Optimizing haul road design – a challenge for resource development in Northern Canada

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ABSTRACT

Mine operation haul roads and ultra-heavy dump trucks should be considered as two components of a single transportation system, with interactions between them. The interactions of this system's components are becoming more important to the operations they serve as the gross vehicle mass (GVM) of the available trucks increases. To illustrate, the maximum GVM of one manufacturer's trucks has approximately doubled in the last 20 years, to exceed 600 tonnes.

The paper focuses on the road component of the transportation system, examining the influence of road conditions on ultra-heavy truck performance. Of the truck power requirements, grade resistance and rolling resistance power demand depend on road inputs, and they dominate the other power requirements. Stiffening granular haul road pavements will reduce rolling resistance and fuel consumption. While placing geosynthetics in the pavement cross section was shown to increase pavement life substantially, it did not increase road stiffness appreciably. Other methods of stiffening haul road pavements are discussed.

The paper advocates the use of more sophisticated pavement design methods such as the Critical Strain Method (CSM), over traditional CBR methods. The displacements, stresses, and strains predicted by the CSM for these ultra-heavy truck loadings should be verified. A full-scale trial is called for and the paper provides the design of a full-scale experiment.

INTRODUCTION: THE TRUCK-ROAD SYSTEM

The haul roads and heavy dump trucks used by mining, oil & gas, oil sands, and forest industry operations should be considered as two components of a single transportation system. There are interactions between the components, each influencing the behaviour of the other. Truck weights have steadily increased (Figure 1), and as they have, the transportation system and the interactions of its components have become more important to the operations they serve. The paper focuses on the road component of the truck / haul road system, examining the influence of road conditions on ultra-heavy truck performance.

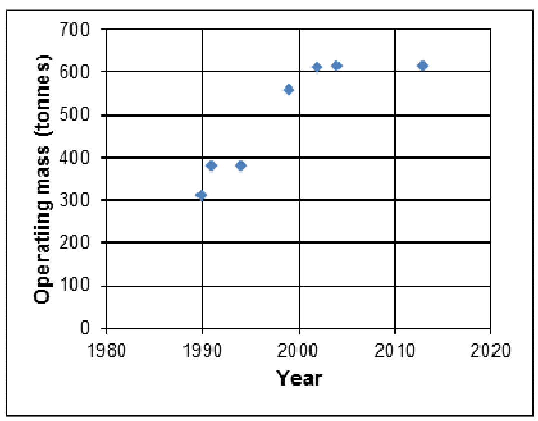


Figure 1. Gross vehicle mass (GVM) for one manufacturer's heaviest model dump truck by year of introduction.

ROADS INFLUENCE TRUCK BEHAVIOUR

Fuel consumption and truck power demand are directly related. The power produced by igniting the fuel in the cylinders less that needed to drive essential engine systems is the gross power, the power that is usually reported in manufacturer's literature. Gross power, less the power drawn by accessories (a compressor, for example), leaves net power. Net power is demanded to overcome the following resistances (Figure 2):

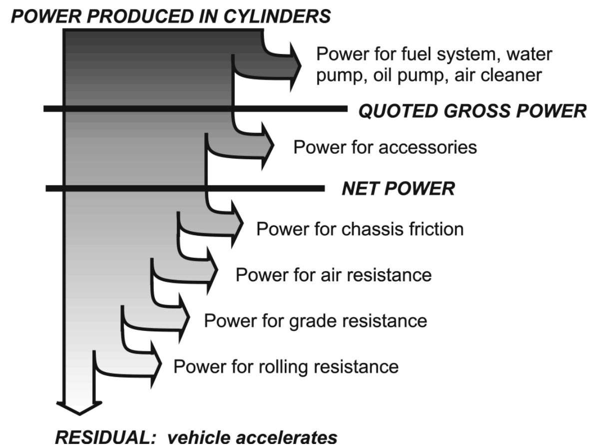


Figure 2. Power breakdown.

- chassis friction – internal friction in the drive train
- air resistance – the drag on the truck plus the frontal air resistance
- grade resistance – the power needed to climb a grade
- rolling resistance – the power absorbed by the deflecting pavement and the distortion and flexing in the tires

If there is a surplus of power, the truck will accelerate. If there is a deficit, it will decelerate.

Grade resistance and rolling resistance power requirements (and therefore fuel demands) are dependent on characteristics of the haul road. They are the basis of the interactions of the truck and haul road.

