A REVIEW OF RESEARCH INTO LOGGING TRUCK/ROAD INTERACTION

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SUMMARY

This paper reviews some relevant research and literature on logging truck/road interaction.

Logging roads are often low standard (compared with highways) and feature steep grades, low strength pavement and poor surface condition. These factors can offer very significant resistance to loaded trucks, resulting in reduced travel speed, increased fuel consumption and increased wear and tear on the truck.

There has been considerable research into truck/road interaction in recent years by FERIC (Forest Engineering Research Institute of Canada), and many of the results are applicable to New Zealand conditions.

A more thorough review and extension of existing research and literature on truck/road interaction by LIRA is recommended, to ensure that existing knowledge is fully available to road builders and truck operators.

Wider use of fuel and performance monitoring equipment in New Zealand (such as the DZL meter used by N.Z. Forest Products Limited) will allow truck operators to better understand truck performance and how to improve it.

Heavy vehicle simulation packages are seen as potentially valuable tools to help in predicting truck performance on existing or design roads. Teamed with road planning packages now becoming available in the industry, they should provide a means of testing different road options for hauling cost as well as roading cost.

A discussion paper for the LIRA Logging Roads Standards Project Workshop - Nelson, July 22 to 24, 1985.

CONTENTS

THE PRINCIPLES OF TRUCK/ROAD INTERACTION

How well a road allows a truck to perform can be measured by the resistances the road offers a given truck.

The resistances are either :

(i) Direct, i.e. offering a physical force to the passage of the truck :

- rolling resistance to tyres
- grade resistance, forcing the truck to lift itself up against gravity
- centrifugal resistance on curves

or,

(ii) Indirect, i.e. impeding the efficient passage of the truck, often by influencing the driver's perception of safety and comfort :

- lane and shoulder widths
- sight distance
- roughness
- special speed restrictions

These interactions have been reasonably well understood for many years, and described in formulae and tables. (e.g. SAE J688 - Truck Ability Prediction Procedure, 1958, McNally 1975).

1. Rolling Resistance

The rolling resistance to tyres is a function of both the surface material, and the stiffness, of a road. Figure I illustrates the action of a tyre travelling on roads of varying stiffness. On a "soft" road, the wheel is continually trying to "climb out" of the depression in the road caused by the weight of the vehicle. (Douglas, 1985). Using this climbing-out-of-the hole analogy, it is often easier to consider rolling resistance as an equivalent grade resistance. Stiffer roads reduce rolling resistance.

