TECHBRIEF

Since 1998, FHWA and the American Association of State Highway and Transportation Officials, the latter through the National Cooperative Highway Research Program (NCHRP), have been jointly financing and overseeing several major pavement technology studies and programs. The immediate aims of the joint effort are the successful completion of the Superpave and Long-Term Pavement Performance research programs initiated under the national Strategic Highway Research Program a decade ago. The long-term goal of both organizations is the development, delivery, and utilization of a broad spectrum of improved technologies that will lead to better-performing and more cost-effective pavements.

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WesTrack Track Roughness, Fuel Consumption, and Maintenance Costs

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Introduction

Accelerated pavement testing facilities are designed to investigate performance of pavement materials and structural designs. They also offer the opportunity to collect, under controlled conditions, vehicle operation data for the trucks used to apply the loading. The loading recently completed at one such track, the WesTrack facility in Nevada, has provided significant data on truck fuel and maintenance costs as a function of pavement smoothness.

WesTrack is an accelerated pavement test facility constructed in Nevada in 1995 for the Federal Highway Administration (FHWA); the FHWA study is currently being completed as National Cooperative Highway Research Program (NCHRP) Project 9-20. The primary objectives of WesTrack are to continue the development of performance-related specifications (PRS) for hot-mix asphalt pavement construction and to provide an early validation of Superpave mixture design procedures. Please see the interim reports and articles listed in "References" for detailed descriptions of the WesTrack project[1] and driverless vehicle integration,[2] as well as interim findings.[3]

Four driverless trucks were used at WesTrack to allow safe vehicle operation in the repetitive and monotonous pavement-loading environment. Over 2½ years, the driverless trucks (figure 1) traveled more than 1.3 million km (820,000 mi) and applied some 4.9 million 80-kN (18,000-lb) Equivalent Single Axle Loads (ESAL's). Throughout the loading period, data were collected on a large number of vehicle parameters, including fuel consumption. Detailed maintenance records were kept.

During the 2½-year loading period, pavement sections located on the track's tangents developed varying amounts of roughness, rutting, and/or fatigue cracking. Some sections eventually required major rehabilitation. The last rehabilitation of WesTrack was conducted in March 1998. Prior to that rehabilitation, the track was in a very rough condition due to fatigue failures of various test sections and deterioration of patched areas (patches had been placed after core and slab sampling). The vehicle and pavement data taken before and after the rehabilitation were used to project the impact of pavement roughness on vehicle operating costs.

Pavement Roughness and Its Effects on the Vehicles

The distinct differences in pavement roughness just before and just after rehabilitation presented a unique opportunity to investigate the effects of pavement roughness on fuel consumption, unscheduled maintenance, and other aspects of vehicle health. To assess the effect of pavement roughness on fuel consumption rate and vehicle health, the relevant data were examined for periods of 8 weeks just before rehabilitation and 7 weeks just after rehabilitation.

The high pavement roughness measured before rehabilitation resulted from fatigue cracking and, more significantly, from deterioration of previously patched areas. Figure 2 shows representative visible cracking (highlighted with white paint) in the fatigued pavement before rehabilitation. The fatigued sections were milled down 100 mm (4 in) and resurfaced in March 1998. In addition, most of the patches from previous core and slab removal areas were milled to a depth of 100 mm (4 in) and repatched.

Figure 1. WesTrack Driverless Vehicles (Gross Vehicle Weight 670 kN [152,000 lb])

International Roughness Index (IRI) values were established for the tangents of the oval track before and after rehabilitation. The data showed that rehabilitation reduced average IRI in the tangents by at least 10 percent. To show the importance of this IRI difference, the track's rolling resistance was estimated using a coastdown test (SAE J1263).[4] This test measures the distance covered by a vehicle while slowing from 32 to 8 km/h (20 to 5 mi/h)—the higher the rolling resistance, the shorter the distance covered during the coastdown. Prior to rehabilitation, the inside (service) lane of the track tangents was relatively smooth compared to the outside (test) lane. It was assumed that the difference in rolling resistance between the two lanes could be used as an estimator of the impact of the difference in their smoothnesses.

