR results can be misleading in non-homogenous soils and different moisture conditions so it is advisable to a large number of readings to discern an average or trend. If the soil is granular and consistently too dense to use the probe it can be assumed to have a CBR of at least 20%. However it is always worth checking that the dense layer is not just a superficial layer overlying a softer strata.

If access is less of a problem, there are more accurate devices such as the Dynamic Cone Penetrometer(DCP) and Falling Weight Deflectometer (FWD) that can give more reliable results. Putting your heel into the surface and declaring the strength is unlikely to be satisfactory!

If rock is exposed along the alignment, it is important to assess its value for paving material and also the possible need to blast, or rip, it out to achieve the proposed alignment. There are a number of standard hand tests that give an indication of rock strength, but you need to be aware that surface deposits can be weathered and weaker than the bed rock and also that strong surface boulders are not necessarily an indication of underlying geology.

Where it is appropriate, the cost and strength of a road can be improved by staged construction. If a formation can be left for up to a year, it will naturally consolidate and dry out, increasing the bearing strength for the pavement. Similarly, if the pavement can be left for a year before use, it will also consolidate and become more dense and less prone to damage.

In most construction methods the formation is first prepared, compacted, shaped and tested before placing the final top layer of the pavement. This reduces water ingress and minimises rutting of the formation.

2. Pavement design

The following table gives an indication of the total thickness of pavement that will be required for the various CBR values. These can vary as moisture content changes and also as a result of applying staged construction. Most forest roads in UK are designed for up to 500,000 Standard Axles of 80kN based on empirical data derived for public roads.

Typical material	CBR (%)	Pavement thickness (mm)
Peat, silt	<2	>850 (consider excavation of the peat or floating the road on peat)
Silty clay	2	700
Heavy clay	3	550
Sandy clay	4	475
Saturated sand	7	325
Fine sand	10	250
Graded sandy gravel	20	150
Rock	250+	Min. 100 to allow grading of surface

- Sub-grade strength often varies extensively under the formation of a new road. Subsequent drying out of the sub-grade and pavement often increases the strength.
- The pavement material needs to be of appropriate strength, but lower layers can often be constructed using a low quality locally won material.

3. Selecting pavement materials

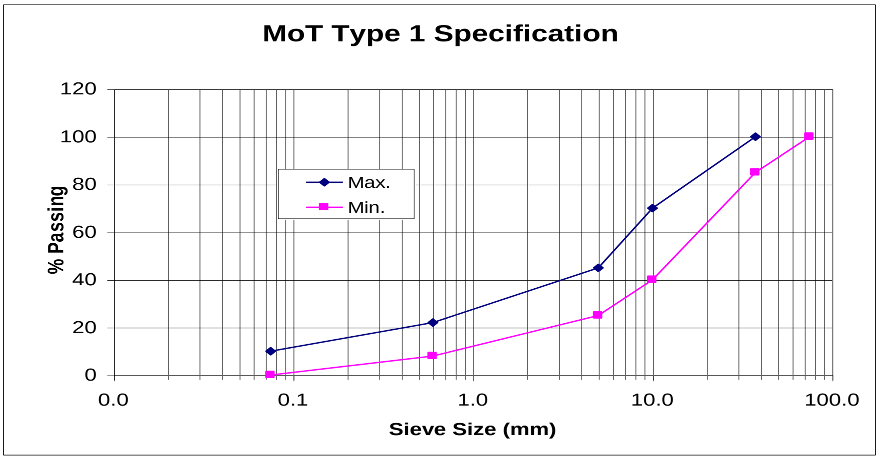
Forest roads are built with aggregates using virtually all types of rocks and gravel in mixtures varying from those “as dug” from a borrow pit to commercially produced stone complying with national specifications. In forestry, there is no single specification that is right for the whole of the UK. It is largely left to each engineer to determine the specification. This is very different from mainstream highway engineering where engineers have little choice but to accept nationally laid down specifications. The winning and placing of roadstone amounts to between 50 and 75 per cent of the construction cost of forest roads so it is vital that the civil engineer appreciates the role of aggregates in forest roads.

