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Engineering and Legislative Options for Improved Timber Haulage in Scottish Forests

Inclusive Stakeholder Approach

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The forest industry in Scotland depends for its economic survival on the efficiency with which it can get the felled timber to the mill. This efficiency is shown to depend on pavement quality, particularly the aggregates used; the truck fleet available to extract the timber; and the interaction of these two factors and the legislative regime, including taxation, under which the forest traffic operates. Although there is a high degree of cooperation within the forest industry—pavement constructors, haulage companies, public and private forest owners, and local government authorities—there is need for a more comprehensive assessment of the interaction of the various factors affecting the forest timber haulage operation. This interaction has been studied in a preliminary manner using a specific highway management tool, HDM-4. Vehicle use regulations and taxation and their application are shown to be particularly constraining on the overall efficiency of the operation.

The Scottish forest industry has great importance for the country, contributing over £1.3 billion (approximately US$2 billion) in terms of sales to the national economy, and over 44,000 people are employed in the forestry and associated timber industries, providing the majority of local income. Thus, the forest industry has a major role in sustaining rural communities and preventing depopulation.

However, the profit margin for many Scottish forests is very small. Therefore, in November 2000, Scottish Enterprise and Highlands and Islands Enterprise, the government's economic development agencies for Scotland, working with the forest industries and local government, developed a strategy for the forest industries entitled *Roots for Growth* (*1*), in which it was observed that the high cost of timber haulage from the forest to the timber mill or other point of sale is the principal issue limiting the competitiveness of Scottish timber production in relation to imports. The main exporting countries in Scandinavia and on the Baltic coast have much lower transport costs.

Roots for Growth identified three broad areas of action for the industry:

1. Promoting innovation,
2. Market and business development, and
3. Infrastructure development (including transport and logistics).

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DEMONSTRATION PROJECT

Focusing on infrastructure development issues, Scottish Enterprise and its partners are supporting a number of demonstration projects looking at innovative solutions to timber transport issues. These projects will help to inform the implementation of the study's key recommendations. Some of the findings of one such project, Review of Timber Haulage and Forest Roads: Solutions for Cost-Effective Transport and Strategic Benefits in Scotland, are reported here. The broad aims of this project are to

1. Identify the cost incurred by haulers and by the forest road operators;
2. Ascertain the variation in these costs consequent upon changes to pavements, vehicles, and the regulatory framework; and
3. Propose changes to pavement construction and maintenance, to vehicles, and to regulations that will increase overall cost efficiency in timber transport.

ISSUES OF CONCERN WITH FOREST ROADS

Forest roads are essential for the carriage of timber by truck to the public roads, ports, and railways. They are normally unsurfaced gravel roads, built and maintained by forest owners or forestry companies that carry the financial burden of their construction and maintenance. In recent years, maintenance costs have increased in response to damage arising from greater numbers of fully loaded axles and reduced time for the roads to recover between loadings.

The damage is related to an increasing intensity of use because

- Gross vehicle weight for most articulated timber wagons has increased from 38 tonnes to 44 tonnes;
- Timber production from Scotland's forests is continuing to increase;
- Modern mechanized harvesting methods produce high volumes of cut timber to forest roadsides in a very short time; and
- Scotland's wood-processing industries now need timber virtually every week of the year, so it is inevitable that forest roads remain in use when wet or thawing, which predisposes them to increased levels of damage.

Despite the considerable cost, there is increasing pressure on the industry to extend the use of internal forest roads wherever possible so as to

- Reduce the physical impact of timber haulage on public roads by taking timber farther through the forest and avoid use of particularly weak sections or bridges, and
- Reduce discomfort and inconvenience to the traveling public and rural communities.

IMPACT OF TIMBER HAULAGE ON COMMUNITIES AND PUBLIC ROADS IN GALLOWAY

The geographical focus of one of the projects is Galloway in southwest Scotland, the most heavily forested region of Scotland. The communities of Galloway have for many years had to bear the ever-increasing size and number of heavy trucks through their towns and villages. In the last 20 years the quantity of timber harvested in Galloway has increased sixfold, to over 600,000 tonnes per year, and stone produced for forest roads has increased to nearly 400,000 tonnes per year. Timber haulage is also affecting the fabric of public roads and causing inconvenience and discomfort to the traveling public. Timber traffic is always on the agenda for the councils and community councils and is the single most frequent reason for public correspondence with Galloway Forest District.

Today, few public roads serving forests in southern Scotland are fully adequate in design, strength, or state of repair. Deflectograph measurements conducted by the Dumfries and Galloway Council last year highlighted the widespread weakness of the public roads. A number of important single-track public roads serve extensive forests; they are weak and twisty, often traversing sections of peat. These roads fall well below nominal current highway design standards, and it would be too expensive to bring them up to this standard. (Indeed, the Dumfries and Galloway Council budget for road maintenance has been reduced by a third over the last 6 years.)