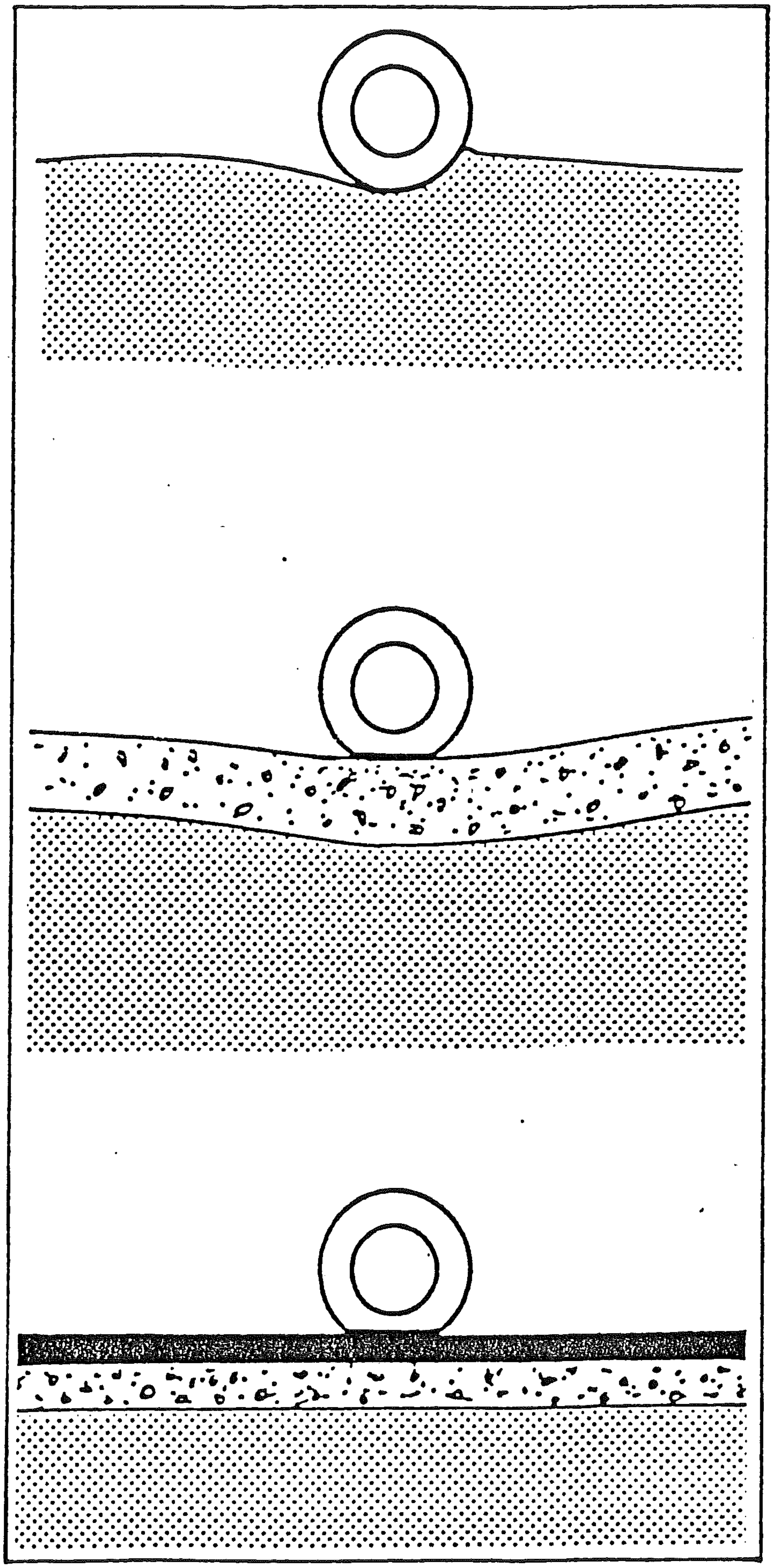


FIGURE 1 - ROLLING RESISTANCE
- Tyre action on progressively stiffened roads.
(from Douglas, 1985)

Table 1 shows typical equivalent grade resistances for different types of road and surface condition. The Table illustrates the significant resistance offered by low quality surfaces.

FERIC tests showed fuel consumption on an ungraded gravel road at 20% higher than on the same stretch of road, but graded. (FERIC, 1983. (Tests on an unloaded truck)).

Local experience suggests that truck travel speed will increase 7 to 8% moving from gravel to seal. (Gordon, 1980).

2. Grade Resistance : *The force required to climb a grade*

The horsepower required to overcome grade resistance can be expressed as : (McNally, 1975)

$$GRHP = \frac{GVW \times g \times V}{37,500}$$

GRHP = grade resistance in horsepower
GVW = gross vehicle or combination weight in lbs.
g = grade, per cent
V = road speed in miles per hour

The above formulae deals with climbing grades (adverse grade). Steep favourable grades also cause a reduction in speed (and therefore efficiency) due to braking to retain control. Figure 2 illustrates.

3. Centrifugal Resistance

On a flat curve, a truck will try to move outward under centrifugal force, therefore resistance is encountered in keeping it on the road. To counteract this, the road can be super-elevated. However, since there is only one unique super-elevation to "free" a certain truck at a given speed of centrifugal forces, trucks travelling at higher or lower speeds will encounter centrifugal resistance again.

Local experience suggests that super-elevation on forest roads should not exceed 10 cm per metre. (Gordon, 1980).

SUGGESTED UNIT ROLLING RESISTANCES

Road Class	Class Description	Surface Condition	Unit Rolling Resistance (1)	Equivalent Grade %
1	Rigid pavement	Smooth, best	8	.8
		Average, fair	9	.9
		Poor, rough	10	1.0
2	Flexible pavement; treated and packed gravel	Smooth	10	1.0
		Average, fair	13	1.3
		Poor, rough	15	1.5
3	Sand-clay, gravel, crushed gravel or stone surface; untreated; deforms under load	Smooth, well-compacted with little or no loose surface material	15	1.5
		Smooth, well-compacted with thin layer of loose or muddy surface material	18	1.8
		Fair, average, some washboard	20	2.0
		Poor, rough, heavy washboard	25	2.5
4	Natural soil and earth roads	Smooth, well graded, dry (not sand)	25	2.5
		Rough, dry (not sand)	28	2.8
		Rough, damp, soft	40	4.0
		Sand, damp	75	7.5
		Sand, dry	100	10.0
		Mud, deep, with bottom	100	10.0
5	Ice; hard-frozen snows; frozen summer roads; no surface deformation	Smooth, no loose snow	10	1.0
		Average, scarified, frozen summer gravel and natural soil roads	15	1.5
		Poor, rough	20	2.0
6	Snow; sub-grade not frozen deeply	Well-packed, 2 inches thick, not hard-frozen	30	3.0
		Poorly packed	50	5.0

Note: (1) expressed as pounds per 1,000 pounds of gross vehicle or combination weight.

TABLE 1 - ROLLING RESISTANCE ON VARYING ROAD CLASSES AND CONDITIONS (McNally, 1975)

Indirect resistances operate mainly by influencing the driver to slow down for safety, i.e. restricted lane width and/or sight distance, or comfort or concern for mechanical damage, i.e. road roughness.

The horizontal alignment of the road (curve radius and curve frequency) affects truck speed as shown in Figure 3. Curve radius has greater influence than curve frequency, although once curve radius is small (less than 60 metres) the frequency of curves also has a noticeable effect on travel speed. (Gordon, 1980).

4. Lane and Shoulder Widths :

The optimum lane width for two lane roads is the overall vehicle width plus 1.2 m, i.e. 3.6 m for most highway class trucks. A reduction in lane width can cause reduction in speed (up to 1 km/hr per 30 cm reduction). This effect is increased when passing or meeting other vehicles (up to 1 km/hr per 5 cm reduction in lane width.

Shoulder widths should not be less than 1.2 m as speeds can drop by 1 km/hr for each 6 cm reduction. (Gordon, 1980).

HOW SIGNIFICANT ARE ROAD-INDUCED RESISTANCES?

