

FUEL COST CONSIDERATIONS REGARDING TRUCK ROLLING RESISTANCE ON DIFFERENT PAVEMENT TYPES

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ABSTRACT

The higher investment cost for Portland cement concrete over asphalt concrete pavements is balanced by lower maintenance costs and a longer technical life. It is also claimed that the truck rolling resistance is lower on concrete pavements. An important actuality as the world continues to grow and emissions must be kept at bay. A number of studies have been made where a truck is driven over different pavement structures and the fuel consumption is carefully measured. They show that the rolling resistance does vary, but it is difficult to assess exactly how much can be attributed to the pavement structure. The present paper deals with assessing pavement hysteresis by evaluating falling weight deflectometer time histories. It was found that the visco-elastic properties of the asphalt had a great influence on the curve. Water present and the subgrade material also affected the curve due to the material damping properties. At a field site, a motorway consisted of asphalt concrete and PCC. The difference in energy losses between the two is significant and can be accounted for when comparing the two materials for life cost analysis purposes. The results support choosing Portland cement concrete for high volume truck roads.

KEY WORDS

CONCRETE ROADS / FWD TIME HISTORIES / ROLLING RESISTANCE /

1 INTRODUCTION

Vehicle costs are important for the optimization of transportation. The well-known Highway Design Manual (HDM) series of programs issued by the World Bank illustrates the fact by having a very detailed input concerning the vehicle fleet. Road roughness affects among other things, the vehicle speed, rider comfort, vehicle wear and accidents. All these can be attributed to costs.

Over the years the magnitude of the vehicle operating costs has fluctuated with the fuel prices. When the price is going up efforts are made to mitigate fuel consumption, and when the price is stabilized for some time more powerful engines are marketed. A more recent view of the costs

comprises carbon dioxide emissions, which were previously ignored. If these are accounted for and with increasing fuel costs it seems like vehicle operating costs are more important than ever. Portland Cement Concrete (PCC) pavements incur higher investments costs than asphalt concrete (AC) ones. The higher cost is balanced by lower maintenance costs and a longer technical life. Sometimes it is also claimed that the truck rolling resistance is lower on concrete pavements and thus carbon dioxide emissions would be reduced too. An important incentive as the world continues to grow and fossil fuel emissions must not increase.

Fuel consumption is depending on acceleration, wind resistance, and rolling resistance. The wind resistance is a function of the vehicle and wind speed. The rolling resistance is depending on the tire friction, internal friction for engine and drive train, plus a component of deforming the surface. The energy is lost as heat as can be seen shortly after a rain shower when pavements are first dry in the wheel tracks.

Much of the losses attributed to rolling resistance are from the tires interacting with the pavement. Lots of research work has been sponsored by the tire industry. Obviously, at times friction is needed to control the vehicle, but coarse macro-texture or tire treads usually demands more fuel. The pavement surface condition affects the fuel consumption also. At a full-scale pavement test facility in Nevada automated trucks on WesTrack demanded 4% less fuel after the track was resurfaced, (Mitchell 2000). The influence of the pavement profile including joints on rolling resistance is rather easy to determine with a truck suspension model, but the losses within the pavement layers and soil are much more difficult to assess. By using a stationary, but dynamic load it is interesting to test the energy attenuation losses in the pavement layers and the soil. On a comparative basis one could see if any pavement type has an advantage over the other. Some preliminary data were used to support the further user and society costs involved.

The economic implications for the society need to consider the investment costs and whether funding is available for the more expensive alternative. In the present paper asphalt and Portland cement concrete is compared using the rolling resistance parameters derived from the field data.

