

Pavement Life Cycle Cost Analysis Based on Hysteresis Data and Analysis of Fuel Consumption Measurements

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Abstract

Higher investment costs for Portland cement concrete over asphalt concrete pavements is compensated by lower maintenance costs and a longer technical life. For sustainability reasons the less rolling resistance on the former pavement type is claimed to be another benefit. However, methods of measuring fuel consumption are difficult to carry out in a consistent manner. The present paper examines some fuel measurements and then uses the hysteresis method as a validation for some of the tests. The data are then used to determine the economical implications and life cycle cost analysis. The results support choosing Portland Cement Concrete for roads with high volume truck traffic.

Introduction

Vehicle operating 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 often 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 the carbon foot print would be reduced too. An important incentive as the world transportation 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

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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, as such a test is not affected surface characteristics. 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.

Research Significance

The present paper addresses the pavement contribution to rolling resistance for pavements from an economical point of view. It is important to include the total carbon footprint, which is essential for assessing the sustainability of various pavement types.

Comparing Fuel Consumption

Stationary tests. Through measurements by a falling weight deflectometer made by the former National Swedish Road Administration on Road E4.65 near Stockholm Arlanda Airport, [Andrén, 1999] and measurements of the relationship between the fuel consumption and the rolling resistance of the tires made by the company Continental, [Reference]. It has been possible to estimate the fuel saving for a 40 ton heavy truck driving on a PCC road compared to an AC road at the speed of 80 km/h. The resulting curves reflecting hysteresis due to visco-elasticity and damping in pavement materials can be seen in Figure 1.

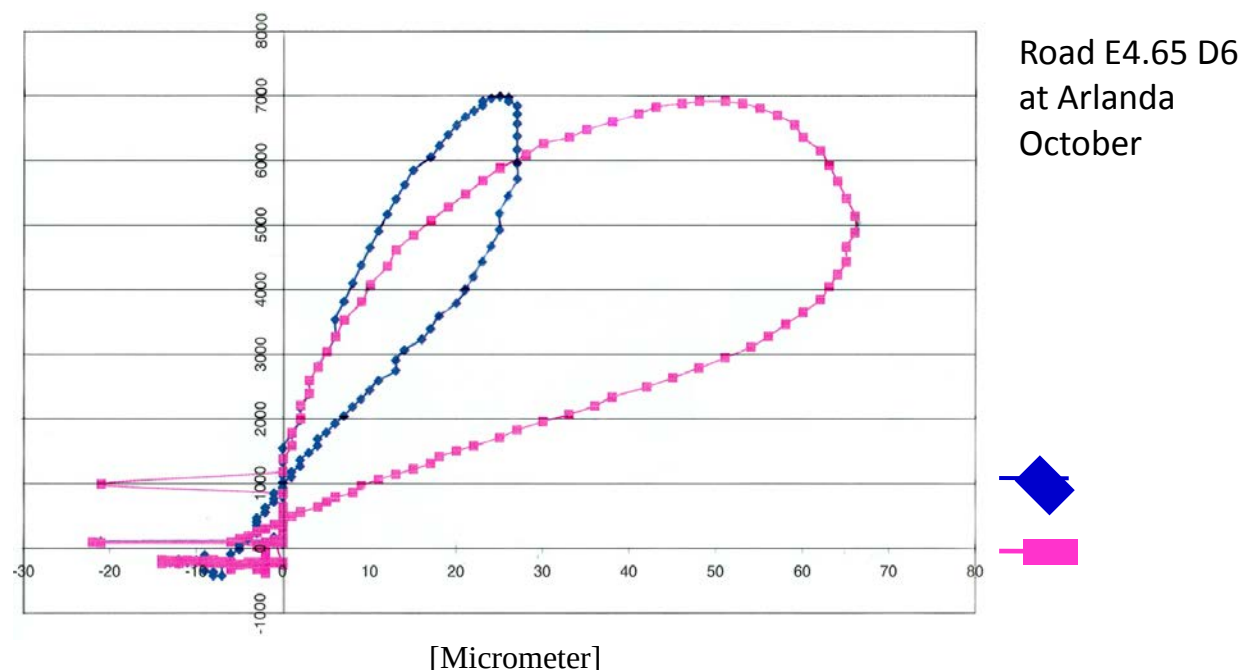


Figure 1. Deflection-load diagram from two parallel pavement types on the same type of subgrade. Load unit is kilogram force.