For the pavement to perform it needs to have a durable, impermeable top layer that spreads the load and sheds the surface water to protect the sub-grade. This can only be achieved by using a well-graded and bound stone of sufficient strength. Some naturally occurring materials have all these features but in most cases as-dug or crushed rock need some form of blending.

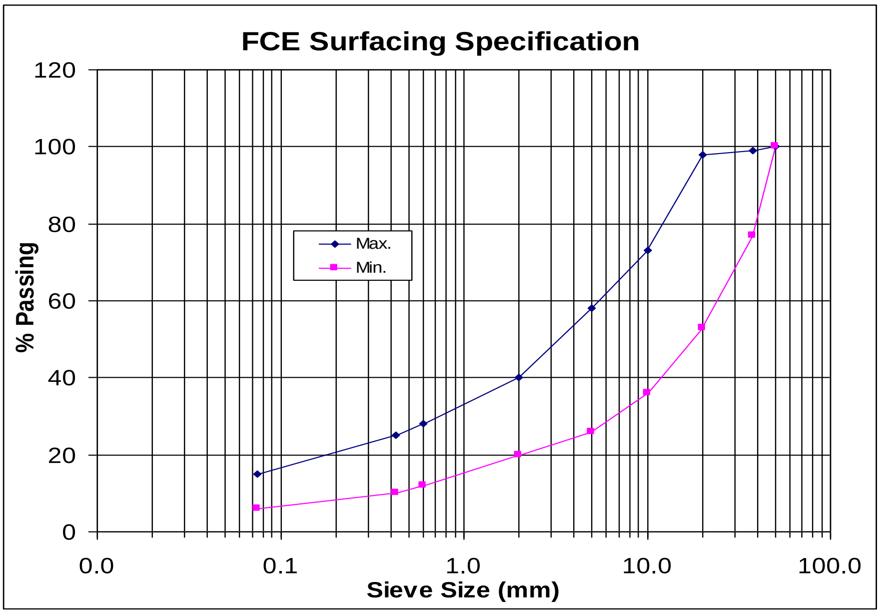
Materials with an Aggregate Impact Value (AIV) value of < 30 should normally be used in pavements, but use of other tests (e.g. magnesium sulphate soundness test) may be needed to give a more complete measure of durability.

- The top 100mm of pavement must be of a durable stone that will not readily break down under the wheel loading. It must also be suitable for grading and rolling. Such material should have an AIV value of < 25 minimum and preferably < 20. If heavy usage by vehicles with tracks is foreseen, the surface material should have an AIV value < 20.
- Surfacing may need a binder / sealer of fines or cohesive material to provide a sealed and smooth running surface. The selection of binder will depend on aggregate type and the potential for any pollution.

Selection and placement of the pavement materials is probably the most important element of a successful road. A well-graded material, such as a Type 1 granular sub-base [Clause 803 of Department for Transport’s Design manual for roads and bridges (DMRB)]:



or the so called “Swedish specification” (which Forestry Civil Engineering (FCE)



has adopted when appropriate) is ideal:

4. Aggregate specification

The role of the constituent parts of a roadstone aggregate can be understood by considering the mix in two main parts. These parts are: -

a) The aggregate which provides the shear or structural strength, where there is:

1. Enough crushed rock or gravel retained on a 20mm sieve (i.e. coarse gravel sizes) to give the strength and hardness needed to resist the abrasive action of traffic and,
2. Enough sand and other material passing the 20mm sieve and retained on the 200 micron sieve to provide the interlocking of soil grains and thus increase shear strength.

b) The binder which holds the above material together, where there is:

1. A quantity of mainly silt and sand (particles 200 micron to 5 microns) to act as a filler and to provide a capillary bond necessary for stability when the binder clay loses cohesion in wet weather.
2. Enough clay (particles smaller than 5 microns diameter) to retain the minute adhesive films after the larger films of capillary moisture have evaporated and thus provide the adhesion through soil suction required to maintain stability during dry weather.