2 COMPARING FUEL CONSUMPTION

In Canada a large study was done on truck fuel consumption on five different pavement surfaces, (Taylor et al. 2001 and Taylor et al. 2006). They included two AC, one PCC and one composite type of pavement. The pavement temperature was cautiously monitored and one conclusion was that it affected the outcome significantly. Note that ambient air temperature also affects fuel consumption but in an opposite manner. The data can be used for estimating the fuel savings for driving on PCC. Tables 1 and 2 show the savings for a 40 ton capacity truck with various loads calculated from the most significant case half-load at 100 km/h

Table 1. Fuel Consumption Savings [cl/km] Asphalt Concrete Type 1 vs. PCC

Speed [km/h]	Empty load	Half load	Full load
100	2.3	3.9	5.4
75	1.7	2.9	4.1
60	1.4	2.3	3.2

Table 2. Fuel Consumption Savings [cl/km] Asphalt Concrete Type 2 vs. PCC

Speed [km/h]	Empty load	Half load	Full load
100	0.9	1.5	2.1
75	0.7	1.1	1.6
60	0.5	0.9	1.3

The data from the Canadian study were collected over a wide range of temperatures and a linear relationship was established. If the temperature was kept within a narrow interval the correlation between the amount of fuel needed and load was significant with a coefficient of determination

near one for asphalt type 1 (yielding more savings) and speeds of 75 and 100 km per hour. The results of this investigation are very near the data shown in Table 1.

By establishing relations for fuel consumption, load, temperature and pavement type the fuel savings for PCC as compared to AC could be established. Higher correlations were derived for asphalt type 1 and the higher speeds. As was reported by Taylor et alia the wind speed and direction may have affected the results. The data from the type 1 AC were extrapolated to a 60 ton truck load and a speed of 80 km/h to be comparable to a test made by the Swedish Transport Research Institute on a site that was subjected to falling weight deflectometer (FWD) tests. The extrapolated data are shown in Table 3 and the VTI data in Table 4.

Table 3. Percent fuel savings based on the Canadian study and 80 km/h and a 60 ton truck load

AC Type	Empty	Half load	Full Load
I	5.9	9.8	13.7
II	2.7	4.4	6.3
Average	4.3	7.1	10.0

Table 4. Mean percent fuel savings based on VTI test at 80 km/h and 60 ton vehicle corrected for wind speed

AC Type	Empty	Half load	Full Load
Test 1	3.9	6.4	9.5
Test 2	2.2	3.6	5.0
Average	3.1	5.2	7.3

Thus, for a 60 ton truck-trailer combination a fuel saving of about 5 – 10 % may be expected. All trucks are not fully loaded. The expected savings for the society are then in the range of 3.5 – 6.5 %. A value of 4 % was further used in the comparison.

3 DYNAMIC TESTING OF PAVEMENTS

In the mid 1990: ies a large correlation study was carried out in Sweden regarding a high-speed Road Deflection Tester, RDT, (Andrén 1999). Well over 100 pavement sections were tested and compared with FWD data. Time histories were sampled so that the effects of truck speed could be assessed. At a dual carriageway test site one direction was constructed as an asphalt concrete pavement and the other direction was a PCC pavement. At the time it was considered interesting to compare the two pavement types as the subgrade, traffic and environment were practically the same. Both sections turned out to have excellent bearing capacity, but the PCC was as expected, much stiffer and did not exhibit temperature related behavior. In the following analysis load-deflection graphs showed less area inside the curve for the PCC plots. The size of the area reflects the energy losses, which however at the time of the study, was of no or little concern. At a later stage, when the alleged more energy efficient behavior of concrete was claimed by the cement industry the present author came to think of this test. Free from difficult fuel measurements or hard to do repeated runs with a truck, it seemed ideal to investigate the pavement contribution to the rolling resistance. A quick check of the historic data showed that there really were too few tests and that the sampling rate was barely adequate for this purpose. It was then decided to do a larger study with more modern equipment.

3.1 *Field test*

A suitable field site was found on European highway 4 about 40 km north of Uppsala, Sweden. The road, a four lane freeway had been in use for about two years on the PCC and one year on the AC pavement part. At the Björklinge interchange, the road pavement type changes from PCC to AC, with only a slight drop in average daily traffic at the interchange. Winters are cold and summers are moderate here; most precipitation occurs in July. Incidentally, the road crosses latitude 60°N right at the test area. The subgrade consisted mostly of glacial till at the test sections, even though the landscape is shifting from old seabed, flat farmland to undulating forest in the area, see Figure 1.