The effect of road resistance on truck performance and cost is much more significant than a simple calculation of the horsepower required (at the wheels) to overcome the resistance.

Significant energy losses occur in a truck between the consumption of diesel fuel and the output power at the wheels. Therefore every extra horsepower required at the wheels must be multiplied up to account for all the losses, before it can be expressed as demand at the injectors. Also a higher rolling resistance incurs higher driveline losses due to the higher torque (therefore higher friction) in the driveline.

Figures 4 and 5 illustrate where the energy goes in powering a 60,000 kg G.C.W. truck along a flat road at 56 km/hr. In Figure 4 the surface is paved and rolling resistance requires approximately 53 kW output at the wheels. Required (fuel) input power is calculated at 353 kW

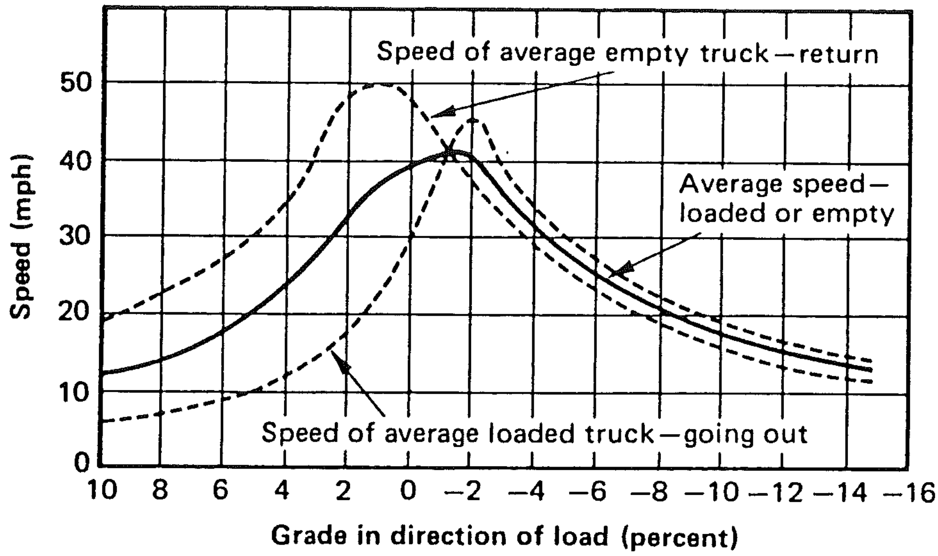


FIGURE 2 - *Graph showing logging truck speed versus road grade for gravel roads (Byrne, Nelson, and Googins 1969, p. 16).*

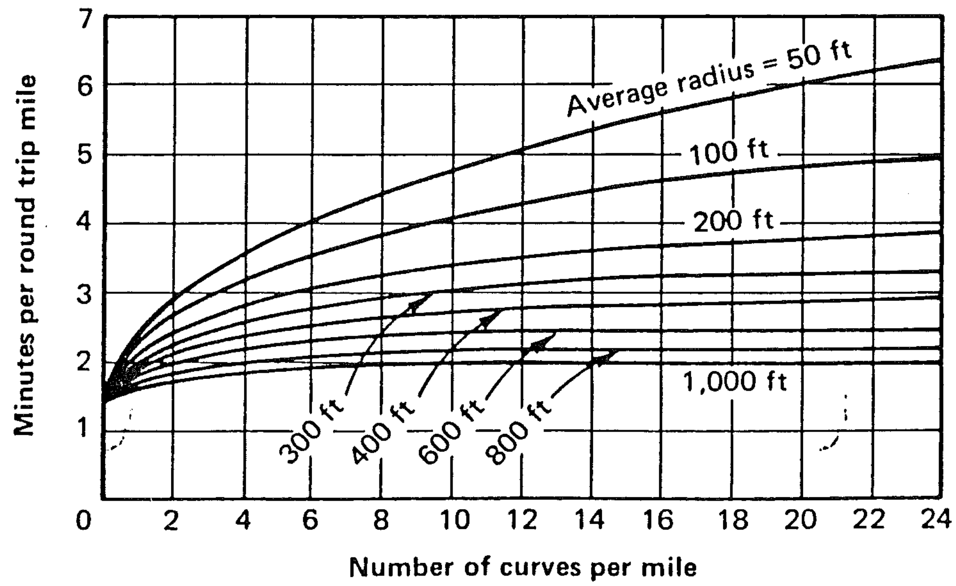


FIGURE 3 - *Graph showing the effect of curves and curve radius on loaded truck travel (Byrne, Nelson and Googins 1969, p. 13).*

In Figure 5 the surface is gravel and 112 kW is required at the wheels. However, input power required at the injectors increases to 584 kW, i.e. an 59 kW increase required at the wheels works back to a 231 kW increase in fuel input! Add to this the increased wear and tear due to dissipation of energy in the driveline.

It is no wonder then that fuel consumption is so sensitive to road resistances and that fuel consumption on logging trucks can reach as high as 9 litres per km on heavy grades. (Slade, 1983).

THE USE OF TRUCK PERFORMANCE PREDICTION IN ROAD DESIGN

The traditional and still most common use of the formulae is to calculate the critical or key limits of the truck to be used, and ensure that the road falls within these limits. For example, maximum adverse grades should not exceed the gradeability and startability of the truck (with suitable allowances for e.g. seasonal deterioration of road surface).