The relation between the areas within the respective curves for PCC and AC is in this case .42. This means that the loss of energy due to the road type for the PCC is 42 % of the AC road at the time of the measurement. As these took place at night at

rather low temperatures even more dissipation could be expected in the AC pavement during the day at higher temperatures. Conversely, upward curling of the PCC slabs would also increase the attenuation in the morning hours.

Speed dependencies. 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 is illustrated by Figure 2. For the same type truck the relation between all the resistances can then according to Aerodynamics for trucks be illustrated as in Figure 3.

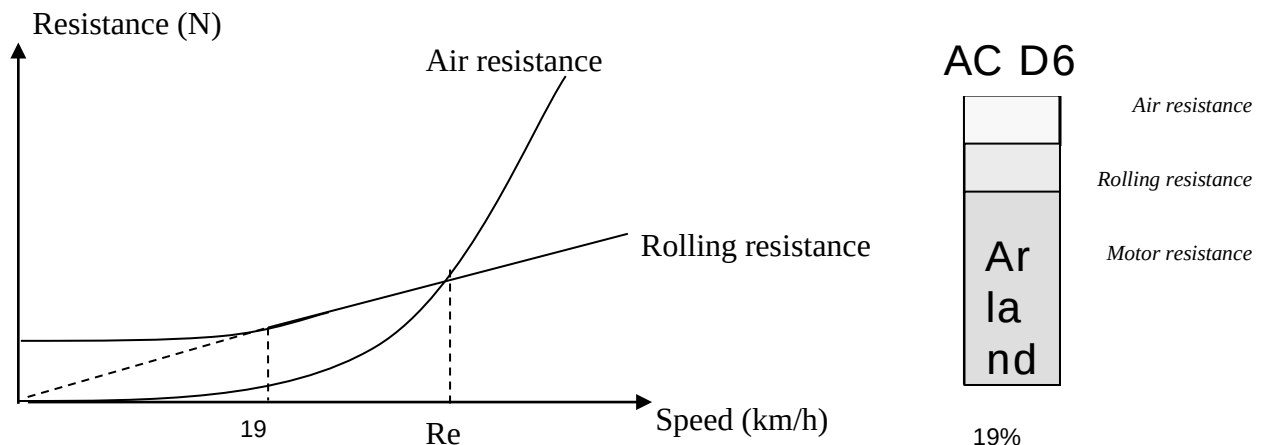


Figure 2

According to the same essay the fuel consumption will then be 3.562 l/10 km (diesel). Thus, the rolling resistance consumption part is $.19 \times 3.562 = .677$ l/10 km. If you suppose that x % of the rolling resistance depends on the compression of the tires you will then get

$$.08 \times X \times .677/100 = .016$$

$$X \approx 30\%$$

The fuel saving by going from AC to PCC will then be
 $(1.00 - 0.42) \times (1.00 - 0.30) \times 100 = 7.7\%$

For a 60 ton heavy truck the fuel saving will then be
 $60 \times 7.7/40 = 11.6\% \approx 12\%$

Canadian field testing. 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). In this study fuel savings driving trucks on PCC pavements over AC pavements were concluded to be in the range of 0.9 to 6.9 percent.

As the fuel consumption is to a large degree dependent on the ambient temperature most of the measurements have been carried out with carefully monitored pavement temperatures. After these linear relationships were established between temperature and fuel consumption for a fully loaded truck, a half loaded truck and an empty truck, at the speeds 100 km/h, 75 km/h and 60 km/h. See Figure 4.