The conventional wisdom is for the depth of any construction layer to be not less than twice the thickness of the largest particle size. This allows the layer to be compacted to a high density without large voids spanned by large particles. Compaction plant is most effective when layers are between 100mm and 225mm thick. Thus a maximum aggregate size for a surface layer would be 100mm. This falls into line with practice in UK where generally the maximum sizes are 100mm for main forest roads and 50mm for forest drives open to the public in private cars.

However, using more open-graded specifications results in increased elastic stiffness and shear strength. An open-graded material could be the better choice in some circumstances. If the area is low lying and in need of good drainage, an open-graded mix could still provide a stiff and permeable base.

It is rare for a forest engineer in the UK to sample and test for grading before building a road. The stone is generally used as it is dug or processed and a balanced mix obtained by taking materials from different parts of the stockpiles. The grading may be assessed by looking at the mix to see if there is a range of different sizes.

Particle Size Analysis is used to determine the grading of the mix. The following gradings are recommended for use in UK forests:

B.S.Sieve size	Percentage passing		
	150mm. Road base	100mm. Road base	40mm. Surfacing
150mm	100		
100mm	70 – 95	100	
40mm	45 – 72	50 –80	100
20mm	30 – 56	35 – 65	60 – 80
10mm	20 – 45	20 – 50	40 – 70
5mm	12 – 32	15 - 40	23 - 55
600um	5 – 15	7 – 16	10 – 25
75um	2 - 8	2 - 8	7 - 15

Often roads are compacted when completed and not during construction which runs contrary to engineering principles. This arises mainly because of the difficulty of rolling in between loads on a single-track forest road. Forest roads are compacted in the wheel tracks of the tippers leaving the centre and edges loose. This unevenness of compaction is not good for the overall structural strength.

5. Transmitting the wheel load through the pavement

The gross weight of a lorry is spread between the axles depending on lorry configuration and loading pattern. The Road Vehicle (Construction and Use) Regulations 1986 – SI 1998 3111, gives the permitted axle weights for these different configurations. This forms the basis for calculating the damaging factor for each of the axles, although axle weighing devices now provide a much better record of actual weight.

The axle load is then transmitted to the road through the tyres. The impact of this load depends on the tyre pressures, single/twin tyres, road friendly suspension, road shape and speed.

A large tyre “footprint” will spread the load better, especially when this is in the main body of the structural pavement. The best result would be with multiple tyres using the full cross-section of the road, the worst result would be single tyres at high pressure right on the edge of the road. Unfortunately, this is exactly what we tend to have with super-single tyres.

For a given load, the tyre footprint can be increased by decreasing the tyre pressure – this is the basis of Tyre Pressure Control Systems (TPCS).

The road surfacing layer, like any unbound material, comprises solids, air and water. The relationship between these three components dictates the behaviour of the surface under load. A well-graded material can be compacted to a high density leaving little room for air and water. This also means that each particle is physically touching another particle thus spreading the load down through the layer with little opportunity for displacement and movement.

When the tyre load is applied the majority of the load is taken directly by the aggregates. If the surfacing had not been compacted so well, there would be more air and water in the mix allowing more room for particle displacement. If the rock is weak, this movement will also crush the aggregate leading to further break-down and movement. Without consistent aggregate interlock the applied load will be taken partially by the aggregate, but also by the water between the particles. Water cannot compress, but it does build up pressure within the pores of the surface. This pressure dissipates with time, but if another series of wheel loads follow the pressure does not have time to dissipate and actually builds up. The applied tyre load is then carried by the particle-to-particle contact, but also by the water pressure. Water does not provide any shear resistance, so that there is more lateral displacement, which leads to further surface movement and the start of rutting.

So the ability of a surface to carry wheel loads depends on the strength of the aggregate, density, moisture content, load and frequency of load.

6. Avoiding damage to the pavement

Rutting of the road surface is often the first manifestation of failure that prompts the engineer to take corrective action. The camber or crossfall needs to be regraded to prevent erosion of the surface. More significantly, it is a consequence of internal pavement strains or failure of the road in carrying the load. Ruts may occur more often in single-track forest roads, because there is no edge restraint and occasionally a lack of construction depth due to the desire to economise with the depth of stone.