The testing occurred at the evening on 2 September, 2008. This was planned so there would be little bending in the concrete slabs due to temperature gradients. The weather cooperated as most of the day had been overcast with some light rain occurring now and then. The air temperature kept constant at 16°C and the AC pavement temperature was recorded 18°C at two different depths. Thus, no gradients were expected in the pavement. From an evaluation standpoint this was most fortunate as the layers could be treated as homogenous. Another bonus was the fact that the temperature was close to the annual average for the AC pavement. Further, the site also coincided with a fuel consumption measurement test carried out by the Swedish Transport Research Institute a few months earlier, (Hultqvist 2010). In comparison with the vehicle fuel consumption test; note that the present paper deals with dissipation of energy in the pavement. Thus, it is related to truck fuel consumption only. Passenger car differences in fuel consumption are mostly depending on the surface characteristics of the road, which do not affect the FWD testing at all.

Due to traffic management control, all testing was done in the right wheel track in the northbound right lane. A seating load of 50 kN was used, and then three load levels of 36, 51 and 65 kN that were repeated twice for a total of 10 drops per station. Twenty-eight stations were sampled each on the PCC and AC sections respectively.



Figure 1. The FWD at the PCC test site on highway E4.

3.2 *Results of stiffness*

The various layers were backcalculated for stiffness. The PCC stiffness was assumed to be a constant 50 GPa as it otherwise would be difficult to assess the properties of the rather thin asphalt bound base beneath it. A four-layer system was used for the PCC model; for the AC only three

layers were needed. The subgrade and unbound base layer properties were found to be similar for the two cases. Details about the properties can be found in a report by (Lenngren 2009).

3.3 Time histories

As a standard procedure the load pulse is not altered for a single test, only the magnitude of the load is. Thus, the bulk or deviator stress influence on the modulus can be established.

By plotting the load and the deformation a hysteresis curve is formed. For a perfect linear elastic response only a straight line will be projected. For most pavements there will be some damping by the materials and for asphalt there is also a visco-elastic response. A typical reaction from a 50 kN load on an intermediate road on cohesive soils is shown in Figure 2. Seven sensors at different offsets 0 – 120 cm are plotted. Most of the hysteresis seen can be attributed to the damping of the soils. In the figure seven curves are shown with different offsets from the center of the load. D_0 is the deformation in the center of load and comprises deflection in all materials under the load. D_{120} on the other hand is at an offset 120 cm away from the center and it represents the deformation deeper down in the structure. By carefully evaluating the different curves it is possible to derive layer moduli and layer attenuation as well.

