HVTT12 - ROLLING RESISTANCE FOR TRUCKS ON AC AND PCC PAVEMENTS

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Abstract:

The rolling resistance for trucks depends on: Energy losses because of the compression of the tyres and the road.

Through measurements by a falling weight deflectometer and measurements by the tyre company Continental it has been possible to calculate the ratio between the rolling resistance on Portland cement concrete (PCC) roads and asphalt concrete (AC) roads. In Canada Measurements have been made by keeping the temperature within a narrow interval. After this linear relationships were established between load and fuel consumption. The slopes in these relationships are proportional to the rolling resistances.
The relation between the rolling resistance on PCC and the rolling resistance on AC is: 0,5-0,8. Because of this the fuel consumption saving for a fully loaded truck driving on PCC instead of on AC is at least 5 - 10 %.

Rolling resistance for trucks on AC and PCC pavements.

Leif Fäldner[1]

INTRODUCTION

Many fuel consumption measurements for trucks are indicating that the fuel consumption is considerable less on Portland cement concrete roads (PCC) than on asphalt concrete roads (AC).
The rolling resistance depends on: Energy losses because of the compression of the tyres and energy losses because of the compression of the road.
It´s only trucks that cause compression of the road.

FALLING WEIGHT ANALYSIS

Through measurements by a falling weight deflectometer made by the Swedish Road Department on Road E4.65 near Stockholm's airport Arlanda and measurements of the relationship between the fuel consumption and the rolling resistance of the tyres made by the tyre company Continental. It has been possible to calculate the fuel saving for a 40 ton heavy truck driving on a PCC road instead of an AC road at the speed of 80 km/h.
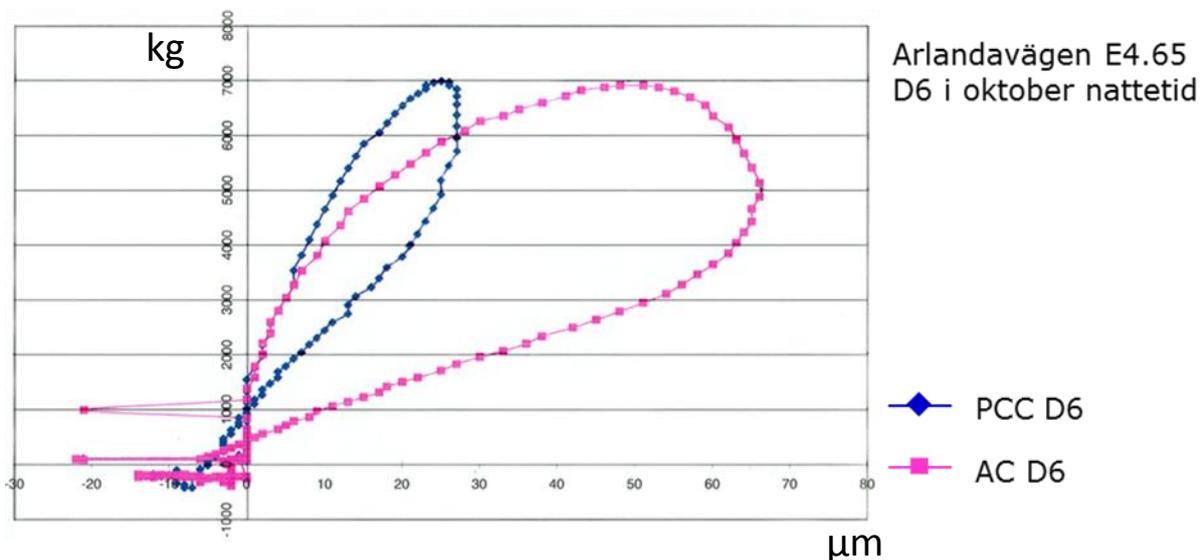The resulting hysteresis curves can be seen in the following diagram. (Figure 1).

Figure 1. Deflection-load diagram from two parallel pavement types on the same type of subgrade. Early study from 1998.

The relation between the areas within the hysteresis curves PCC and AC is in this case 0,42. This means that the loss of energy because of the compression of the PCC road is 42 % of the compression of the AC road. According to Aerodynamics for trucks (Haraldsson H. et al 2005, The University of Lund) the relationship between the air resistance, the rolling resistance and the speed for a 40 ton heavy truck, driving on an even AC road without any wind can be illustrated by figure 2.