INDUSTRY RESPONSE

Forest Enterprise, in collaboration with private-sector neighbors and with local authority support, has developed proposals for a strategic forest road network and railhead. The purpose of the proposed road network is to redirect timber traffic away from communities and from the weaker public roads through the forest to trunk roads and the railway. The aim is to address public concerns and also to help the councils' stretched road maintenance budgets to go further. There is also scope for joint venture initiatives between the councils and woodland owners, to promote forest road bypasses of weak bridges and unsuitable public roads. In proposing such initiatives, the forest industry is trying to help, but nevertheless the survival of the industry depends on the fitness of the public road network.

However, for the maximum public benefit, the use of the forest road network, expressed in tonne-miles (1 tonne-mi = 2.205 kip-mi = 1.609 tonne-km), may increase fivefold. The timber industry could not survive a proportional increase in the costs of maintaining its forest roads, so the high cost of road maintenance is the principal issue tackled in this project, with a focus on three interrelated subjects:

- Forest road construction and maintenance materials and specifications,
- Forest vehicle specifications, and
- Management of traffic.

ROAD CONSTRUCTION

Forest roads in Galloway are suffering from their increased use, with many becoming deeply rutted or impassable in winter. The worst problems appear when roads are used very intensively, for example, to load ships with timber. In such cases it is not uncommon to haul more than 40 truckloads within 24 h. This traffic intensity poses problems to both forest and rural public roads (although by normal criteria of highway design such usage is still very low). Forest road engineers have found it difficult to prepare roads to reliably take such traffic in wet weather. On public roads over peat, council engineers have sometimes tackled the problem by limiting traffic to a load every 3 to 4 h to allow the road time to recover. This practice limits damage, but it is generally unsatisfactory in that the volume of timber that may be hauled is well below that necessary to match demand.

Conventional public road construction requires that all unsuitable subsoil, including topsoil, be removed until a load-bearing soil or rock is encountered. In the forest environment, economics prevent removal of large quantities of unsuitable spoil where overlay construction would be cheaper and the large pavement deformations are acceptable. Constructing a stable formation on a side slope is preferred for a forest road. It reduces cost since it gives the shortest movement distance for the excavated spoil. It only has to be cast to the side with one machine rather than using several machines to haul and place it elsewhere. A side drain is constructed on the uphill side of the road to intercept groundwater and to dry the subgrade area where the road metal is to be placed (Figures 1 and 2) (*2*). This drying process improves subgrade strength. Layers of stone according to subgrade strength are placed to carry traffic and disperse wheel loads down onto the road foundation.

The current specification for forest roads in the public sector is as follows:

- Design speed: 25 km/h (15.5 mph);
- Design loading: full national highway authority loading, currently 44 tonnes (97 kips);
- Road width: 3.4 m (±200 mm) (9 ft 9 in. ± 7 in.), widened on inside of bends to suit radius;
- Felled width: 25 m recommended;
- Maximum gradient: 10% with small lengths (<200 m) up to 12.5% allowable with caution;
- Minimum gradient: 2% recommended;
- Facilities: passing places, turning places, harvesting facilities supplied as required;
- Road construction depth: chosen by relation to California bearing ratio (CBR) of subgrade, varies from 150 mm (6 in.) to >850 mm (2 ft 9 in.);
- Construction: normally water-bound, material as available;
- Surfacing: as required, good quality material, normally water-bound, occasionally bituminous, depends to some extent on road classification;
- Cross slope (camber or crossfall): 4.5% recommended minimum, above 8% only to be used with care;
- Geotextiles: used occasionally for particular reason;
- Culverts: minimum size, 300 mm (1 ft), although 450 mm (1 ft 6 in.) preferred, spacing as required; and
- Road classification: Class A, main road; Class B, spur road; Class C, other road; Class C not normally used for harvesting.