However, the calculations are time consuming and require knowledge of the subject. They tend therefore to be done initially to set policies for e.g. maximum grade, desirable minimum stiffness, desirable combinations of horizontal alignment, etc. These policies are readily understood and used by road builders. It is quite feasible for the policies to become used outside the initial area of application and even, in time, to start determining the type of truck that can be used!

The objective of this approach is to satisfy the truck/road interaction but not to optimise it.

Also because of the laboriousness of the calculations, it is unattractive to explore the real consequences of combinations of road designs. For example, a short 10% adverse grade, with good sight distance and minimal curvature, following a long 2% favourable grade, is a totally different proposition for a loaded truck than a long 10% adverse grade directly following a sharp curve out of a low quality spur road. Yet both would satisfy a policy of maximum 10% adverse grade.

Formulae are almost useless for predicting travel time over a distance of road with varying alignment and surface condition.

A useful refinement of formulae is to use them to create look-up charts and tables. An example is the Truck Travel Time Manual used by the New South Wales Forestry Commission.

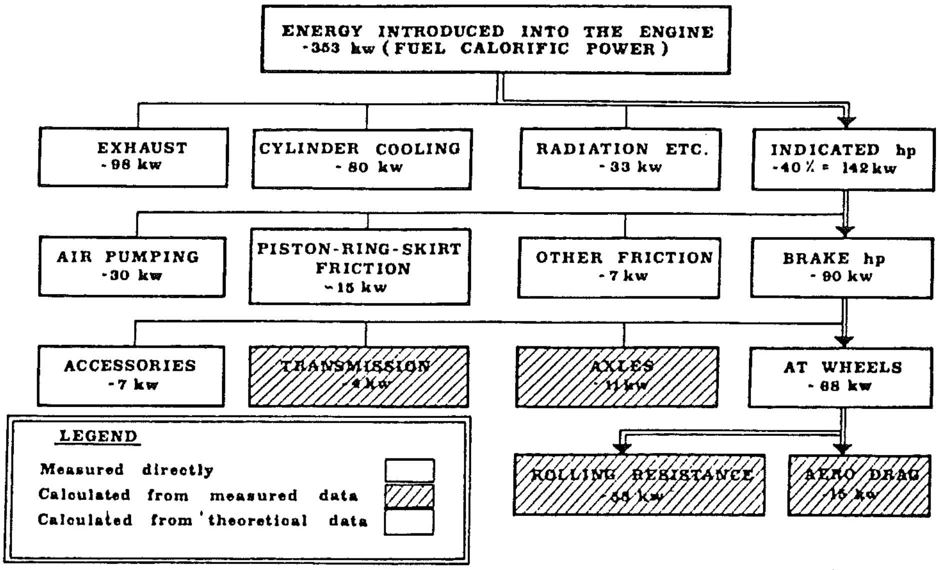


FIGURE 4 - Energy balance on a straight paved road (G.C.W. 60 000 kg steady speed of 56 km/h, direct drive, summer conditions dry & + 32°C

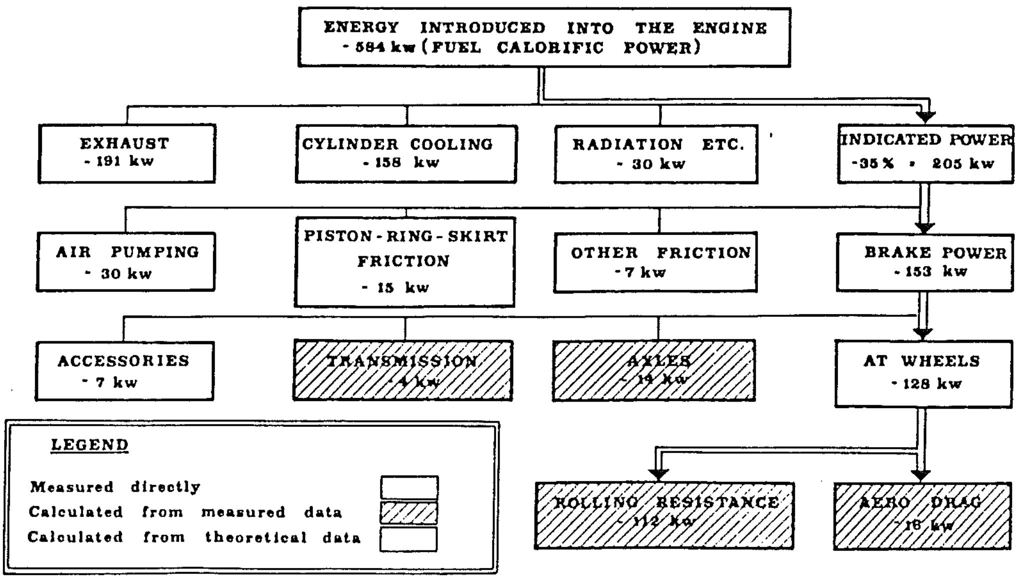


FIGURE 5 - Energy balance on a straight, flat gravel road (same unit and conditions as for Figure 4).

(Ljubic, 1984)

With a comprehensive description of the road, the expected truck travel time can be built up, section by section. Addition of load/unload and delay times produces a cycle time which can be extended to haulage cost.