Andrew Dawson of Nottingham University identifies three modes to classify rutting in the ROADEX report on “Permanent Deformation” [ref: www.roadex.org] : -

Mode 0	The compaction of non-saturated materials after construction by traffic. This mode is self-stabilising and causes the material to stiffen. We see this most times in the construction of a forest road where the tippers impose better compaction in the wheel tracks than the vibrating roller does outwith the tracks.
Mode 1	In weaker granular materials, local shear close to the wheels may occur. This give rise to a characteristic dilative heave immediately adjacent to the wheel track. The material undergoes large plastic shear strains leading to relatively loose, heaved material.
Mode 2	When the aggregate is better, then the whole pavement may rut. This can be visualised as the sub-grade deforming with the aggregate deflecting bodily.
Combined Modes	Nothing is ever simple and, in practice, rutting will take place in a combination of the three modes above.

Andrew Dawson goes on to say engineers may minimise rutting by:

- Selecting high quality aggregate.
- Compacting the aggregate well, so as to maximise its performance.
- Making the layers thick to reduce the stresses applied to the sub-grade.

7. Vehicle selection

The road structure performs in relation to the applied loads and the materials in the pavement and subgrade. We have examined the road design side of the equation but the selection of vehicles and the resulting load patterns is equally important. Consideration needs to be given to:

1. Reducing wheel loads by using twin tyres, tyre pressure control systems to reduce inflation, reduced loads etc.
2. Reducing impact on the road surface by ensuring a smooth surface, gradients within specification, use of drivers trained to minimise impact, legal loads, lower speeds etc.
3. Reducing use by non-road vehicles such as forwarders with band tracks.

8. Best practice for usage

Road Facts:

1. The strength of a road pavement is reduced to half its dry strength when it becomes very wet. Avoid the HGV use of the road in very wet weather if possible.
2. Clean side drains allow rain to drain away quickly. Regular monitoring and maintenance is essential particularly following periods of heavy rain.
3. Roads are strong when frozen but are greatly damaged when used while they are thawing. Roads must not be used by HGVs in periods of heavy thaw.
4. Do not use salt to de-ice roads – Salt attracts moisture and keeps the road excessively wet for a year or more.
5. Muck brought on to roads that becomes mixed with the roadstone greatly reduces road performance in wet winter conditions.
6. An overloaded vehicle greatly decreases the life of a road.

Drivers should: -

7. Drive smoothly and carefully at a speed where they can stop safely. Remember it takes much longer to stop on a gravel road.
8. Reduce speed in line with the prevailing weather, road geometry and road surface conditions.
9. Where possible vary their position on the road from preceding road users and spread wear over the road.
10. Drive their vehicle round the outside of bends, increasing their visibility distance and avoiding breaking the inside edges or the ends of culverts.
11. Drive in an appropriate gear for the vehicle weight / road gradient and engage in good time.
12. Excessive power transmitted to the road surface causes corrugations or ravelling of the surface and loss of roadstone.
13. Keep vehicle wheels away from road edges that are weaker and away from soft verges where you may be bogged.
14. Align their vehicle approaching bridges to avoid hitting handrails and kerbs.

Vehicle operators should: -

15. Ensure they comply with Road haulage of round timber code of practice in particular that vehicles are not overloaded and that the maximum axle weights are not exceeded.
16. Avoid lifting non-drive axles of tractor units to increase traction.
17. Avoid intensive use of the road over short periods of time. Spread the road usage out into a slow and steady rate in order to allow the road to “recover”.
18. Use twin or multi-wheeled vehicles as appropriate and avoid the use of ‘super-single’ vehicles where possible.

Conclusion

Forest roads are being built across the country every working day through the year. They are often located in areas of extreme landscape and environmental sensitivity or in areas of peat or hard granite that many “normal” civil engineers would declare as impossible or far too expensive for the required purpose. It is under these conditions that forest engineers work to provide low-cost roads that meet the demanding requirements of their customers.