Grade resistance power can be determined analytically:

$$GRP = 0.0273\,(GVM \times V \times G) \qquad \text{Eq. 1}$$

where:
GRP = grade resistance power [kW]
GVM = gross vehicle mass [tonnes]
V = vehicle speed [km/hr]
G = road longitudinal gradient [%]

On the other hand, rolling resistance cannot be determined analytically, and must be estimated empirically, for example:

$$RRP = 0.0273\,(URR + 0.622\,V) \times GVM \times V \qquad \text{Eq. 2}$$

where:
RRP = rolling resistance power [kW]
URR = unit rolling resistance [kg/tonne GVM]
GVM = gross vehicle mass [tonnes]
V = vehicle speed [km/hr]

Example values of the URR are provided in Table 1.

Table 1
Typical unit rolling resistances, *URR* (after McNally [1])

Road type	*URR* [kg/tonne GVM]
rigid pavements (Portland cement pavements)	8 – 10
flexible pavements (asphalt, compacted crushed rock)	10 – 15
crushed gravel, gravel, or sandy clay	15 – 25
"earth" roads	25 – 100
ice roads, frozen roads	10 – 20
compacted snow	30 – 50

IMPROVING TRUCK PERFORMANCE

Stemming from Equations 1 and 2, there are two practical ways road characteristics can be used to improve truck performance: changing the alignment and changing the pavement structure.

Alignment

The road alignment – particularly the vertical alignment – can influence truck performance greatly. The typical ultra-heavy haul truck power-to-weight ratio is about equal to that of a ride-on garden tractor pulling a pickup truck filled with firewood. Obviously its grade-climbing abilities should not be taxed with steep grades. Figure 3 shows the impact of a moderate grade on a 600 tonne GVM dump truck: within 250 m of starting the climb at 50 km/hr, the truck's speed has been brought down to about 16 km/hr, about the same speed as a good long distance runner. Attention to the vertical alignment can have significant effects on truck speeds and turn-around times.

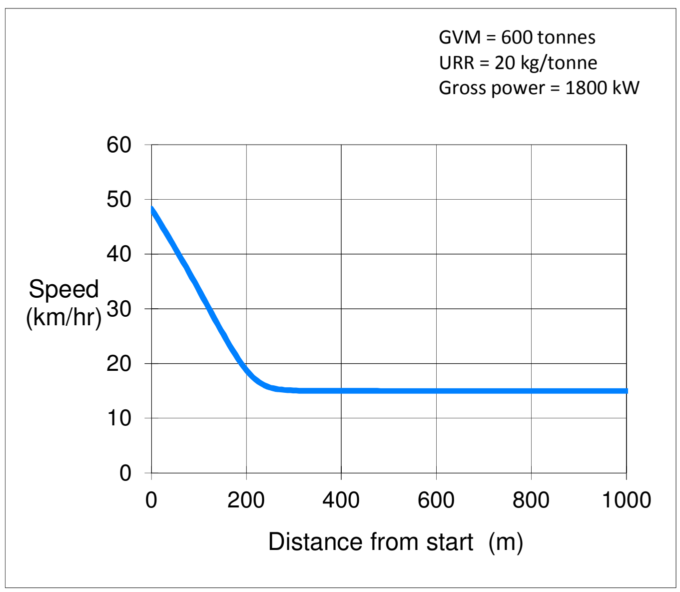


Figure 3. Speed affected by gradient of 4%. Truck begins climb at 50 km/hr.

Because of the impact that road alignment has on truck performance and cost, the alignment of haul roads should take a higher priority in mine plans than it often does. Often it is a matter of the road alignments being developed once the mine plan is completed, rather than the roads being considered as integral to the mine plan.

Pavement Structure Design

Pavement design should aim toward stiffer pavements, to reduce the unit rolling resistance (Eq. 2), thus rolling resistance power requirement, and fuel consumption. Design methods more sophisticated than those based on CBR are required. The critical strain method (CSM) is one such method. The design criterion for the CSM is that vertical strain should be less than a limiting amount, everywhere in the pavement structure [2}. The limit on vertical strain, dependent on the number of passes of the design axle load, is given in Equation 3a [3]:

$$\varepsilon_{max} = \frac{80{,}000}{\mathrm{N}^{0.27}} \qquad \text{Eq. 3a}$$

or

$$N = \left[\frac{80{,}000}{\varepsilon_{\max}}\right]^{3.7} \qquad \text{Eq. 3b}$$

where:
ε_{max} = the limiting vertical strain
N = the number of passes of the design axle load during the road's life

STIFFER ROADS – THE CHALLENGE

The stiffness of the road structure – the ratio of the wheel load to the vertical deflection of the road surface – is a key element in reducing rolling resistance and truck operating costs. To examine the issue, the deflections and strains were modelled for a 450 tonne GVM dump truck on a three-layer granular pavement built on a soft subgrade. The details are given in Table 2.