A much more useful refinement is to put the formulae together in a computer simulation. Guided by a control logic, which mimics the decisions of a driver with regard to; gear changes, accelerating, decelerating, etc. the computer keeps churning through a cycle of formulae, recalculating the truck's performance at predetermined intervals.

It is possible to "run" a truck over a road and predict its performance (time, fuel consumption, etc.) on as fine or as gross a level of intensity as required.

The input to a simulation is :

- the road description. A description of the horizontal and vertical geometry, road surface, speed limits, traffic controls, etc.

- a truck specification, including weight, horsepower, gear ratios, tyre sizes, efficiency, etc. and detailed information on engine characteristics, e.g. a "fuel map", torque rise, etc.

Two heavy vehicle simulation packages have been around for about fifteen years :

- The Cummins Engine Co., Vehicle Mission Simulation (VMS) . (Cummins Engine Co.,1982)

- A subprogram of Integrated Civil Engineering System, ICES, called ROADS, which in turn has a vehicle simulator.

VMS is used as a marketing tool by Cummins to calculate the performance of different truck specifications on a given road and thus identify the best combination for a prospective truck buyer. It has been used in New Zealand at Kinleith and on the Napier/Taupo route for specifying logging trucks.

FERIC used VMS in a research project in 1983 to study the performance of different truck combinations on a given logging road route. (Smith, 1981).

One of the drawbacks of using simulations is inputting the road description. In general, it is gathered by hand, using an inclinometer, compass, tape or odometer, etc. to accurately describe the horizontal and vertical alignment of the road, to which is added subjective assessment of surface condition, etc. It is a very time consuming exercise and consequently Cummins tend to run a client's proposed truck specification over one of a large collection of "library" roads which approximates the client's haul. The library of routes held is very extensive, 130,000 miles in 1982. (Cummins Engine Co.,1982)

To reduce the input work, FERIC used an automated road recorder, fitted into a vehicle, which could be run over the road at up to 40 km/hr and record road geometry. Comments on road surface, speed restrictions, sight restrictions, traffic controls, etc. could be taped over by voice. The road recorder was built by the B.C. Ministry of Forests at an estimated cost of $500,000 and was not trouble-free. An interface was built to feed the road description directly to VMS.

VMS has been found to be reasonably accurate when compared with actual runs. Its major limitation is that it does not cater very well for lower quality pavement descriptions.

<u>ICES ROADS</u> is used by the M.O.W.D. in New Zealand. It was originally developed at M.I.T. in the U.S. and in the last 10 years or so has been taken over and marketed and supported (in the U.S.) by McDonnell-Douglas Corporation.

It was used by the author in the course of graduate studies in Canada, 1975-1977, and is considered more flexible and more applicable to lower quality roads than VMS. It is also much easier to manipulate road descriptions in ICES ROADS than in VMS, and it can therefore be used to test "paper" roads, before they are built.

In recent years there has been a lot of activity in building heavy vehicle simulators, e.g. HEVSIM (Buck, 1982).

(Bob McCormack, Scientist at the Forest Research Institute, Rotorua, will describe his work in developing and testing road recording and truck simulation and monitoring equipment in a separate presentation to the workshop).

RECORDING OF TRUCK PERFORMANCE

An alternative to using predictive formulae to estimate truck/road interaction is to record actual truck performance. Most activity in this area has centered on monitoring fuel consumption. (Ljubic, 1984). However, the use of data loggers allows the collection of a whole range of other factors too - speed, torque, temperature, gear ratio, etc.

This information can then be matched to a road description to record truck/road interaction.

FERIC have now moved from using the structure of VMS to :

- digitizing a road description using a road recorder
- measuring a very comprehensive set of performance factors - speed, torque, temperature, vibration, etc.

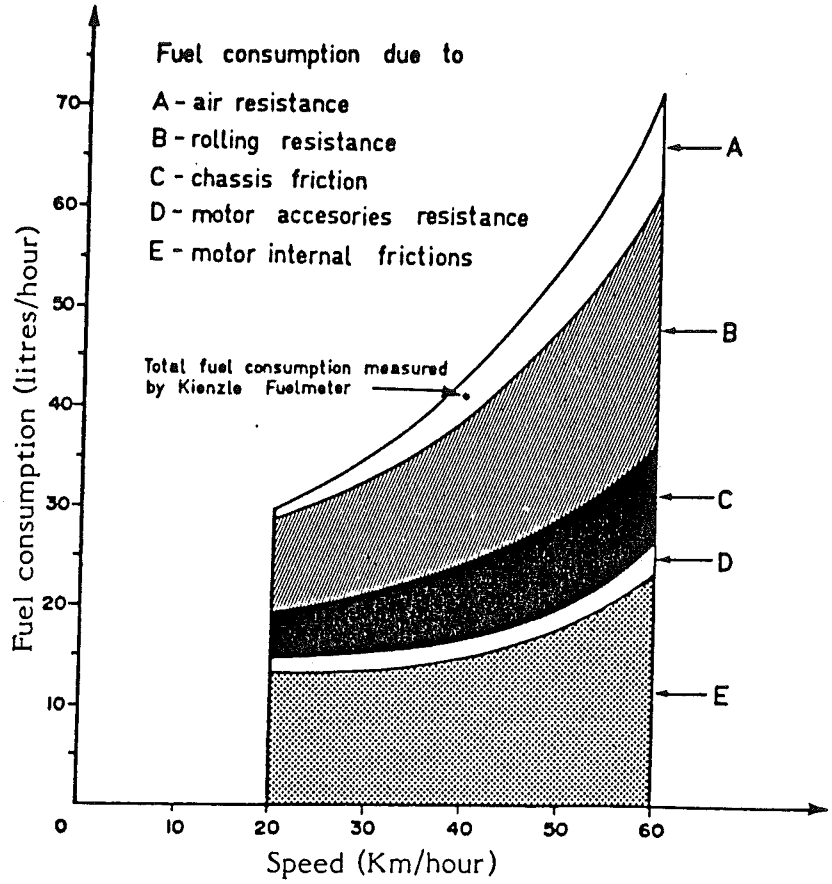
The intention is to derive the relationships between truck and road rather than use the standard formulae. The objective of their project now is to identify ways of improving truck efficiency.