Each road is unique and requires an individual design and assessment of ground conditions that lead to the design of pavement thickness, drainage etc. There is no doubt that a skilled machine operator can make a good road without excessive planning or supervision, but if a road fails, it can have disastrous consequences for safety, environmental pollution or landscape. For these reasons the stress on good planning and design should continue. The landscape and ecology of an established forest can be irreversibly damaged within hours by the indiscriminate use of a large civil engineering machine.

Although forest roads rarely hit the headlines, it gives a sense of satisfaction to see timber lorries using roads and bridges that were a nightmare to build, but are now an accepted part of the forest landscape.

David Killer
Head of Forestry Civil Engineering

Appendix 1 - Forestry Commission road specification

Forestry Commission road specification with reference to the DfT Design Manual for Roads and Bridges (DMRB)

This specification is the standard for forest roads built by outside parties on FC land. Any reduction in this standard is to have the FC engineer's written approval before construction starts. Road survey and design should also have taken place before felling takes place.

Design speed	25 km/h.
Design loading	Full C&U (currently 44 tonnes).
Road Width	3.4 m running width (+/- 200 mm) - widened on inside of bends to suit radius (see table page 3).
Road alignment	Roads shall fit into the landscape and be constructed to a uniform horizontal and longitudinal profile. They shall avoid unstable ground and any features that require preserving.
Felled width	25 m average recommended.
Max gradient	<8% in general to be preferred, but gradients up to 10% acceptable. Small lengths (<200m) up to 12.5% may be permitted provided that they are contained within an overall gradient of 10%. For restrictions on gradient on bends, see table.
Min gradient	2% except over short sections on crests and sags. (This is an important requirement.)
Passing places	20m long and at least 3m wide with 10m splays. Spaced to be inter-visible with a maximum spacing to be agreed.
Bridge approaches	Minimum approach straight is 20m.
Turning places	Turning "T's" to be 26m in overall length (i.e. from far edge of road to end of 'T'), 4m wide with 11m radii.

Harvesting facilities	Ramps and stacking areas supplied as required. For guidance: ramps provided every 40m; stacking areas 30m by 3m provided every 200m. Surfaced where there is a risk of erosion.
Earthworks	Earthworks will be undertaken in accordance with Clauses 601 & 602 of the DMRB. Unsuitable materials to be stripped and removed. The formation shall be shaped to keep it free of standing water.
Cuttings	Cutting slopes must be stable and free of overhangs and loose rock. The maximum slope to be 30% for slopes up to 2m high. For slopes more than 2m high, the maximum slope to be 1 in 2 (50%) for fine grained soils, 1 in 1½ (67%) for other soils, and 1 in 1 for rock slopes.
Embankments	Unless agreed beforehand, the fill material to be free draining and non-cohesive, placed in layers and effectively compacted in accordance with Clause 612 of the DMRB. Slopes as for cuttings.
Roadside drains & ditches	A roadside ditch shall be provided on the uphill side of a road and on both sides where the road formation is at or below the adjacent ground. Drains shall have a depth of not less than 150 mm below the formation edge and a longitudinal gradient of not less than 2%. Ditches and drains shall not lead directly into watercourses. Catchpits, settlement ponds and filters will be provided in and adjacent to the drains and culverts to avoid pollution and sedimentation of watercourses.
Culverts	All pipes shall be to Clause 501 of the DMRB - excavated in accordance with Clause 502; bedded, laid and surrounded in accordance with Clause 503; and backfilled in accordance with Clause 505. Laid in natural ground or on bed of original watercourse where applicable. Minimum size 300 mm although 450 mm preferred. Inlets to be provided with erosion protection. Outfalls should be so constructed as to eliminate possible erosion. Ditch relief culverts should be spaced as required with a maximum spacing of 200m. Where appropriate, culverts to be designed for 1 in 50 year storm. Where the diameter is greater than 1.5 m, the culvert to be designed for 1 in 100 year storm.
Geotextiles	Used as necessary over silty clay and peat formations.