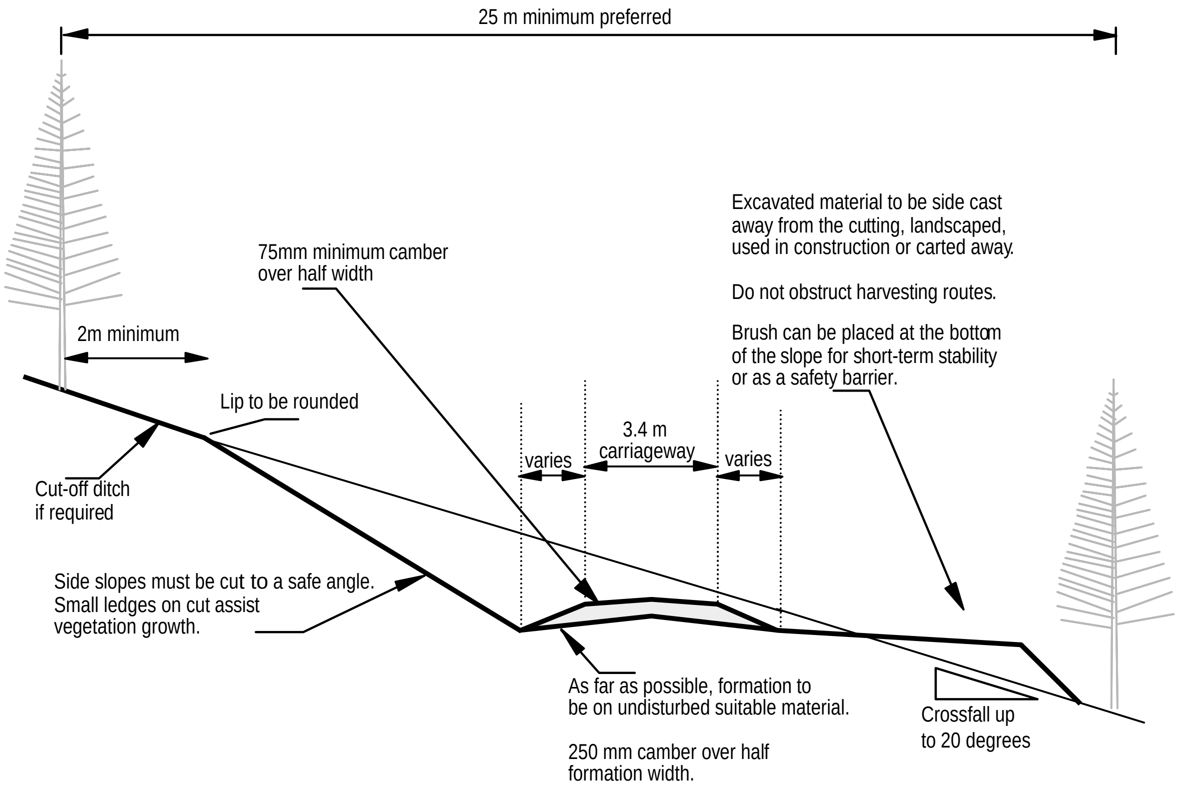

FIGURE 1 Typical road cross section (*2*) ("Carriageway" means running surface width; there should be sufficient "structural" width to ensure adequate lateral support to the carriageway.).

ROAD MATERIALS

Greywacke, an interbedded sequence of soft shales, siltstones, and sandstones, is the predominant rock in southern Scotland and has been used in the construction of most forest roads. The rocks in the better quarries appear to have undergone more metamorphism and have fewer bands of shale.

FIGURE 2 Appearance of typical forest pavement.

The study has begun to confirm that greywacke quarries often do not provide a suitable surfacing stone. The quarried rock is hard enough when first quarried, but it deteriorates in place. An examination of the surface of many forest roads reveals the flakiness of the material, with typically nearly half of the exposed stone exhibiting breakdown. The soft, thinly laminated shales and siltstones quickly degrade to form an excess proportion of fine material in the aggregate mix. This process leaves the harder sandstones floating around in a clayey matrix.

It is desirable to have simple methods to assess the available aggregates so that the worst-performing materials can be excluded. Many conventional tests (e.g., particle crushing tests) have been found to be unreliable or poorly discriminating. Most of the candidate materials are poor, but tests must be used to ascertain how poor. Also, the relatively uncontrolled gradings—some very coarse, some fine—mean that results based only on one size fraction (as is common with many laboratory tests) are likely to be unrepresentative of in situ performance. To study this effect, particle breakage and abrasion should be assessed on the whole grading. A gyratory device generating a moderate grinding action is being investigated as a solution to this problem (*3*).

WEATHER EFFECTS

In addition to traffic-induced damage, forest pavements have to withstand rain and frost. In parts of the Galloway forests, rainfall is 2.5 m (100 in.) per year. Thus, even with good drainage provision, it is impractical to ensure a fully drained pavement under all weather conditions, especially considering the very limited funds available for maintenance. The effective stress within the granular pavement layers may thus be lower than desirable, resulting in a lessening of the load-carrying capacity of the layer. Frost causes aggregate loosening by localized ice lensing and particle damage in weaker aggregates. Together with the traffic loading, these two factors may result in significant pavement deterioration.

PAVEMENT STUDY

A comprehensive investigation of existing pavements was performed by Forestry Civil Engineering in conjunction with the University of Nottingham. This investigation was to assess in some detail the types of distress and their probable causes. Cross-sectional trenches were dug across the pavements and measurements taken of the thicknesses of the various layers in the pavement. Samples of the materials forming the pavements were also taken and conveyed to the laboratory. Particular distress features sought were as follows:

1. Evidence of subgrade intrusion (where a soft clay subgrade pushes its way upward into the aggregate layers of the pavement because of an excessive kneading or pumping action caused by flexure of the pavement under repeated axle loading). This feature might indicate an unduly flexible pavement, a subgrade soil with high mobility, or both.
2. Evidence of subgrade depression due to a surface rut (which may have been infilled by maintenance intervention) that is pressing the subgrade surface down through the aggregate layer (Figure 3*a*) (*4*, pp. 101–108). This feature might indicate inadequate load spreading by the aggregate, which could be a consequence of its low stiffness or of the thinness of the layer.
3. Evidence of aggregate layer thinning due to shear within the aggregate layer (Figure 3*b*) (*4*, pp. 101–108). Usually this distress is characterized by localized heave on either side of the ruts, which occurs when an aggregate has inadequate shear strength in the zone near the wheel. The highest shear is typically observed at a depth equal to 30 to 50% of the wheel-print width.
4. Evidence of aggregate degradation in the form of localized excessive fines. If found in the aggregate beneath the wheelpaths but not elsewhere, this distress would indicate traffic-induced damage. If found across the top of the pavement, it might suggest environmental (especially freeze-thaw) damage.

In fact, the chief distress (observed in 80% of the excavations) was Type 3 distress. There was also evidence that aggregate degradation (Type 4) has an important role in reducing strength and inhibiting drainage. However, it was not altogether clear whether this degradation was a consequence more of traffic, environmental effects, or damage (or inadequate control) during construction. It may be that significant fines generation was a consequence of damage during the crushing, handling, placing, and compaction process.

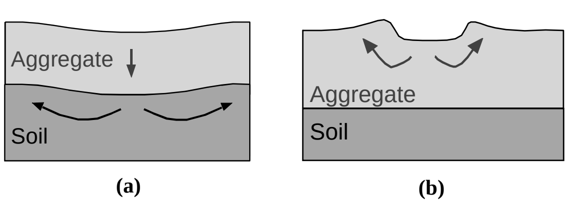

FIGURE 3 Modes of rutting (*4*, pp. 101–108): (*a*) soil displacement caused by inadequate load spreading and (*b*) inadequate shear strength in aggregate.

It is very likely that the aggregates' deterioration, for whatever reason, had a significant impact on the material strength. Thus, on the basis of the trenching operations, it is concluded that poor aggregate quality and poor grading are the primary causes of rutting distress in current Galloway forest roads.

Materials sampled from the in situ investigations of forest roads were graded and assessed for plasticity. The grading results are shown in Figure 4.

All the plasticity assessments found that the material was nonplastic. However, there was quite a wide range of liquid limit values, indicating that some of the fines were considerably more hydrophilic than others. The grading curves (Figure 4) show that most of the materials are high in fines. In many conventional aggregate specifications a maximum proportion of the mix of 10% is allowed to be smaller than 75 μm. However, three of the gradings have proportions in the range of 12 to 20%.

A number of solution methods are being considered:

1. Asphalt surfacing—likely to be uneconomic except perhaps on some main roads;
2. High-quality stone throughout the pavement—likely to be uneconomic;
3. Decreasing stone quality with depth in the granular pavement layers (i.e., use the best material only where loading stresses are greatest)—a plausible solution method at more modest expense;
4. Better aggregate grading control so that dense, stable mixtures can be produced;
5. Limited binder treatment to stiffen aggregate and to provide greater shear resistance;
6. Limited binder treatment (e.g., by lime stabilization)—may be suitable where excess clayey fines cause a problem since the lime acts largely upon the clay fraction;
7. Changing pavement cross sections to improve crossfalls and aid drainage, for example, by providing a coarse underdrain; and
8. Better compaction.

All of these techniques are likely to have a financial impact and hence must be carefully costed against the increase in pavement life and reliability that they can be expected to provide.

VEHICLES

Because haul distances in Scottish forests are relatively short and all vehicles use sections of the public highway, it is necessary for timber haulage vehicles to meet the vehicle construction, use, and taxation regulations for normal highway use. Thus, currently the haulage fleet is essentially a conventional haulage industry fleet with only a few adjustments for the forest environment and the timber loads to keep on-highway transport within legal requirements (Figure 5). However, keeping the vehicles suitable for the public highway creates less-than-optimum use within the forest, as discussed next.

FUEL TAXATION

In Scotland, as in other parts of the United Kingdom, fuel used in vehicles is subject to taxation such that approximately 75% of the total fuel price is tax. Untaxed diesel fuel can be purchased but may