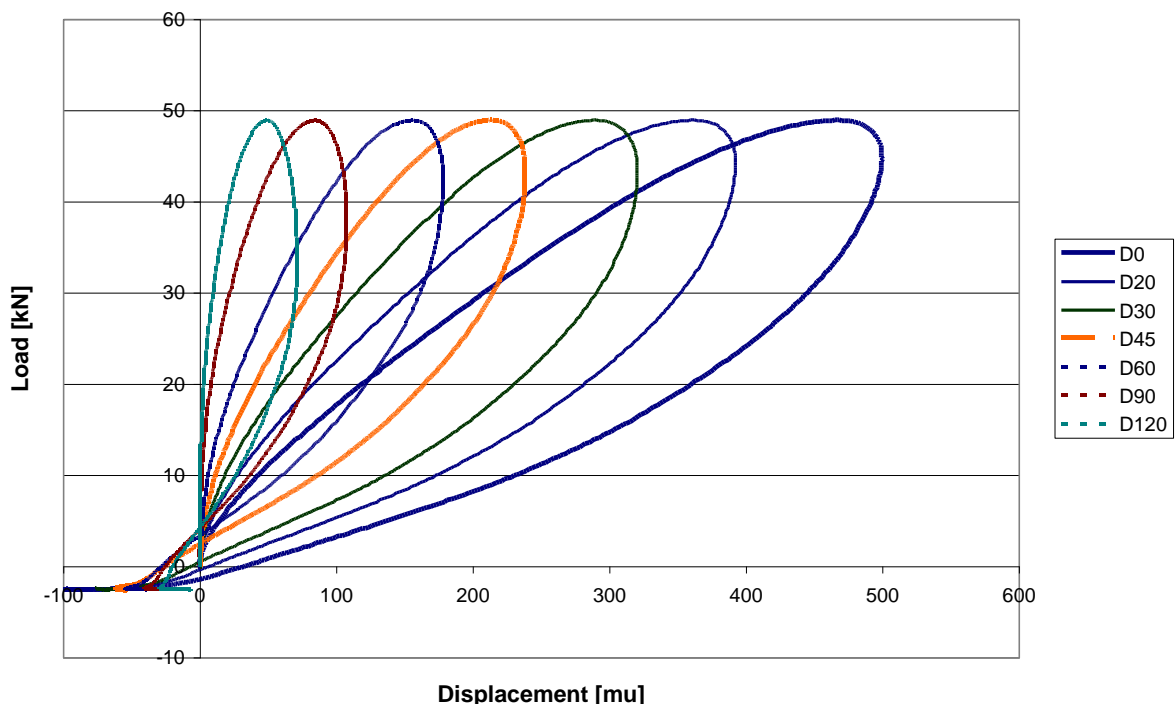


Figure 2. Load-Deflection diagram from an intermediate road. Curves represent different offsets from the center of the load.

3.4 Energy loss estimation, a first attempt

The exact loss of energy to the pavement system is difficult to assess by these measurements. First, there is a rubber plate between the load cell and the pavement that may affect the results. The machine is calibrated with this in mind, but nevertheless it is an uncertainty. Further, the sampling deteriorates with time, so the tail end of the curve has to be managed somehow. During the test procedure, there is slight shift of the load to the support legs that may also influence the results. In the present paper some decisions had to be made about treating the data. They may not be the best way to reflect absolute numbers and they are not validated through experimental setups. However, they represent a first trial. Further discussion of how to best analyze the data from research and instrument manufacturers is appreciated.

A time history evaluation program was written to manage the data, try various different ways of handling the tail data, present the material, and export to spreadsheet programs. As the data were

sampled at 100 ns rate the difference in deformation for each step was small, the area under the curve was estimated by adding the product of load and delta-deformation over a given time span. As the rise time of the machine used is approximately 25 ms, about 50 ms is a good value to start with for a time window. On a road surface there is always some noise going on mostly due to passing traffic. Therefore it is difficult to define the start of a load by just reading the load cell value as it is fluctuating. Instead the curve is defined in time by the instant where the load reaches 5% of the peak load. Then it is up to the analyst to sample from that point or some other preset value. The peak load is depending somewhat to the stiffness of the specimen, so it will in turn affect the start point. However, at this end of the curve it is not that important as any accumulated area is small. It was noticed at the present site that the sampling offset varied a few milliseconds for the reason just mentioned. Handling the tail end is more difficult. First of all, there is a drift in the sensor output. The time it takes for the displacement sensor to reach zero varies depending on the specimen. There is a small shift of the dead weight from the support legs to the loading plate et cetera. For the present case it seemed like the time for the load or any displacement sensor to reach zero varied too much. The sampling window was then kept constant to 60 ms from the start time, approximately 10 ms before the 5% maximum load was reached. A Simpson's rule integration was also tried on these curves in addition to the step approximation. Generally, it yielded a 2% smaller surface as the slope on average for the deflections are in that range, so this was to be expected. However, for some of the lower loads, it seemed as the simple step accumulation was less affected by the tail end effects. In the following the step approximation is used.

4 RESULTS

Figure 2 shows time histories from an intermediate two-lane road AC pavement road. It yielded a hysteresis loss of approximately 8.4 Nm for the standard axle wheel load. This will be approximately 17 J per 10 ton axle, for the 60 ms duration. This corresponds to 280 Watt at continuous operations. If 100 kW is needed for coasting a 40 ton vehicle, a little bit more than one percent or 1 kW can be attributed to the rolling resistance on this type of road, (Taylor et al. 2001 and 2006). Four times 280 Watt is just about 1 kW. Bear in mind though, there are some uncertainties about these values, but it seems that they are fairly close to the experimental data.