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For the same truck the relation between all the resistances can then according to Aerodynamics for trucks be illustrated by figure 3.
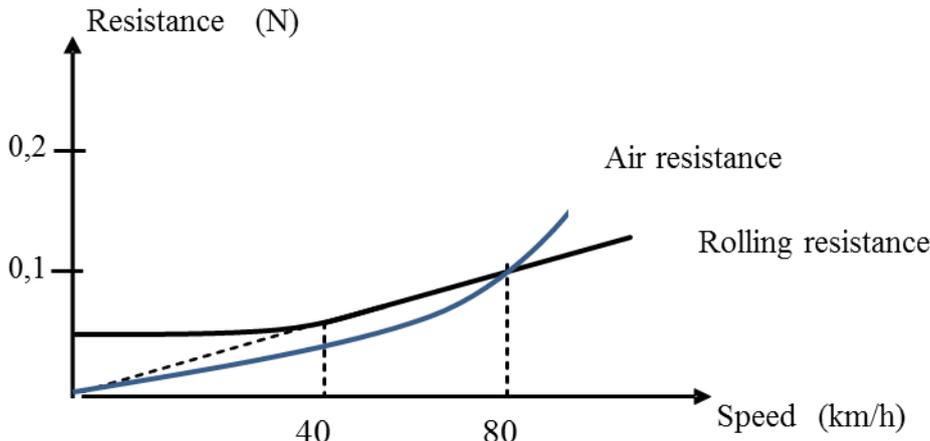
Resistance (N)

Resistance relations at the speed 80 km/h

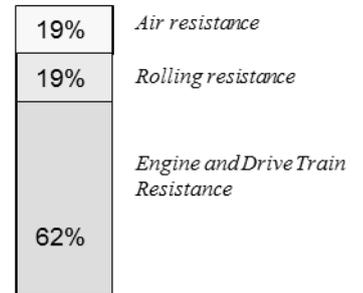*Figure 2 and 3*

According to the same essay the fuel consumption will then be 3,562 l/10 km (diesel).
According to figure 2 the rolling resistance dependent fuel consumption will then be
0,19*3,562=0,677 l/10 km.
According to Sven Eric Johansson Continental 8% reduction of the rolling resistance of the tyres will give a consumption saving of 0,016 l/10 km.
If you suppose that x % of the rolling resistance depends on the compression of the tyres you will then get
0,08 * X * 0,0677/100 = 0,016
X ≈30%
The relation between the rolling resistance RR_{PCC} on PCC and the rolling resistance RR_{AC} on AC is then:

$$\frac{RR_{PCC}}{RR_{AC}} = \frac{0,7 \cdot 0,42 + 0,3}{1.00} = 0,6$$

RESEARCH METHOD

In Canada Measurements have been made by keeping the temperature within a narrow interval (Taylor et al 2001 and Taylor et al 2006). After this linear relationships were established between load and fuel consumption driving on PCC and on AC at the speeds 100 km/h, 75 km/h and 60 km/h.
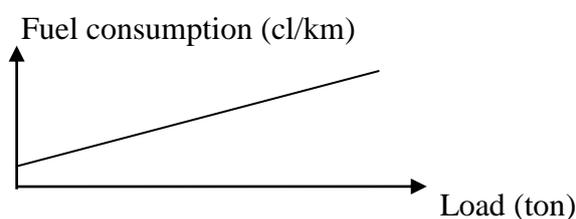
See figure 4:

Fuel consumption (cl/km)

Load (ton)

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Figure 4

For AC you got the following relationship:

At the speed 100 km/h:

$$Y = 0,4027X + 30,441$$

Where:

Y = The fuel consumption (cl/km)

X = The load (ton)

$R^2 = 1,00$

At the speed 75 km/h:

$$Y = 0,2983Y + 25,446$$

$R^2 = 0,99$

At the speed 60 km/h:

$$Y = 0,3251Y + 19,303$$

$R^2 = 0,97$

For PCC you got the following relationship:

At the speed 100 km/h:

$$Y = 0,2168X + 30,551$$

$R^2 = 0,94$

At the speed 75 km/h

$$Y = 0,2470X + 24,885$$

$R^2 = 0,88$

At the speed 60 km/h:

$$Y = 0,2787X + 19,104$$

$R^2 = 0,95$

The constant terms in the equations should be directly proportional to the air resistance and should therefore be equal for PCC and AC. This is almost the case. The slope in the equations should be directly proportional to the rolling resistance.