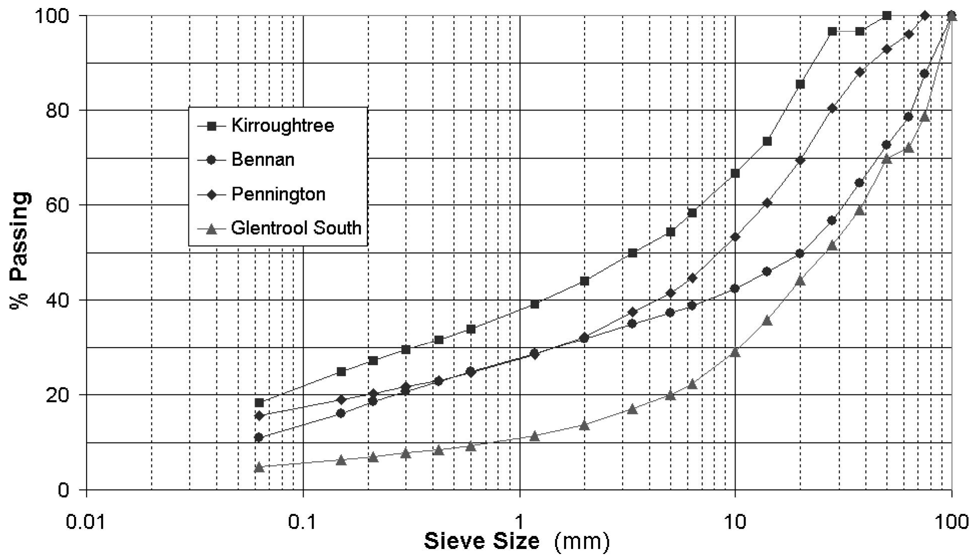

FIGURE 4 Measured gradings of aggregates used in Galloway Forest.

only be used on the public highway in excepted vehicles as defined by the relevant regulations. Timber transport trucks are not excepted vehicles. Clearly, haulage economies could be significantly altered if such fuel could be used. However, it seems probable that use of this fuel will only be legally possible so long as timber transport vehicles do not travel along public roads for more than 1.5 km in passing from one forest to another.

FUEL CONSUMPTION

It is known that trucks use more fuel per mile on forest roads than they do on tarmac roads, but no hard data were available to quantify this comparison. Volvo Truck, of Barrhead, was commissioned to calibrate the on-board computers installed in two test vehicles. Tire inflation pressures were checked so that all vehicles involved were of equal standing. One test vehicle was driven along a preset route, which started near Ayr on the Ayr bypass and concluded at Minishant on the A77 trunk (main public) road, a distance of 9.3 km (5.5 mi). Once the vehicle reached Minishant, the information collated by the computer was downloaded and recorded. In the second part of the trial, the vehicle was taken 9.3 km through the forest, where it was loaded to its maximum gross weight, and the trials continued in the reverse order following the same procedure as above. The findings of these trials are shown in Table 1.

FIGURE 5 Typical Scottish forest haul truck.

Table 1 demonstrates a substantial difference between the costs of traveling in the forest and those on the public road. It must be noted too that even on Class A public roads, timber vehicles have higher fuel consumption than do typical road vehicles of the same weight. One reason for this difference is aerodynamics, since typical road vehicles have smooth surfaces by virtue of containers or curtains, and most are fitted with air management kits. This retrofit allows these vehicles to move through the air with the least amount of resistance, thus ensuring a higher fuel economy. This retrofit is not practical for timber carriage, because the overall dimensions of the trailer change every time the vehicle is loaded, and indeed 50% of the time the vehicle is empty, when the air management kit works against fuel efficiency. Furthermore, trucks with timber trailers might have as many as 5 solid walls of timber and 10 protruding bolsters for air to negotiate before it reached the back of the vehicle.

OTHER VEHICLE COSTS

Standing costs (Table 2) are also greater for timber haulage in comparison with general haulage. Insurance is close to four times the price of general haulage insurance, owing to a higher frequency of claims from the timber sector and timber equipment cost that is twice that of general haulage equipment.

The cost of tires is more than twice the average in general haulage, partly because of the factors discussed in the next section. Timber haulage vehicles also suffer from a large proportion of tire punctures or destruction by stones. This damage is partly caused by sharp stones that slice the sidewalls of tires, which can lead to

- Immediate blowout of tires;
- Delayed blowouts 2 or 3 weeks later because of corrosion of the steel banding (chords) following ingress of moisture; and
- Major repair even when stones only penetrate the running surface of the tires; unfortunately, tire manufacturers will seldom repair such tires because of excessive damage to the chords.

TABLE 1 Comparison of Fuel Consumption on A77 and Forest Road

Public Highway A77			
Ayr bypass to Minishant	(EMPTY)	Minishant to Ayr bypass	(LOADED)
Distance	5.5 Miles	Distance	5.5 Miles
Fuel	0.8 Gallons	Fuel	1.1 Gallons
Average speed	34 MPH	Average speed	32 MPH
Time taken	10 Min 45 Sec	Time taken	12 Min 26 Sec
Fuel consumption	6.88 MPG	Fuel consumption	5.00 MPG
Forest Road			
Linnfern Gate to Changue	(EMPTY)	Changue to Linnfern Gate	(LOADED)
Distance	5.5 Miles	Distance	5.5 Miles
Fuel	1.4 Gallons	Fuel	2.3 Gallons
Average speed	15 MPH	Average speed	10 MPH
Time taken	22 Min	Time taken	33 Min 38 Sec
Fuel consumption	3.92 MPG	Fuel consumption	2.39 MPG