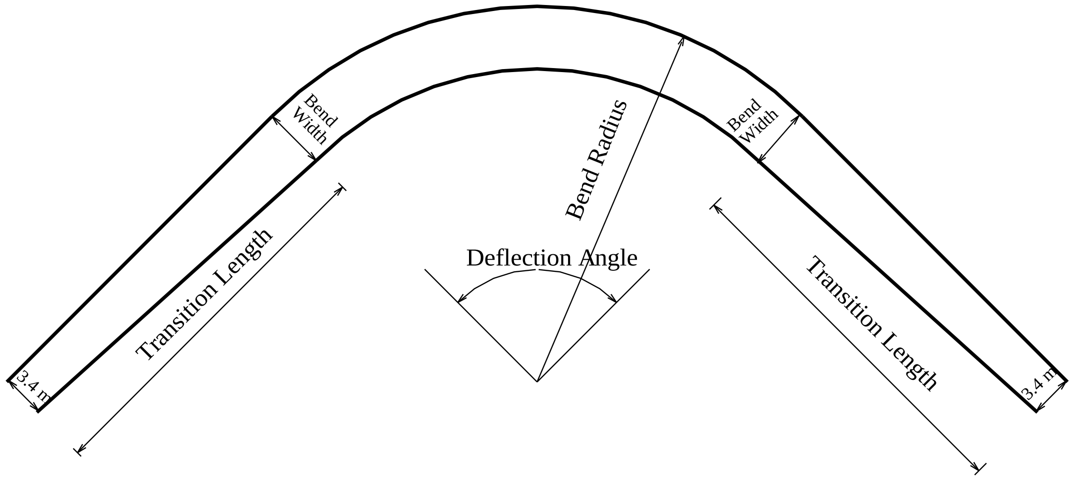
Road construction	Capping layer of durable rock or road base to Clause 613 of DMRB to improve subgrade CBR to a minimum of 5%. Road metal Granular Sub-base Type 1 to Clause 803 and laid in accordance with Clause 801 of DMRB. Material for the running surface shall have a minimum Magnesium Sulphate Soundness Value of 85. Principal or arterial forest roads shall have a minimum compacted surfacing thickness of 100mm of aggregate complying with the “Surfacing Specification for Principal Forest Roads”.	
Road metal thickness	Subgrade	Min. Road Construction Depth
	5% CBR	450 mm
	7% CBR	325 mm
	10% CBR	250 mm
	>10% CBR	To be agreed by FCE Engineer, but 100 mm minimum.
Cross-slope (camber or crossfall)	The surface shall be cambered with 5% falls from the crown, or with a 5% crossfall sloping inwards on steep side slopes.	
Water guidelines	*Forests and water guidelines, 4th edition*. Account must also be taken of any special requirements of EA/SEPA.	
Fuel spillage	A written procedure to be in place prior to work start.	
Signs	The site to be adequately signed.	
Blasting	Excavation of rock by blasting shall only be undertaken by suitably qualified personnel appointed in writing.	
Quarrying	The method of working (and re-instatement where applicable) of borrow pits and quarries must be in accordance with the *Quarries Regulations 1999,* and approved by FC.	

Horizontal bend recommended widths and gradients

Outside Radius	Minimum widths for maximum angle of deflection (^{o})				Transition Straight length	Maximum gradient on outside radius
	15	45	90	180		
	Running surface width					
m	m	m	m	m	m	%
90	3.8	3.8	3.8	3.8	-	10
60	4.0	4.0	4.0	4.1	20	8
45	4.0	4.2	4.5	4.5	20	7
30*	4.0	4.7	5.0	5.1	25	6.5
25		4.8	5.1	5.3	30	5
20		5.0	5.6	5.9	30	4.5
15			6.3	7.0	40	4
10**				10.0	40	5 on diagonal