For AC the mean slope K_{AC} is:

$K_{AC} = (\ 0{,}2108+0{,}2470+0{,}2787)/3$

$K_{AC} = 0{,}3420$

For PCC the mean slope K_{PCC} is:

$K_{PCC} = (0{,}2108+0{,}2470+0{,}2787)/3$

$K_{PCC} = 0{,}2475$

So according to these measurements the mean ratio between the rolling resistance RR_{PCC} on PCC and the rolling resistance RR_{AC} on AC is:

$RR_{PCC}/RR_{AC} = 0{,}2475/0{,}3420 = 0{,}7$

According to the falling weight analysis the relation is :

$RR_{PCC}/RR_{AC} = 0{,}6$

So both relations agree reasonably well with each other.

According to calculations made by Detroit Diesel the mean relation is 0.75.

Coast down measurements

A coast down measurement is performed by letting the vehicle roll freely (clutch down, gear in neutral position) between the start and end points.
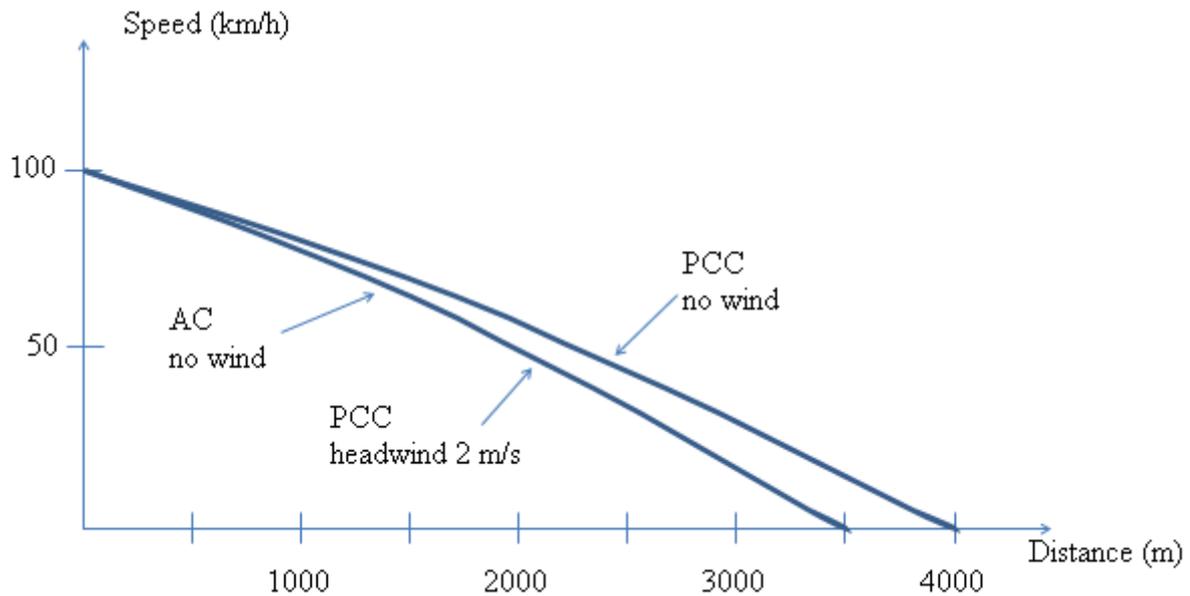The velocity is measured continuously along the road strip, see figure 5.

Figure 5

The velocity curves depend on the vehicles weight, starting velocity, front area, air resistance coefficient and the air density and the rolling resistance coefficient.