Other FERIC studies involve the use of the "coast down" technique (see also Hindin, 1985 for New Zealand work with this technique). Results to date have quantified factors influencing fuel consumption, e.g. tyre pressure and type (Figure 7).

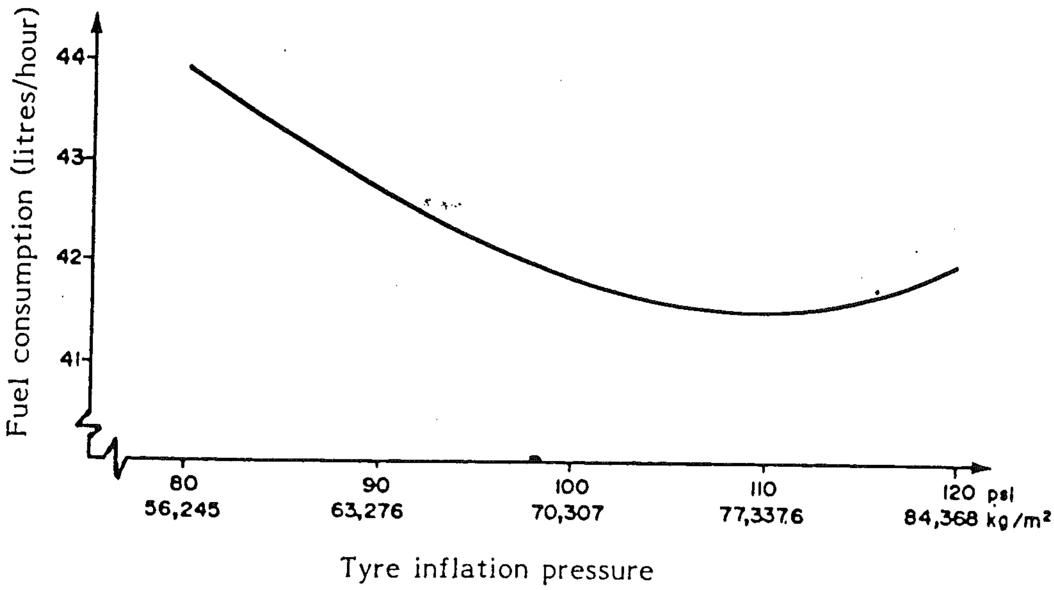
N.Z. Forest Products Limited have a sophisticated fuel flow meter and data logger, DZL (Slade, 1983). The main objective of its use is to monitor fuel consumption, but the data logger allows the recording of a range of other performance factors. It therefore becomes a very useful device for measuring truck/road interaction. Studies to date have looked at the effects of :

- gross weight
- tyre pressure and type
- transmission type
- engine horsepower rating
- driver influence
- engine type
- axle ratios

It is hoped that some of the results of this work will be published soon.



Energy balance



Fuel consumption vs. tyre inflation pressure

FIGURE 7 - SOME RESULTS FROM FERIC STUDIES ON FACTORS AFFECTING LOGGING TRUCK FUEL CONSUMPTION (Ljubic, 1984)

CASE STUDIES IN TRUCK/ROAD INTERACTION

Three examples of case studies where an overall analysis of truck performance versus road design has been carried out are :

1. Sloan, 1984 "The effect of truck design on road standards, road construction and timber hauling costs in Southwest Virginia."

   In this study the costs of building roads to suit truck configurations ranging from a 2-axle 30,000 lb. G.V.W. truck to a 5-axle 75,000 lb G.V.W.truck were estimated.

   The results were :

   (i) Road construction cost ; the cost of the highest standard road design was only 4% higher than the lowest standard ($355,000 for a 7.52 mile stretch versus $341,523). The only construction items to show significant difference were excavation - 42,388 cu.yd. versus 40,349 cu. yd. respectively and crushed aggregate 4,926 tons versus 4,716 tons respectively.

   (ii) Haul costs for the 5-axle truck were only 53% of the 2-axle truck

   Over a 20-year life, the comparative present net costs were estimated as :

2-axle	30,000 lb.	truck	$ 754,000
5-axle	75,000 lb.	truck	$ 564,000

   i.e. a clear justification for building the higher standard road to allow use of the larger truck.

2. Galbraith, 1977. Unpublished graduate paper - "A total energy budget for the construction and use of a forest road".

   For an 11 km stretch of an arterial logging road, carrying 560,000 m^3 p.a., the following <u>energy</u> inputs were estimated :

(i) The energy consumed in producing road construction and maintenance equipment and logging trucks.