Mile = 1.609 km
Gallon = imperial gallon = 1.2 US gallons = 4.546 liters
MPH = mile per hour = 0.447 m/s
MPG = mile per imperial gallon = 0.354 km/l

TABLE 2 Demonstration of Costs of Timber Haulage Vehicles Compared with Typical Road Haulage Vehicles

	Typical Road Haulage			**Timber Haulage**		
Annual Mileage	70,000 miles			70,000 miles		
Life of Tractor in Years	7 years			3 years		
Life of Tractor in Miles	490,000 miles			210,000 miles		
Life of Trailer	12 years			5 years		
Replacement Cost of Tractor	£48,940			£60,670		
Replacement Cost of Trailer	£20,948			£50,180		
Fuel Consumption (tarmac road)	9.8 MPG			6.0 MPG		
Fuel Price per Liter	£0.62			£0.62		
Tire Life in Miles for Tractor	58,000 miles			25,000 miles		
Tire Life in Miles for Trailer	49,000 miles			20,000 miles		
	Cost £/yr	**Cost pence/ mile**	**% of total cost**	**Cost £/yr**	**Cost pence/ mile**	**% of total cost**
Vehicle Road Tax	£1,200	1.72	2%	£1,200	1.72	1%
Insurance	£2,297	3.27	3%	£8,510	12.16	6%
Depreciation of Tractor	£6,169	8.81	8%	£14,255	20.36	11%
Depreciation of Trailer	£1,746	2.49	2%	£11,785	16.84	9%
Total Standing Costs	**£11,412**	**16.29**	**15%**	**£35,750**	**51.08**	**27%**
Fuel	£20,106	28.72	27%	£32,839	46.92	25%
Tires (for both tractor and trailer)	£2,591	3.70	4%	£5,580	7.97	4%
Vehicle Maintenance (for both tractor & trailer)	£7,345	10.49	10%	£10,720	15.31	8%
Total Running Costs	**£30,042**	**42.91**	**41%**	**£49,139**	**70.20**	**37%**
Employment Costs	£19,674	28.11	27%	£28,244	40.35	22%
Overheads	£12,248	17.49	17%	£18,000	25.71	13%
Total Costs Overall	**£73,376**	**104.8**	**100%**	**£131,133**	**187.3**	**100%**

NOTE: Figures based on 44 tonne (gross) articulated vehicle with costs as of December 2001
£1 ≈ US$1.4 at time of paper preparation

Not surprisingly, use in the forest environment of a vehicle designed primarily for asphalt roads causes excessive strain on all components and raises maintenance costs. This factor is recognized by the Department of Transport, which requires, as a condition for obtaining an operator's license, that the service inspections be conducted at 4-weekly intervals rather than the usual 6-weekly intervals. In most cases timber haulage vehicles have to be replaced after 3 years because of excessive maintenance costs and down time, as opposed to 7 years for general haulage trucks. With trailers, the expected life is 5 years versus a 12-year expectation in general haulage. Thus depreciation is a major influence on higher standing costs.

Employment costs are also higher because drivers have to be highly skilled and dedicated to this job. For example, drivers of timber haulage vehicles often have to grade and sort timber at the forest roadside. They also have to make risk assessments in highly variable conditions and endure extreme weather and its effects on forest road conditions. The greater demand for wages is also fueled by comparisons with the harvesting sector, in which machine operators are paid considerably higher wages than those of most truck drivers. These problems can lead to difficulties in retaining the best drivers.

In addition, overhead costs are 33% more than in general haulage because of the higher amount of administration involved with many short journeys rather than a few long hauls.

OTHER VEHICLE CONSIDERATIONS

Trials were performed with different truck-trailer combinations to study their turning and hill-climbing abilities and to observe their interaction with the pavement surface during turning and climbing. All the vehicles were commercially available and at a conventional highway standard. The trials showed the following results:

- An eight-wheel (two-steering-axle) truck caused less scrub damage than a six-wheel truck with only one steering axle;
- Trailers with tridem axles cause considerably more pavement damage because of scrubbing on cornering than do trailers with tandem axles;
- It is probable that on an uneven forest pavement, the load spreading across the three tridem axles is not as good as that on a more planar conventional highway surface, thus somewhat negating the conventional benefits of an extra axle in reducing pavement damage;
- Trailers do not necessarily follow the same path as the truck that is pulling them; this feature has costly implications for pavement width, vehicle safety, or all three; pulling trucks need to have limited tail swing (rear-axle overhang) to avoid this problem; and
- An articulated truck needs operational twin drive axles if drive wheel spin (and associated pavement damage) is to be avoided.

The issues of twin tires versus super-single tires have been well reviewed for conventionally surfaced pavements (*5–7*). However, for unsealed pavements there are several additional problems. Twin tires scrub the pavement surface more on cornering (particularly when located on the trailer) and are damaged more quickly than super-single tires because of this scrubbing effect. Also, twin tires spread the load better on a planar pavement surface, but on a rutted or significantly cambered forest pavement, the inner tires can be disproportionately loaded, carrying as much as 100% of the vehicle load to the pavement. This disproportion results in localized pavement distress and rapid inner tire wear (30% faster than outer tires).