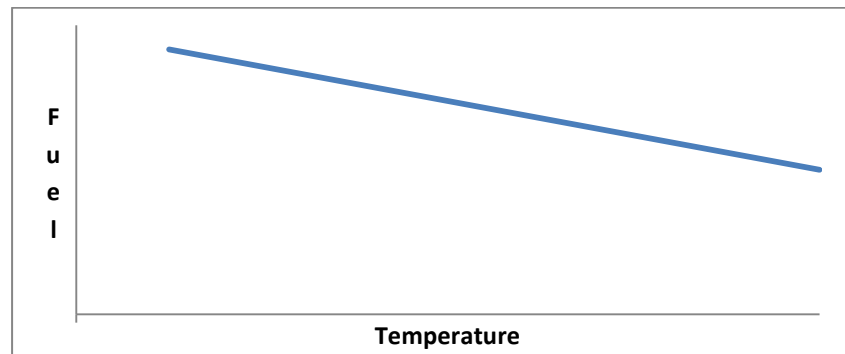


Figure 4. Fuel Consumption as a function of Temperature (Schematic)

Since the degree of significance varies a lot the present author chose the most significant case, (half load and 100 km/h). In this case a coefficient of determination (R^2) of 1.00 and .90 was determined for AC types 1 and 2 respectively. If the speed is constant the saving of fuel consumption by driving on PCC instead of on AC depends only on the difference in rolling resistance and truck load. This means that the saving of fuel consumption can be calculated with the help of the following Figure 5:

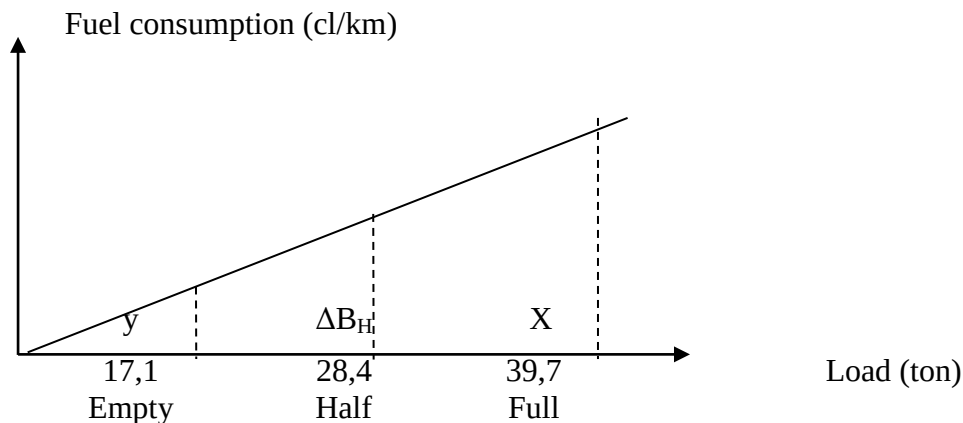


Figure 5

Where:

ΔBH = The saving of the fuel consumption by driving on PCC instead of on AC at half load and the speed 100 km/h

X = The saving of the fuel consumption by driving on PCC instead of on AC at full load and the speed 100 km/h.

Y = The saving of the fuel consumption by driving on PCC instead of on AC at full load at the speed 100 km/h.

$$\text{Then } X/39.7 = Y/17.1 = \Delta BH / 28.4$$

$$X = 1.379 * \Delta BH$$

$$Y = .6071 * \Delta BH$$

The results are shown in Table 1 below:

Table 1. Comparison AC type 1 and PCC of measured and calculated savings, (cl/km)

Load	Measured savings	Calculated savings @100km/h	Calculated savings @75km/h	Calculated savings @60km/h
Full	5.8	5.4	4.05	3.2
Half	3.85	3.85	2.8	2.3
Empty	1.7	2.3	1.7	1.4

For AC Type 2 $\Delta BH = 1,5$ cl/km yields the following result.

$$X = 1.379 * 1.5 = 2.1 \text{ cl/km}$$

$$X = .6021 * 1.5 = .90 \text{ cl/km}$$

The results for AC Type2 vs. PCC are shown in Table 2 below.