(ii) Diesel fuel energy consumed by equipment during the construction and maintenance of the road.

(iii) Diesel fuel energy consumed by trucks in hauling wood over the road.

It was found that only 7% of the total energy budget was consumed in the construction and maintenance of the road and within this only 0.8% of the total energy was consumed in determining the vertical and horizontal alignment of the road.

The remainder of the energy budget, 93%, was consumed in the manufacture and use of the truck, and within this, 83% was diesel fuel energy.

The road was constructed through some reasonably difficult country and included adverse (loaded) grades of up to 10%.

The major conclusion was that 0.8% of the energy had gone into determining the vertical and horizontal alignment of the road, which was the major determinant of the 83% of the energy budget, i.e. how much fuel the truck used. It was deduced that, from a total energy point of view, considerably more effort could have gone into improving the road alignment, for a significant overall reduction in energy consumption.

Table 2 shows the diesel fuel consumption part of the study only, which gives a similar answer - 1.5% of the fuel is invested in determining 89% of the fuel use.

TABLE 2 - ESTIMATED TOTAL DIESEL FUEL CONSUMPTION IN CONSTRUCTING AND USING A FOREST ROAD. (From GALBRAITH, 1977)

Operation	Equipment	Fuel Consumption (litres/km)	
Subgrade construction			
(i) Bulldozing -grubbing	220 kW bulldozer	470	
Bulldozing -earthmoving	"	3,630	
(ii) Compaction	20 tonne compactor	380	
(iii) Grading	130 kW grader	90	
(iv) Culvert installation	50 kW backhoe	70	
		4,640	1.5 %
Pavement (gravel)			
(i) Extraction and loading	190 kW loader	1,390	
(ii) Crushing	180 kW crusher	470	
(iii) Hauling	9 m^3 truck	9,110	
(iv) Grading	130 kW grader	50	
(v) Compacting	20 tonne compactor	80	
		11,100	3.5 %
Maintenance			
(i) Grader work	as above	4,140	
(ii) Gravel dressing	"	12,660	
(iii) Reconstruction		1,570	
		18,370	6 %
TOTAL road fuel consumption		34,110	11 %
Truck fuel consumption			
40 tonne semi-trailer	260,000		
56 tonne bi-train	312,000		
Average		286,000	89 %
TOTAL diesel fuel consumption		320,000	100 %

The results of these two studies indicate that, for the cases involved, considerably more effort could be justified in improving road alignment to reduce haul cost and/or energy consumption and improve the overall result. In each case there are factors which tend, on reflection, to perhaps over-emphasise the truck part of the interaction, e.g.

- (Sloan, 1983) the 2-axle truck is not a very efficient transporter.
- (Galbraith, 1977) the road is a very high use, arterial route.

3. Anderson P. and Sessions J.,1985. Gradeability and cost considerations in vehicle operations on steep roads.

   This paper (a Master's thesis) was presented to the Mountain Logging Symposium in Vancouver in May, 1985. It examines the use of very steep roads in coastal Oregon. The road builder is often faced with the choice of locating a cheap, steep road on dry stable ridges, or achieving an easier but more expensive alignment across a slope. Trucking options on steep grades include :

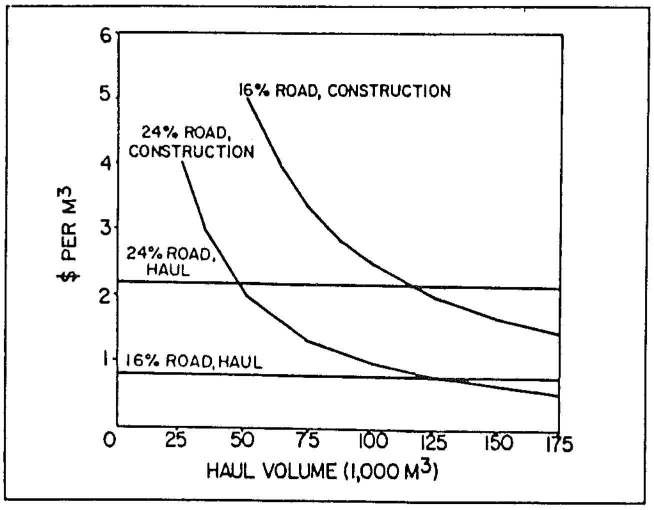
   - operation in dry, favourable conditions (up to 26% grade).
   - 6 x 6 axle configurations.
   - use of assist vehicles, e.g. an old bulldozer, to help trucks up or down very steep slopes (up to 40%).

   The study presents some graphical solutions to allow readers to analyse their own particular situation. (See Figure 8).

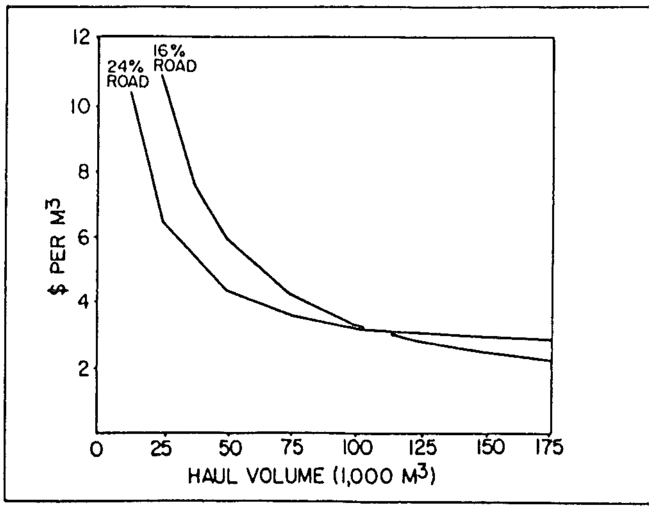
   Solutions are generally most dependent on volume to be hauled over the road. The authors note that steep road grades are becoming increasingly common in the Pacific Northwest.