In addition to the tire-wear issue, the vehicles are less stable when running, in effect, only on the inner tires of a dual tire pair. This lack of stability leads to greater roll and to faster chassis deterioration, decreased overturning safety, as well as increased vehicle costs from the more extensive material and fabrication costs of twin-wheeled vehicle elements. In fact, it is becoming more difficult to source twin-tired rigs since truck manufacturers for the conventional haulage market are increasingly moving to super-single construction in order to reduce costs for that market.

The haulage companies collaborating in this study noted that although road camber on forest roads is very important to enable surface water to drain, high camber tended to make the trailers bounce sideways rather than vertically on their suspensions. This oscillating motion implies serious strains and damage to the air suspension system, which is not designed to take such imposed loads. Such sideways oscillation will also have an impact on the forest road pavement.

The project also investigated the use of nonstandard timber trucks that distribute the load across more axles, with the tires positioned across the full width of the truck; that aspect of the study is beyond the scope of this paper.

ROAD NETWORK MANAGEMENT

Study Method

Given the increasing demands on the forest pavement network, it is becoming increasingly important to apply modern management techniques so that service can be maximized for the available funding. For the Galloway study area, the highway development and maintenance tool HDM-4 was applied. HDM-4 allows the engineer to compare a wide range of options of vehicle type and road design and maintenance strategies. In the Scottish forestry context, the model is perhaps more complex than required but provides a standard and established methodology to evaluate and decide on optimum timber transport solutions for the industry.

To use the HDM-4 approach it was necessary to form a working model for the Galloway area, replicating deterioration, roadworks, user, and socioeconomic and environmental effects in a manner that is calibrated for the local situation. Road deterioration and works effects for unsealed roads depend on several factors, including roughness, material loss, rutting, surface looseness, and impassability. Each of these factors is modeled using previously established relationships that were calibrated on the basis of local experience using a simple classification approach for the inputs (as opposed to precise enumeration of values). Road user effects include vehicle operation costs, travel time costs, and accident costs. Zero growth rate was assumed since, for any pavement, the traffic only depends on the volume of timber being accessed.

Nine road sections within the Carrick part of the Galloway Forest were analyzed using HDM-4. Information was collected on section length, width, vertical and horizontal alignment, surfacing material and thickness, subgrade material characteristics, and roughness.

Traffic level was defined in terms of annual average daily traffic (AADT) for the nine road sections, which variously carried between 10 and 30 vehicles per day. The vehicles were 10% tipper truck, 20% timber transport truck, and 70% light vehicles. The economic analysis parameters used include analysis period of 20 years and a discount rate of 5%.

Six pavement maintenance strategies were investigated with varying resurfacing and regravelling periods and spot treatment policies.

Currently, alternative constructions have not been investigated. In general, road sections carrying high traffic levels will experience a faster rate of roughness progression than do those with low traffic levels. Material loss is affected by traffic volume, road geometry (in particular the vertical alignment), and material properties. Road surfacing materials with a high percentage content of coarse or large-size particles exhibit a slower rate of material loss when compared with road surfacing materials with a higher percentage content of fine particles.

Pavement Maintenance Strategies

For all but one of the sections, the economically best maintenance strategy for a traffic loading of 20 or 10 AADT is to regrade once a year and spot repair (or patch), replacing 20% of annual material loss when the surfacing material thickness falls below 50 mm (2 in.).

In general, for roads carrying about 25 AADT, the economically best maintenance strategy changes to resurfacing or regravelling every 10 years, grading twice a year, and spot repair (or patching) by replacing 20% of annual material loss when the surfacing material thickness falls below 50 mm. For the road with the steepest gradient (RF = 81 m/km), this change in preferred maintenance strategy occurs at 20 to 22 vehicles per day. Therefore, road geometry has a significant effect on selection of the optimal maintenance strategy for a road section. It was also observed that grading frequency is a key factor in determining the optimal maintenance strategy to be applied to a road section.

Savings in Vehicle Operating Cost

These best maintenance strategies define the highest overall efficiency of the combined vehicle and road network system. Taking the vehicle operating cost alone, it was possible to show that the lowest average roughness and the lowest average vehicle operating cost per vehicle kilometer were obtained with a more intense pavement maintenance strategy in which the >25 AADT strategy (see previous section) is used but with resurfacing or regravelling every 7 years. The percentage saving in vehicle operating cost when compared with the prediction using the base alternative is about 4.8% for a Volvo FM12 timber truck.

Concluding Remarks

The trial application demonstrated the capabilities and suitability of using HDM-4 to develop and derive solutions for cost-effective transport and strategic industry benefits in Scotland, but results remain interim pending a more detailed calibration and full sensitivity analyses.