Table 2.
Numerical model input values.

Truck details			
truck configuration	two-axle truck front axle: two single tires rear axle: two dual-tire wheels (i.e. four tires on this axle)		
dimensions of tire/road contact patch	1016 mm wide x 798 mm long		
assumed uniform vertical pressure exerted on tire/road contact patch	920 kPa		
Road details			
	Thickness (m)	**Modulus (MPa)**	**Poisson's ratio**
surfacing or capping layer	0.5	250	0.30
base layer	1.0	100	0.30
subbase layer	1.5	50	0.30
subgrade	infinite	5 (equivalent to CBR = 0.5)	0.49

Finite difference computer software was used to determine the strains and thus the limiting number of passes the design axle could make. The maximum vertical strain occurred in the base layer with a value of 6600 με. Equation 3b predicts a design life of approximately 10,000 passes of the design axle.

The Effect of Geotextiles

The vertical deflection at the road surface was estimated to be 27.6 mm. The same road cross section, with the addition of a high strength geotextile (Table 3) at each of the surfacing/base, base/subbase, and subbase/subgrade interfaces was estimated to deflect 27.2 mm.

Table 3
Geotextile characteristics

	Direction	**Tensile strength (kN/m) @ strain**	**Tensile modulus (kN/m)**	**Poisson's ratio at 2% strain**	**Poisson's ratio at 5% strain**
wide strip tensile test results (ASTM D 4595), average of 6 tests	cross-machine	74 @ 6.7	1440	0.39	0.28
manufacturer's literature	cross-machine		1310 @ 2%		

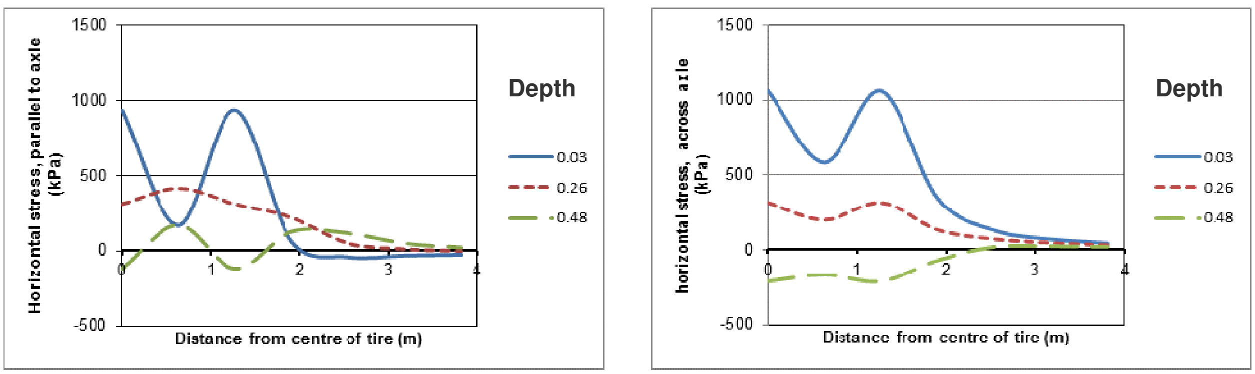
Stiffness being related to the inverse of the deflection, the cross section was thus about 1.3% stiffer, a negligible amount. However, the presence of the geotextiles altered the strains in the cross section enough to increase the maximum number of passes of the axle load from 10,000 to 15,000 – a 50% increase. Therefore a marginal increase in road section stiffness came with a substantial increase in design life.

Design Method

The above deflections and strains were determined through numerical modelling using finite difference software. The software predicted strains, and the strain values were input to Equation 3b to estimate the design life in numbers of passes of the design axle load. The software modelled the geotextile as a linearly elastic material perfectly bonded to the soil on either side of it.

Importantly, the pavement layers were modelled as being incapable of sustaining tension.

Using simple linear elasticity permits significant tensions in the cross section, for example across the bottom surface of the surfacing layer (depth = 0.48 m), as shown on Figure 4.



(a) **(b)**

Figure 4. Horizontal stresses (a) parallel to axle, and (b) across the axle, at the depths shown in the Legend.

If a traditional approach is adopted, ignoring the tensions, considerably more optimistic – and incorrect – results are obtained. Table **4** illustrates this. If tensions are ignored (and therefore permitted in the model), two *erroneous* conclusions are drawn:

1. Comparing Case 1 with Case 2, the geotextile layers provide no reinforcing effect – the deflections, vertical strains, and design lives (implied number of passes of the design axle load) are concluded to be the same.
2. Comparing Case 1 with Case 3, or Case 2 with Case 4, the design life is concluded to be much larger – more than 3.5 times, for this example – than it really is.