   This study is particularly relevant to New Zealand as, in many new forests, establishment roads are often located on dry, stable ridge tops. Upgrading existing alignments is often the first option to be considered in providing logging capacity roads.

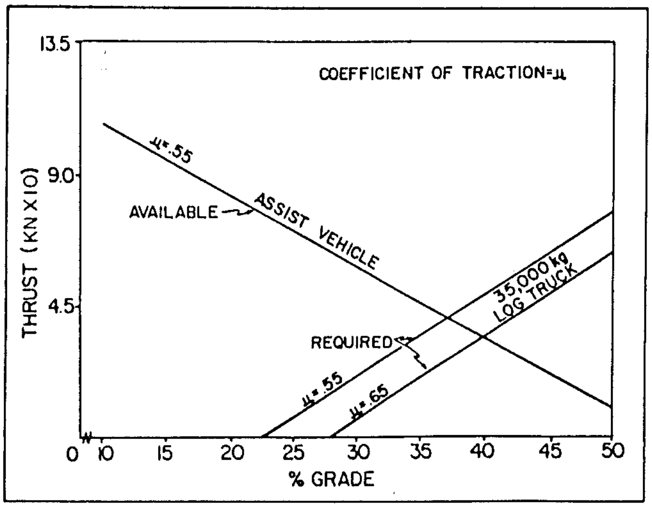
These three studies illustrate the point that the best road <u>and</u> truck solutions are very site-specific.



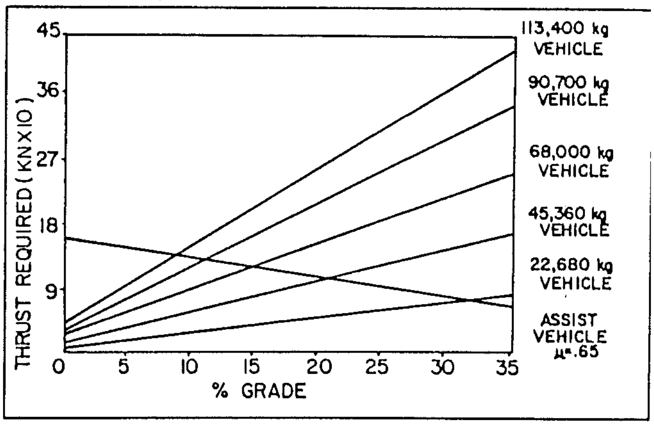
1. Construction and haul costs for a 24% and a 16% road.



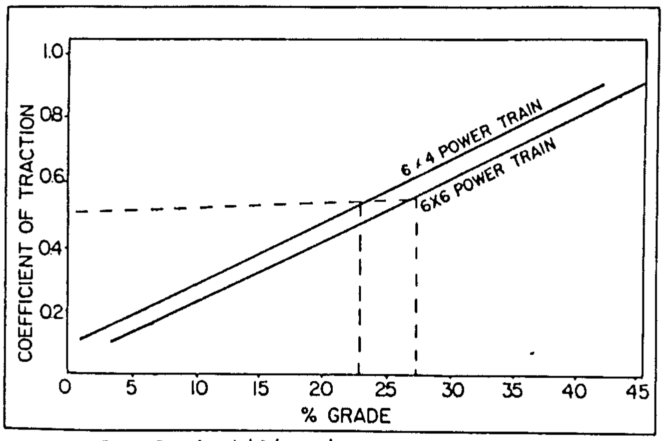
2. Combined construction and haul costs for a 24% and a 16% road.



3. The effects of coefficient of traction on log truck gradeability.



4. Thrust required from an assist vehicle to move unpowered vehicles of various weights up adverse grades.



5. Gradeability increase from powering the front wheels.

FIGURE 8 - GRAPHS FROM ANDERSON AND SESSIONS (1985) REGARDING TRUCK GRADEABILITY ON STEEP ROADS

FUTURE DIRECTIONS

The New Zealand forest industry faces a major programme of constructing new logging roads and upgrading establishment roads in the next 15 years.

The key question is - what standard of road should be built? (for each individual situation).

The answer can best be provided by an analysis system which looks at both road and truck costs.

It would appear that, given two "aids" :

(i) the road planning and design packages being developed at F.R.I.

(ii) a reliable,easy-to-use, heavy truck vehicle simulator

it should be possible to explore a number of options of road location and design standard for a given harvest area, and then to estimate the trucking cost on each option. This should allow selection of a more optimum solution to reduce the overall transportation cost.

It is recommended that LIRA pursue the availability of suitable truck simulation packages and test and assess their use.

In parallel, LIRA could continue with a more thorough search of truck/road interaction literature and research, and produce summary information on the known interactions, for the industry's use and guidance.

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