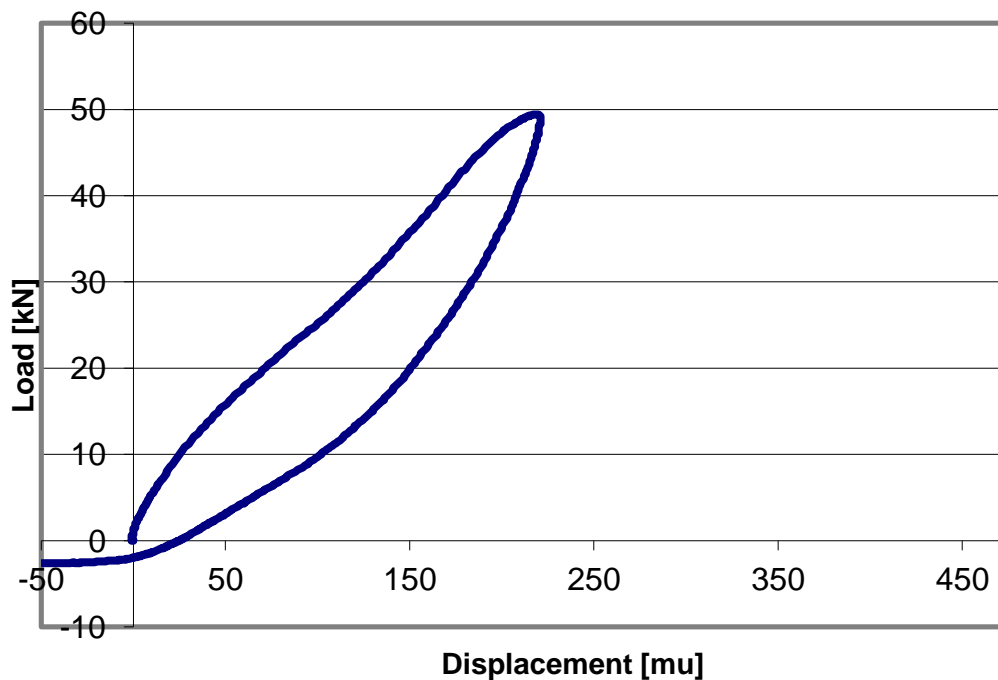


Figure 3. Load displacement diagram. Asphalt Concrete on stiff unbound materials

Figure 3 shows a load-displacement diagram on a typical asphalt concrete motorway. The asphalt layers comprise of 185 mm and the granular layers are well compacted and stiff. So this is the expected attenuation from the asphalt layer or about 4Nm.

Figure 4 shows the PCC response for one of the 50 kN drops being near the average work area of .5 Nm. It is drawn to the same scale as Figure 3 and obviously the stiffness is indeed high as the maximum displacement is a mere fifth of a millimeter. The response is not entirely elastic; the slab is after all resting on a 10 cm thick asphalt layer. Nevertheless, little hysteresis work is excited and thus the pavement response contribution to rolling resistance ought to be just about as low as it can be.

Figure 5 shows a near average 50 kN drop for the asphalt pavement. It too displays a relatively small work area, even though it is four times greater than for the PCC example. The difference is significant. The relative difference on the total rolling resistance is of course smaller as this represents only the pavement contribution. It is obvious that the asphalt road is much better than the intermediate example seen in Figure 2 with a value of about 1 Nm. The concrete road hysteresis is still even better at .5 Nm. It shows that there is indeed a lot of potential to save fuel by choosing a higher quality pavement. Note that the deformation scale in figures 3 - 5 is deliberately set to correspond to the deflection on an intermediate road. Thus, the very good bearing capacity on these roads is demonstrated.