DISCUSSION OF RESULTS

It is clear from this multifaceted study of the demonstration project in southern Scotland that the efficient and economical operation of timber haulage operations involves many stakeholders. The forest owners' priority is to extract timber from the forest to the mill or other point of sale at minimum cost, but this concern immediately leads to tension between investment in the construction and maintenance of the forest pavement and payment of the costs incurred by the timber hauler. The HDM-4 model provides a tool by which the overall costs may be minimized since it allows the impact of pavement maintenance decisions to be assessed with regard to road user costs and pavement maintenance costs.

It has been determined that poor-quality aggregate is a major contributor to rapid pavement deterioration. A number of solution methods are available, but the best method is likely to depend on the preferred pavement maintenance strategy (as examined by HDM-4) as well as the costs of probable alternatives.

The haulage contractor also has an interest in pavement performance since speed and ease of accessing the forest and vehicle maintenance costs are highly dependent on the pavement quality provided. Although, in theory, the contractor can select a vehicle most suited to the quality of the available pavement, in practice options are severely limited by the need to have a vehicle that can legally access the public highway. Contractors are forced to purchase vehicles designed with only conventional pavement use in mind. Increasingly these are becoming less suitable and less economic for the forest pavement environment.

If the forest pavement provider and the timber hauler cooperate, options are available to minimize the overall timber transport and road maintenance costs within the current options. More dramatic savings arise from the possibility of running off-highway forest-specific vehicles, because the vehicles are both better suited to their task and able to be made less damaging to pavement. However, this option is only likely to be feasible where forest blocks are contiguous and lead directly to a mill or to a railhead. In specific cases this route is under consideration although it would require significant investment by the forest owners in the pavements and rail-truck transfer facilities and by the vehicle operators in new rigs. Such an alternative would be well-liked by local authorities and local communities since it would keep the heavy timber traffic off the relatively narrow rural public road network, thereby increasing safety for traffic and pedestrians and slowing damage of the publicly funded highway network, and it would increase amenity value in villages from which the traffic had been removed. There is therefore an argument for the authorities to contribute to removal of timber vehicles from the public network.

This support from government would, in effect, be partially achieved if the vehicles never accessed the public network but ran as more efficient forest-tuned vehicles on untaxed fuel. However, the legal framework does not allow for partial tax exemption. Thus a partial compromise in which specific timber vehicle routes are provided by the forest industry to avoid village centers, for example, would attract none of this indirect support. For specific measures of this sort to be attractive to the haulage operator and forest pavement provider, there needs to some kind of payback for the increased operating costs incurred by operations on longer lengths of forest pavements. A way of achieving this would be to partially remit taxation on the vehicle, the fuel it consumes, or both. Currently legislators seem to have little interest in doing this, perhaps because the tax legislators are remote from the local communities (and industries) that stand to benefit.

At a local level there is already a high degree of linkage among the haulers, forest owners, and authorities, such that voluntary restrictions on use of sections of the public highway by the forest industry are undertaken in exchange for local authority support of the use of other public road sections (e.g., by maintenance or removal of weight restrictions). Inevitably, flexibility of approach at a national level is less developed. However, there is a case for government to reconsider the fuel and vehicle taxation regime in the forest industry in the light of the constraint of that regime on the social and economic prosperity engendered by the industry. The industry has the expertise in its pavement and vehicle operating sectors to respond collaboratively and positively to the demands for more efficient and socially acceptable timber transport if the government framework will facilitate it.

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REFERENCES

1. *Roots for Growth: A Strategic Framework for the Scottish Forest Industries.* Scottish Forestry Industries Cluster, Kilmarnock, Scotland, Sept. 2000.
2. *The Forestry Civil Engineering Handbook.* Internal document. Forestry Civil Engineering, Peebles, Scotland, Oct. 2000.
3. Dawson, A. R., and M. Mundy, eds. *"Courage," Construction with Unbound Road Aggregates in Europe.* Final Report. European Commission, Brussels, Belgium, Dec. 1999.
4. Dawson, A. R. Rutting in Unsurfaced Roads: Materials and Structure Interaction Effects. In *Proc., Symposium on Thinly Surfaced Pavements,* University of New Brunswick, Fredericton, Canada, 1997.
5. Bonaquist, R. An Assessment of the Increased Damage Potential of Wide Based Single Tires. In *Proc., 7th International Conference on Asphalt Pavements* (S. F. Brown and R. G. Hicks, eds.), International Society for Asphalt Pavements, Nottingham, United Kingdom, 1992.
6. Cole, D. J., and D. Cebon. Truck Tires, Suspension Design and Road Damage. In *Proc., International Rubber Conference IRC'96,* June 17–21, Manchester, England, 1996.
7. Gillespie, T. D., S. M. Karamihas, M. W. Sayers, M. A. Nasim, W. Hansen, N. Ehsan, and D. Cebon. *NCHRP Report 353: Effects of Heavy-Vehicle Characteristics on Pavement Response and Performance.* TRB, National Research Council, Washington, D.C., 1993.