The coastdown test was conducted using a 160-kN (35,900-lb) tractor semi-trailer. This limited observation showed that test lane rolling resistance was 3 percent higher than that of the service lane. Such a difference would be expected to significantly affect fuel consumption.

Figure 2. Example of Pavement Roughness in Fatigued Test Sections

Fuel Economy and Pavement Roughness

The power a truck requires at a given time is a function of its speed and weight, tire/road surface interaction, aerodynamic drag, and grade. Power requirements fall into three categories—overcoming (1) wheel rolling resistance, (2) air drag, and (3) pavement grade. Rolling resistance, in turn, is the sum of all resistance impeding the free rolling of the vehicle. The power required to overcome rolling resistance includes the power required to overcome irregularities in the pavement, the flexing of tires, the deformation of the road surface, and friction, each of which may depend on the vehicle's gross weight and/or speed. Given that the vehicles' gross weight, speed, and aerodynamic profile were fixed and that the vehicles used were very well maintained throughout the WesTrack experiment, increases in fuel consumption noted on vehicle performance/health monitoring computers could be directly attributed to increased pavement roughness. In other words, deterioration of the track led to increased motion resistance to the trucks.

To validate the effect of pavement quality changes on fuel economy, data from two identical WesTrack vehicles, WT-3 and WT-4, were examined for periods just before and after the March 1998 rehabilitation. The fuel rate, fuel temperature, engine torque, and engine speed from the Detroit Diesel Electronic Control (DDEC) units were analyzed, as were other vehicle parameter data. The WesTrack computers recorded vehicle data twice per second while the trucks operated. Fuel use data from the daily inspections and refueling of the WesTrack trucks were also analyzed.

The average fuel mileage over an 8-week period before rehabilitation was 1.79 km/l (4.2 mi/gal) for the 2 trucks. After rehabilitation, average fuel mileage over a 7-week period was 1.87 km/l (4.4 mi/gal). This indicates a 4.5 percent improvement in fuel economy as a direct result of the improvement in pavement roughness after rehabilitation.

Table 1 is a summary of environmental and engine parameter data for the periods just before and just after rehabilitation. The average engine torque was 913 N-m (674 ft-lb) before rehabilitation and 881 N-m (650 ft-lb) after. The average engine speed was 1,456 rev/min. This corresponds to calculated powers of 139 kW and 134 kW (187 and 180 hp) before and after rehabilitation, respectively. Other environmental influences on fuel consumption were also evaluated. Temperature effects were compensated for within this calculation—average air temperatures were lower for vehicle operation before rehabilitation than for after. Average wind speeds for the periods before and after the rehabilitation were 5.6 km/h (3.5 mi/h) and 7.9 km/h (4.9 mi/h), respectively, with consistent average wind direction (table 1). Given the oval track design (trucks traveled both with and against the wind during each circuit of the track), wind effects were at least partly negated. Because the average wind speed was higher after rehabilitation than before, the reported improvement in fuel consumption may actually be less than it would have been if the wind speeds did not differ. Overall, the improvement in fuel consumption would have been slightly greater than 4.5 percent if it were possible to eliminate all environmental effects—*i.e.*, if wind speed, temperature, etc., were the same before and after rehabilitation.

If the fuel consumption changes noted at WesTrack were extrapolated to a fleet operation of 1,600,000 vehicle-km (1,000,000 vehicle-miles), the savings would be 46,600 l (10,260 gal) of fuel as a result of operating on smooth pavement rather than rough. From both a fleet operator's perspective and an environmental protection standpoint, these savings are substantial.