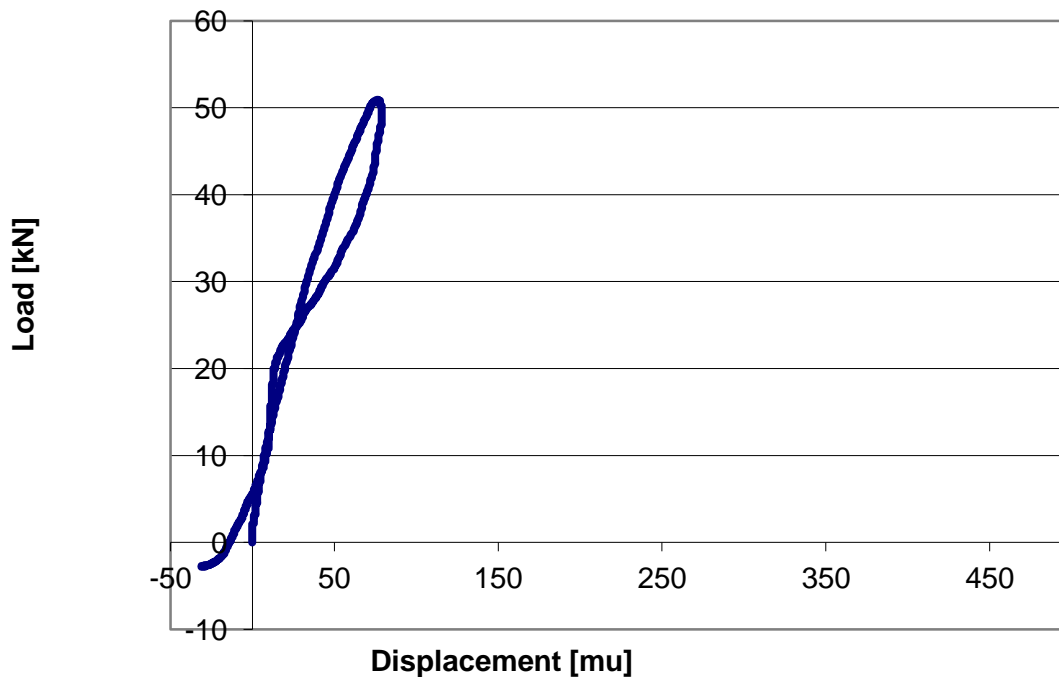


Figure 4. PCC Load displacement diagram. Do area is .423 Nm.

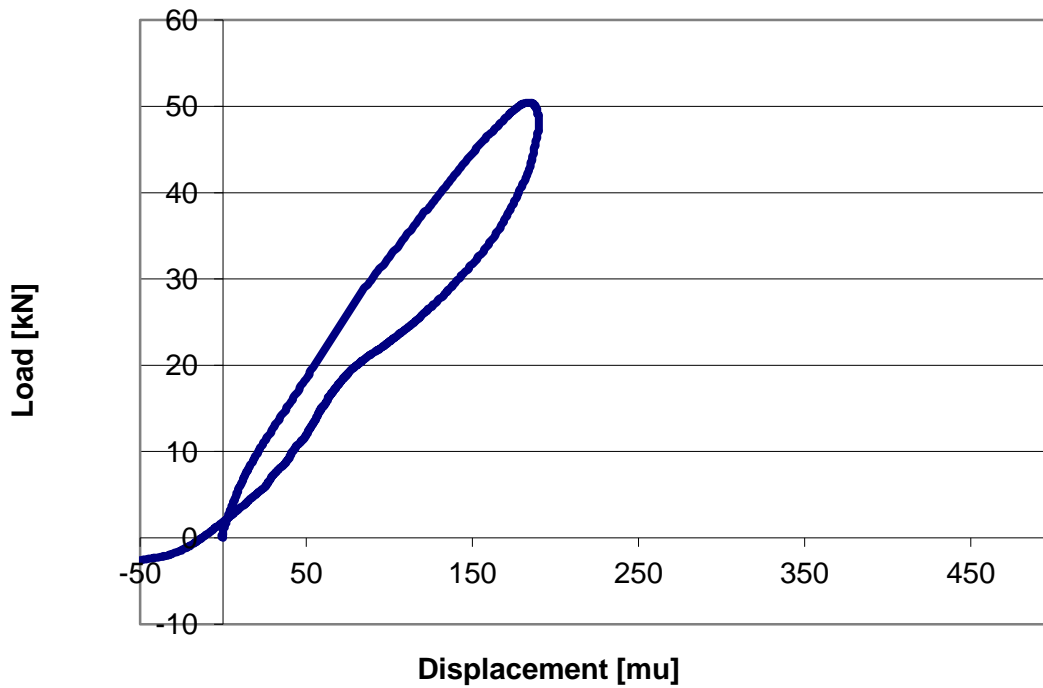


Figure 5 AC pavement Load-Displacement diagram. Do area is 2.2 Nm.