In actual fact, for this example, the design life can be increased by 50% with the installation of geotextiles at the interfaces. However, as shown, the realistic design life with or without geotextiles is substantially less than might be thought.

Table 4. No-tension analysis results

Case (a)	Surface deflection under a tire (mm) (b)	Maximum strain in base layer under a tire (με) (c)	Implied number of passes of design axle load (Eq. 3b) (d)	Maximum strain in subgrade between tires (με) (e)	Implied number of passes of design axle load (Eq. 3b) (f)	Pavement design life† (passes of design axle load) (g)
Case 1: no geotextile, subgrade CBR=0.5	20	4200	54,000	2900	210,000	54,000
Case 2: geotextile at all interfaces, subgrade CBR=0.5	20	4200	54,000	2900	210,000	54,000
Case 3: no geotextile, subgrade CBR=0.5, tension not allowed	28	3700	87,000	6600	10,000	10,000
Case 4: geotextile at all interfaces, subgrade CBR=0.5, tension not allowed	27	3800	79,000	6000	15,000	15,000

† maximum number of passes of design axle load, the *lesser* of the values in columns (d) and (f)

Building Stiffer Roads

With an appropriate model (no-tension model) it is shown that building the road with geotextile inclusions does reinforce it significantly, but only stiffens it a slight amount. The benefit is on the road side rather than the truck side of the interactions between truck and road. With the reinforcement of the pavement, a thinner pavement may be designed, using less material.

Stiffer roads can be achieved with other means:

- lime treatment of the subgrade, if cohesive
- cement treatment of the lower layers (not recommended for the surfacing layer)
- roller compacted concrete
- inclusion of geocell layers

From the operational point of view, it is best to leave the surfacing layer untreated, and treat the lower layers. A treated surfacing layer if/when broken up, becomes a difficult and expensive thing to repair. An untreated granular surfacing layer is amenable to routine maintenance such as grading and pothole filling.

The treatments listed above should be investigated in the ultra-heavy truck context, particularly with full-scale trials.

RESEARCH

It has been shown that without the no-tension analysis, numerical modelling can give inaccurate predictions of road section behaviour, and that those predictions are on the non-conservative side. However, the tension-free analysis results have not been verified. Full-scale trials should be mounted using the ultra-high loads that the trucks now impose.

Instrumented trial cross sections should be designed to measure deflections, strains and stresses at key locations. Noting that while the vertical stresses are continuous across the pavement layer interfaces, the vertical strains are discontinuous at the layer interfaces, at a minimum, the following should be monitored under traffic:

- road surface deflections under the centre of a tire, between the two tires of a dual wheel, and at the axle mid-point;
- vertical strains at the bottom of the surfacing layer, just below the tops of the base and subbase layers, and just below the top of the subgrade;
- longitudinal and transverse horizontal strains just above the bottoms of the surfacing layer and the base layer; and
- vertical stresses at the surfacing/base, base/subbase, and subbase/subgrade interfaces.

The cost of such trials, which will be substantial, is justified by the potential for savings in truck operating costs, and the improved understanding of the behaviour of the pavements built for ultra-heavy trucks. That understanding and therefore the pavement design methods have not kept pace with the increase in weight and cost of operation of ultra-heavy trucks.

CONCLUSIONS

Given the work described, the following are concluded:

- ultra-heavy trucks and the haul roads they run on should be considered as two components of a transportation system;
- the components interact with one another;

- the interactions stem from the vertical alignment of the haul road and the rolling resistance of the tires;
- truck performance (speed, turn-around time, fuel consumption) is strongly affected by road gradient;
- truck performance (fuel consumption) is affected by road stiffness;
- while the installation of high strength geotextiles at the layer interfaces had negligible effect on road stiffness, road design life was substantially increased (50%) in one case studied;
- with the extreme weights of trucks now typical, design methods more sophisticated than traditional CBR methods should be used, for example, the critical strain method;
- the numerical modelling performed as part of the critical strain method should not permit tensions to develop in the granular pavement layers;
- permitting tension to develop leads to the erroneous conclusion that geotextiles do not reinforce pavements, and leads to a substantial overestimation of pavement design life (a factor of at least 3.5 in the one case studied); and
- carefully designed, instrumented full-scale field trials should be performed to verify the predictions of the critical strain method of design for ultra-heavy trucks on granular pavements.

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