Table 2. Comparison AC type 2 and PCC of measured and calculated savings @ 100 km/h

Load	Measured savings [cl/km]	Calculated savings [cl/km]
Full	1.8	2.1
Half	1.5	1.5
Empty	.2	.9

The measured savings are in accordance with the calculated savings. Since the rolling resistance is directly proportional to the speed you get the fuel consumption savings for the speeds 75 km/h and 60 km/h by multiplying the savings in Table 1 with 0.75 and 0.60. The measured results at these speeds were not consistent for half the cases. All cases considered, for 2/3 of the tests the measured savings were in accordance with the calculated savings. In the other cases the results were not consistent with the theory. The plausible explanation is that the effect of the wind was ignored. Each measurement was made within a narrow temperature interval, so that the effect of temperature could be determined. Then 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 6:

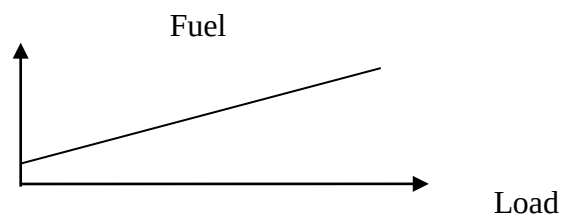


Figure 6. A linear relationship was established between load and consumption

For an AC type pavement the following relationships were established with Y = The fuel consumption (cl/km) and X = The load (ton).

$$\text{At the speed 100 km/h : } Y = .4027X + 30.441 \quad R^2 = 1.00$$

$$\text{At the speed 75 km/h : } Y = .2983X + 25.446 \quad R^2 = .99$$

$$\text{At the speed 60 km/h : } Y = .3251X + 19.303 \quad R^2 = .97$$

Similarly for PCC pavements the following relationships:

$$\text{At the speed 100 km/h : } Y = .2168X + 30.551 \quad R^2 = .94$$

$$\text{At the speed 75 km/h : } Y = .2470 + 24.885 \quad R^2 = .88$$

$$\text{At the speed 60 km/h : } Y = .2787X + 19.104 \quad R^2 = .95$$

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:

$$K_{AC} = \frac{(.4027 + .2983 + .3251)}{3} = .3420$$

For PCC the mean slope K_{PCC} is:

$$K_{PCC} = \frac{(.2108 + .2470 + .2787)}{3} = .2475$$

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

$$RR_{PCC}/RR_{AC} = .2475/.3420 = .72$$

According to the falling weight analysis the relation is :

$$RR_{PCC}/RR_{AC} = .6$$

The latter does not reflect the effects of texture, megatexture and roughness.

The most significant relations were derived for AC at the speeds 100 km/h ($R^2 = 1.00$) and 75 km/h ($R^2 = .99$). Since the rolling resistance is proportional to the speed for every type of pavement the relations between the slopes are equal to the relations between the speeds. By using the two most significant cases (AC at the speed 100 km/h and 75 km/h) the lower speed can be extrapolated for the AC. The PCC equations are then assumed to have the overall ratio of .72 to the AC. The new adjusted equations will then be:

For the asphalt concrete pavement:

$$\text{At the speed 100 km/h: } Y = .4072X + 30.44$$

$$\text{At the speed 75 km/h: } Y = .2983X + 25.45$$

$$\text{At the speed 60 km/h: } Y = .2146X + 19.30$$

For Portland cement concrete pavement:

At the speed 100 km/h: $Y = .2931X + 30.44$

At the speed 75 km/h: $Y = .2983X + 25.45$

At the speed 60 km/h: $Y = .1739X + 19.30$

According to these equations driving on PCC rather than AC renders less fuel consumption $\Delta B(X)$ (cl/km) :