5 CONSEQUENCES OF CHOOSING PAVEMENT TYPE

At the Björklinge field site, the Swedish Transport Research Laboratory also carried out tests on fuel consumption for passenger cars. (Results will be published after the present paper is written). A difference in fuel consumption was found here as well, much due to the surface texture. In reality this means that the difference in fuel consumption for trucks is even greater and in compliance with the Canadian study. A 60 ton truck-trailer combination was tested at two occasions at a constant driving speed of 80 km an hour or about 22 meter per second. The data were corrected for wind speed. The fuel savings on the PCC versus the AC pavement was 21 and 37 milliliters per kilometer respectively. This corresponds to 5.0 and 9.5 % of the total consumption. Thus, the savings at the site could be expected to be within the range of 5 – 10%. The test data with the FWD support this finding.

In the aforementioned Canadian study the strongest correlation between temperature and fuel consumption was found for a speed of 100 km/h and half loaded vehicles. As the example is fairly common further calculations comparing AC and PCC pavements were carried out in the present study. As the air temperature has a very strong influence on the fuel consumption it is difficult to discern any direct effects of pavement temperature and rolling resistance. From theory we know that the visco-elastic nature of asphalt concrete should be affected by temperature to a large degree, but it is not conclusive from this study. An average difference between pavement types is tabulated below. Note that this may include secondary effects like volume earth affected by the load. Pavement surface texture is contributing as well.

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

$$\Delta S/\Delta I \geq \Lambda \quad (1)$$

and

$$\Delta S/\Delta I = (S_A - S_B) / (I_B - I_A) \quad (2)$$

Where:

S_A is the Gross Present Value of Asphalt Concrete Investment

- S_B is the Gross Present Value of PCC Investment
- I_A is the Asphalt Concrete Investment costs
- I_B is the PCC Investment costs
- Λ is the shadow price for the investment

$\Delta S/\Delta I$ 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.

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

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

	ADT		
Truck rate	12000	15500	20000
14%	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

The combination where the GBCR is above 3 is shaded green and for those situations the PCC pavement is viable.

6 CONCLUSIONS

Truck rolling resistance comprises a number of different components from internal friction to pavement-tire interaction. Field studies have shown a measureable difference between pavement types, but with inconclusive results. Test must be done bi-directionally, but the wind speed may not be constant. Further the temperature affects the results in many ways. Fuel consumption is affected, but the visco-elasticity of asphalt pavements does so in an opposite manner.

An estimate from drive tests indicates that at least a third of the rolling resistance can be attributed to the pavement, maybe more so on smaller roads. For AC pavements higher values can be expected at hot weather and lower ones at cold temperatures. Truck fuel consumption is also depending on the temperature, but usually more fuel is needed at lower temperatures for other purposes. So this is why it is difficult to discern differences through drive tests. Further, surface friction, joints and roughness all affect the drive test results as well. A thorough analysis of FWD

time history data can contribute to the understanding of pavement hysteresis and how much it contributes to rolling resistance.

In the present test the PCC pavement exhibited about four times lower work loss as AC pavements at the mean annual average temperature. Other tests show that thick asphalt pavements have high hysteresis at hot temperatures. By theory they should also be less sensitive at lower temperatures. More field testing could confirm this assumption.

For thin pavements quite large losses occur in the soil and unbound materials. Poorly compacted materials mean large losses. Other, highly compacted friction material exhibited an almost linear elastic response and thus very losses were kept low. Thus, extra efforts like extended compaction during the construction of roads could be worthwhile if these measures are included in life cycle cost analyses.

The pavement does contribute significantly to truck rolling resistance and this should be factored in when choosing pavement type. The FWD can be used for environmentally proofing selected highways. The FWD seems to be viable for this purpose. However, there are a few uncertainties of how to treat the tail end of the time history curve. Some studies need to be done on calibration and the test method.

The Gross Benefit/Cost Ratio should be about three or more to justify a higher investment cost for PCC pavements. With a fuel savings of 4 % and with a truck rate of 14 % this occurs for ADT volumes of little more than 12000 vehicles. Thus, for most high volumes roads and motorways a PCC pavement type is indeed justified.

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