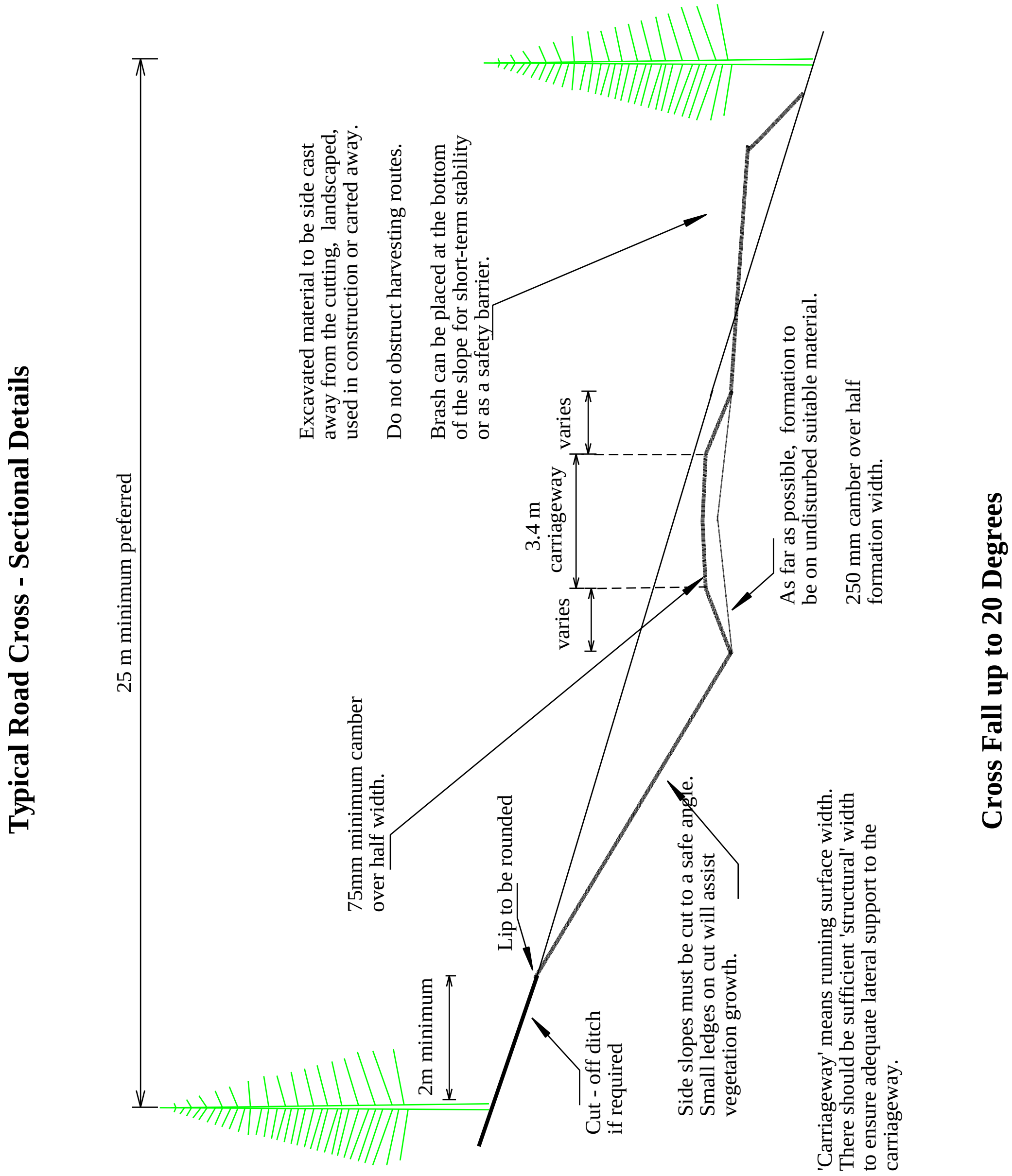
* Preferred minimum radius

** Absolute minimum hairpin



Bend Widening

Example cross-section



Typical Road Cross - Sectional Details

Cross Fall up to 20 Degrees

Excavated material to be side cast away from the cutting, landscaped, used in construction or carted away.

Do not obstruct harvesting routes.

Brash can be placed at the bottom of the slope for short-term stability or as a safety barrier.

As far as possible, formation to be on undisturbed suitable material.

250 mm camber over half formation width.

75mm minimum camber over half width.

Side slopes must be cut to a safe angle. Small ledges on cut will assist vegetation growth.

'Carriageway' means running surface width. There should be sufficient 'structural' width to ensure adequate lateral support to the carriageway.