At the speed 100 km/h $\Delta B(X) = .1184X$

At the speed 75 km/h $\Delta B(X) = .0877X$

At the speed 60 km/h $\Delta B(X) = .0710X$

Table 3. Calculated savings (cl/km) for most significant cases and different speeds

Speed	Empty Load	Half Load	Full Load
100 km/h	2.0	3.2	4.7
75 km/h	1.5	2.5	3.5
60 km/h	1.2	2.0	2.8

The calculated savings in Table 3 are indeed in accordance with the calculated savings in Table 1.

Swedish Transport Research Institute Field Study.

On two different occasions the Swedish Transport Research Institute (VTI) measured the fuel consumption with a 60 ton Scania truck and trailer combination, Hultquist (2010). The tests took place on PCC and AC pavement types on a road where the subgrade condition did not vary much. The pavement layer thicknesses for the respective types are listed in Tables 4 and 5. The design life is 40 years for all layers, except the AC materials which are 20 years.

Table 4. Pavement layer thicknesses and Moduli for the PCC pavement

Layer	Thickness [mm]	Modulus [Mpa]
PCC (Fixed)	200	50000
Asphalt Base	100	10000
Unbound layers	780	180
Subgrade	Semi-infinite	370

Table 5. Pavement layer thicknesses and Moduli for the AC pavement

Layer	Thickness [mm]	Modulus [Mpa]
Asphalt layers	170	12200
Unbound layers	1080	240
Subgrade	Semi-infinite	375

The 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 adjusted for wind speed. The fuel savings on the PCC versus the AC pavement was 44 and 52 milliliters per kilometer respectively. This corresponds to 10.9 and 12.2 % of the total consumption. Thus, the savings at the site could be expected to be within the range of 10-13 %. However, in reality many trucks carry less loads, so the average savings

should be in the range from 3.5 – 6.5 %. In reality this means that the difference in fuel consumption for trucks is even greater and in compliance with the Canadian study. Note that for this heavy load, much of the rolling resistance is likely to occur in the tires. As regarding the pavement type, the effect is very much depending on the unbound layers and the soil as higher loads deform a much larger volume of soils.

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:

$$\frac{\Delta S}{\Delta I} = \frac{(S_{AC} - S_{PCC})}{(I_{PCC} - I_{AC})} > \Lambda \quad (1)$$

Where:

S_{AC}	is the Present Value of Asphalt Concrete Agency and User Costs
S_{PCC}	is the Present Value of PCC Agency and User Costs
I_{AC}	is the Asphalt Concrete Investment costs
I_{PCC}	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). ΔS comprises about 40% for the truck fuel savings and 55 % less agency maintenance costs. 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 6 and 7 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, mentioned above as a realistic value for the average truck load. The combination where the GBCR is above 3 is shaded green and for those situations the PCC pavement is viable over the asphalt type.

Table 6. Gross Benefit/Cost Ratio for choosing PCC over AC Pavement at 4 % Fuel Savings

	AADT		
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

AADT means average of the number of vehicles per day

Table 7. Gross Benefit/Cost Ratio for choosing PCC over AC Pavement at 5.5 % Fuel Savings

	AADT		
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

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 during the test.

The fuel consumption tests in Canada found that the influence of temperature was the most significant parameter. As the temperature varies and could not be controlled, the data were arranged into narrow ranges to better compare pavement types. In such cases the gain (less consumption) per km for a 40 ton truck on a concrete pavement is 14 to 54 milliliters. The highest value is for a fully loaded truck going at 100 km/h.

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 thick 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 such as climate control. 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.

The pavement does contribute significantly to truck rolling resistance and this should be factored in when choosing pavement type. The FWD seems to be viable for this purpose and could be used for environmentally proofing selected highways.

The Gross Benefit/Cost Ratio should be about three or higher 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 AADT 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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