Maintenance Costs

The increase in pavement roughness also increased the frequency of fatigue failures in the truck and trailer components. For example, trailer frames began to fracture (four occurrences) and required reinforcing welds during the time just before pavement rehabilitation. Steering motors and other components loosened more frequently. Figure 3 shows the number of trailer spring failures (the 4 trucks' trailers have a total of

Table 1. Summary of Environmental and Engine Parameter Data Before and After Rehabilitation

	Before Rehabilitation 1/5/98-3/1/98		**After Rehabilitation 3/13/98-5/6/98**	
Number of Kilometers	38,970		48,942	
Environmental	**Avg**	**St Dev**	**Avg**	**St Dev**
Ambient Temperature (°C)	2.3	5.2	6.5	5.6
Maximum Relative Humidity (%)	75.8	20.7	64.8	22.4
Minimum Relative Humidity (%)	66.8	22.2	54.3	22.0
Wind Speed (km/h)	5.6	5.5	7.9	6.1
Engine Parameters				
Fuel Rate (liters/h)	32.2	4.5	31.0	4.2
Output Torque (N-m)	913.1	138.8	881.1	131.5
Engine (rev/min)	1,456.1	6.4	1,455.8	5.6
Engine Load (%)	51.6	6.5	50.0	6.2
Throttle (%)	59.4	4.2	58.4	4.0
Fuel Temperature (°C)	35.6	0.8	40.2	0.6
Calculated Power (kW)	139.3	21.2	134.4	20.1

Notes: 1 mi = 1.6 km; 1°F = 1.8°C+32; 1 mi/h = 1.6 km/h; 1 gal/h = 0.22 l/h; 1 ft-lb = 0.738 N-m; 1 hp = 1.34 kW

40 springs) per million ESAL's during different trafficking periods. During the 2½-year track loading, 8 of 17 spring failures occurred within 2 months prior to the March 1998 track rehabilitation, resulting in the large increase in the rate of spring failures. In contrast to the 8 failures generated during the application of 265,000 ESAL's to the track in the 8 weeks before rehabilitation, the 350,000 ESAL's applied in the 7 weeks after rehabilitation resulted in only 1 spring failure.

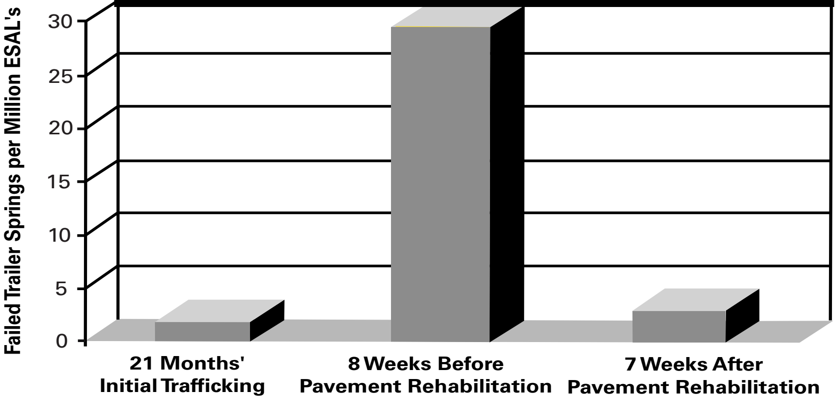
Fatigue and exposure to varying degrees of stress over their lifetimes certainly contributed to the spring failures. Nevertheless, the low number of spring failures observed after rehabilitation is an indicator of severe loading of the trucks by the rough pavement just before rehabilitation.

Key Findings

- An increase in pavement roughness increased the fuel consumption of trucks applying loads to WesTrack pavement test sections. Under otherwise identical conditions, trucks used 4.5 percent less fuel/km on smooth (post-rehabilitation) pavement than on rough (prerehabilitation) pavement.

- An increase in pavement roughness increased the frequency of fatigue failures of truck and trailer components during the WesTrack loading.

Figure 3. Effect of Pavement Condition on Truck Health



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Key Words: Asphalt concrete pavement, pavement roughness, truck fuel consumption, truck maintenance costs.

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