How the velocity depends on the drive time is described by the following force equation;

$$m\,x'' = mg \cdot R \cdot x' + 0.5\,C_d \cdot A \cdot \zeta\,x'^2$$

where

m= weight of the truck (kg)

x= drived distance (m)

$x^{`} = dx/dt =$ velocity (m/s)

t= drive time (s)

$x^{``} = dx'/dt =$ retardation (m/s^2)

g= acceleration due to gravity (m/s^2)

Rx`= rolling resistance coefficient

C_d= air resistance coefficient

A= frontarea of the truck (m^2)

ζ= air density (kg/m^3)

This equation can be written as:

$$x'' = a \cdot x_1 + b\, x'^2 \qquad \textbf{(1)}$$

where

$$a = g \cdot R$$
$$b = \frac{C_d \cdot A \cdot \zeta}{2m}$$

By solving this differential equation one gets the velocity v (km/h) as a function of the drive time t:

$$v(t) = \frac{a \cdot e^{at}}{\beta - b \cdot e^{at}} \qquad \textbf{(2)}$$

where

$$\beta = b + \frac{3{,}6a}{v_0}$$
$$v_0 = \text{starting velocity (km/h)}$$

By help of equation (2) the drive distance s can now be calculated for every time value T as:

$$s(T) = \int_0^T \frac{x'(t)\, dt}{a} = \int_0^T \frac{e^{at}\, dt}{\beta - b \cdot e^{at}}$$

From this one gets the following expression:

$$s(T) = -\frac{1}{b} \cdot \ln \frac{\beta - b \cdot e^{aT}}{\beta - b} \qquad \textbf{(3)}$$

For every value of the velocity v e^{aT} can be calculated by help ofd the following equation;

$$\int_0^T x''(t)\, dt = \left[x'(t) = \right]_0^T \frac{v_0 - v}{3{,}6}$$

$$\frac{a \cdot e^{at}}{\beta - b \cdot e^{at}} = \frac{v_0}{3{,}6} = \frac{v_0 - v}{3{,}6}$$

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One then gets the following expression;

$$e^{aT} = \frac{(2v_0 - v) \cdot \beta}{3,6a + (2v_0 - v) \cdot b} \qquad (4)$$

By putting this expression into equation (3) the distance s can now be calculated for every given value of the velocity v.

This has been done for a 40 ton heavy Scania truck with the starting velocity 100 km/h on AC and PCC roads. The results can be seen in figure 5.
If there ia head wind the force equation will be:

$$x'' = a \cdot x' + b (x' + u)^2$$

where

u = headwind (m/s)

In anlougously the same way the following equations (5), (6) and (7) has been derived:

$$v(t) = \frac{A + B\, e^{2\sqrt{\Delta}t}}{C + D\, e^{2\sqrt{\Delta}t}} \qquad (5)$$

where

$$\Delta = a\,(0,25a + bu)+3b^2$$

$$\beta = 0,5\, a + bu$$

$$A = v_0\, b\, (\sqrt{\Delta} - \beta) + 3,6\, (\Delta - \beta^2)$$

$$B = v_0\, b\, (\sqrt{\Delta} + \beta) - 3,6\, (\Delta - \beta^2)$$

$$C = b\, (3,6\, (\sqrt{\Delta} + \beta) + v_0\, b)$$

$$D = b\, (3,6\, (\sqrt{\Delta} - \beta) - v_0\, b)$$

$$s(T) = \int_0^T x'\,(t)\, dt = \int_0^T \frac{A+ B e^{2\sqrt{\Delta}t}}{C+D e^{2\sqrt{\Delta}t}}$$

$$s(t) = \frac{1}{2\sqrt{\Delta}} \left[\frac{B}{D}\, \ln \frac{C + D\, e^{2\sqrt{\Delta}t}}{C + D} - \frac{A}{C} \cdot \ln \frac{D + C\, e^{-2\sqrt{\Delta}t}}{C + D} \right] \qquad (6)$$

$$e^{2\sqrt{\Delta}t} = \frac{(2v_0 - v) \cdot C - 3,6\, A}{3,6\, B - (2v_0 - v) \cdot D} \qquad (7)$$

By putting the expression (7) into the equation (6) the distance s can now be calculated for every given value of the velocity v.

This has been done for 40 ton heavy Scania truck with the starting velocity 100 km/h and the headwind 2 m/s on a PCC road. The result con be seen in figure 5:

The Swedish Transport Rescarch Laboratory has done coast down measurements with a 60 ton heavy truck on AC and PCC roads. These measurements gave almost the same velocity curves for AC and PCC.

Since such a small headwind difference as 2 m/s can change the result radically this is not so surprising.

According to the earlier equations the rolling resistanse cofficient u can be expressed as:

$$\mu = R\,x' = \frac{av}{3{,}6g}$$

The parameter a can be derived by the following equations;

From this one gets the following expression;

$$s(T) = -\frac{1}{b} \cdot I\,n\,\frac{\beta - b \cdot e^{aT}}{\beta - b} \qquad \textbf{(3)}$$

$$e^{aT} = \frac{(2v_0 - v) \cdot \beta}{3{,}6a + (2v_0 - v) \cdot b} \qquad \textbf{(4)}$$

The result of this is:

$$a = \frac{b((2v_0 - v)\,e^{-bs} - v_0)}{3{,}6(1 - e^{-bs})}$$

So by knowing vehicles weight, front area, air resistance coefficient, starting velocity and the air density the parameter a by the help of values of the driving distance and velocity from a velocity curve from a coast down measurement. Then the rolling resistance coefficient u can be calculated as:

$$\mu = \frac{av}{3,6g}$$

By using a velocity curve made by the Swedish Transport Research Laboratory I have calculated the rolling resistance for a car on AC at the speed of 80 km/h by using classical mechanics. The calculated rolling resistance coefficient was then 0,012.
This value is about the same as the rolling resistance coefficient that was measured by a TUG trailer.
The reason that I have chosen to calculate the rolling resistance coefficient for a car and not for a truck is that the Swedish Transport Research Laboratory have not yet velocity curves for trucks.

PRELIMINARY RESULTS

The relation between the rolling resistance on PCC and the rolling resistance on AC is:
0,5-0,8, probably around 0,7.
Because of this the fuel consumption saving for a fully loaded truck driving on PCC instead of on AC is at least 5 - 10 %.
This means that the average consumption saving for a truck is 3,5-6,5%

CONCLUSIONS

The relation between the rolling resistance for trucks on PCC and the rolling resistance for trucks on AC has been calculated by using two very different methods with results very near each other.
This supports very strongly the idea that the rolling resistance for trucks on PCC is considerably less than that on AC.
This explains why the fuel consumption for trucks is less on PCC than AC. Analysis of fuel consumption measurements in Canada and Sweden is indicating that the fuel consumption saving for a 60 ton heavy truck driving on PCC instead on AC is at least 5-10 % which means a big gain for the society and the environment.

CONSEQUENCES OF CHOOSING PCC INSTEAD OF AC

The implications for a higher investment can be expressed in the following way:

$\Delta S/\Delta I = (S_A - S_B)/ (I_B - I_A)$

Where:
I_A = The AC investment cost
I_B = The PCC investment cost
S_A = The present value of the social costs (user and road holder costs) of the AC investment
S_B = The present value of the social costs (user and road holder costs) of the PCC investment

ΔS/ΔI is usually referred to as the Gross Benefit/Cost Ratio (GBCR). The shadow price (Λ) is the marginal yield of the investment for the society. It is decided by looking at the present money available in the national budget and it is presently about 2.8 in Sweden. By applying this formula for the AC and PCC alternatives and using the National Swedish Road Administration data bank for investments, road holder maintenance and user' costs for various amounts of traffic the GBCR was calculated. Users' costs were affected the most by the fuel savings for the commercial vehicles. Secondary causes include accident costs related to rutting. All costs related to the condition of the pavement such as vehicle wear and the like are based on an optimum pavement management maintenance strategy. These are of course needed to be evaluated before the economic relations are being calculated. In the tables 5 and 6 below the GBCR while choosing a PCC pavement is shown for some common high volume traffic roads in Southern Sweden. The fuel savings are for 4 and 5.5 % respectively. The combination where the GBCR is above 3 is shaded green and for those situations the PCC pavement is viable over the asphalt type.

	ADT		
Truck rate	12000	15500	20000
14%	2.1-2.2	2.8-2.9	3.7-3.9
20%	2.7-2.9	3.7-3.9	4.0-4.2
30%	4.1-4.3	5.9-6.1	8.5-8.9

Table 5. Gross Benefit/Cost Ratio for choosing PCC over AC Pavement at 4 % Fuel Savings

ADT means average of the number of vehicles per day

	ADT		
Truck rate	12000	15500	20000
3.8	2.8-2.9	3.8	5.0-5.1
20%	3.8-3.9	5.1-5.2	6.0-6.1
30%	4.7-6.0	8.2-8.5	11.9-12.2

Table 6. Gross Benefit/Cost Ratio for choosing PCC over AC Pavement at 5.5 % Fuel Savings

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