

Organizational Results Research Report

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Pavement Smoothness and Fuel Efficiency:

An Analysis of the Economic Dimensions of the Missouri Smooth Road Initiative

Prepared by
Missouri Department
of Transportation

FINAL REPORT

OR07-005

Pavement Smoothness and Fuel Efficiency:
*An Analysis of the Economic Dimensions of the
Missouri Smooth Road Initiative*

Prepared for the
Missouri Department of Transportation
Organizational Results

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The opinions, findings, and conclusions expressed in this publication are those of the principal investigators and the Missouri Department of Transportation. They are not necessarily those of the U.S. Department of Transportation, Federal Highway Administration. This report does not constitute a standard or regulation.

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16. Abstract This study investigated the affect of pavement smoothness on fuel efficiency, specifically examining the miles per gallon in fuel savings for smooth versus rough pavement. The study found a 53% improvement in smoothness which resulted in over 2.4% improvement in miles per gallon. Vehicles used for the study were 2006, Navistar equipped, tandem dump trucks.			
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Executive Summary

This study investigated the effect of pavement smoothness on fuel efficiency, specifically examining the miles per gallon in fuel savings for smooth versus rough pavement. The study found a 53% improvement in smoothness which resulted in a 2.46% improvement in miles per gallon. MoDOT was interested in a study of fuel efficiency related to pavement smoothness for three reasons:

1. Missouri was constructing the Smooth Road Initiative (SRI), a plan to provide 2,200 miles of smoother pavement, brighter road markings, and other safety improvements in three years. The initiative is the first part of a three-part plan to use Amendment 3 funds to improve the state's highway system.
2. From other studies, there is reason to believe that smoother roads improve fuel efficiency.
3. MoDOT wants to provide good information to stakeholders and customers on behalf of better transportation.

Previous research has related fuel savings to smoother pavement, although the reports had significant variations in results and conditions. This study was set up to test real world conditions in Missouri and compared fuel efficiencies before and after pavement resurfacing. MoDOT staff drove four dump trucks on a 22-mile loop of I-70 in Lafayette County east of Odessa, Missouri. Before resurfacing each truck was driven more than 50 hours and more than 2,000 miles on the test loop at a target speed of 60 miles per hour. This was repeated after resurfacing.



Figure 1, Before and After Roadway.

“Before” paving loops were driven in May, while the “after” paving loops were driven in September and October. The same drivers were used before and after. Dump trucks carried a pair of concrete barriers to provide a loaded condition. Great care was taken to assure that the trucks were in similar conditions for all loops to avoid changes such as air pressure in the tires.

All four trucks were new tandem-axle, diesel dump trucks. Two trucks had automatic transmissions and two had manual transmissions. MoDOT had the unique opportunity of using the latest technology with the dump trucks, by installing International Navistar's AWARE system on them. The AWARE system is an onboard monitoring system that automatically downloads vehicle performance information, including miles of travel and fuel consumption. The system also includes an emergency button that makes the vehicle locatable by GPS. Fortunately this feature was not needed during this study, but could be highly useful in emergencies.

Pavement smoothness was measured with the Automated Road Analyzer (ARAN van). The average International Roughness Index (IRI) before paving was considered to be moderately rough at 130.23. After overlay placement, the pavement IRI was smooth at 60.99. This represents more than a 53% improvement in smoothness.

Before paving, the diesel dump trucks averaged 5.97 miles per gallon. After paving they averaged 6.11 mpg. This 0.14-mpg improvement represents more than 2.4% mpg savings. The gasoline powered SUV averaged 21.30 mpg before and 21.47 mpg after, another 0.17 mpg improvement or slightly less than 1% savings. While these numbers are small per vehicle, with all the vehicle miles driven on the smoother roads of the SRI, these savings represents millions of gallons of fuel saved, per year.

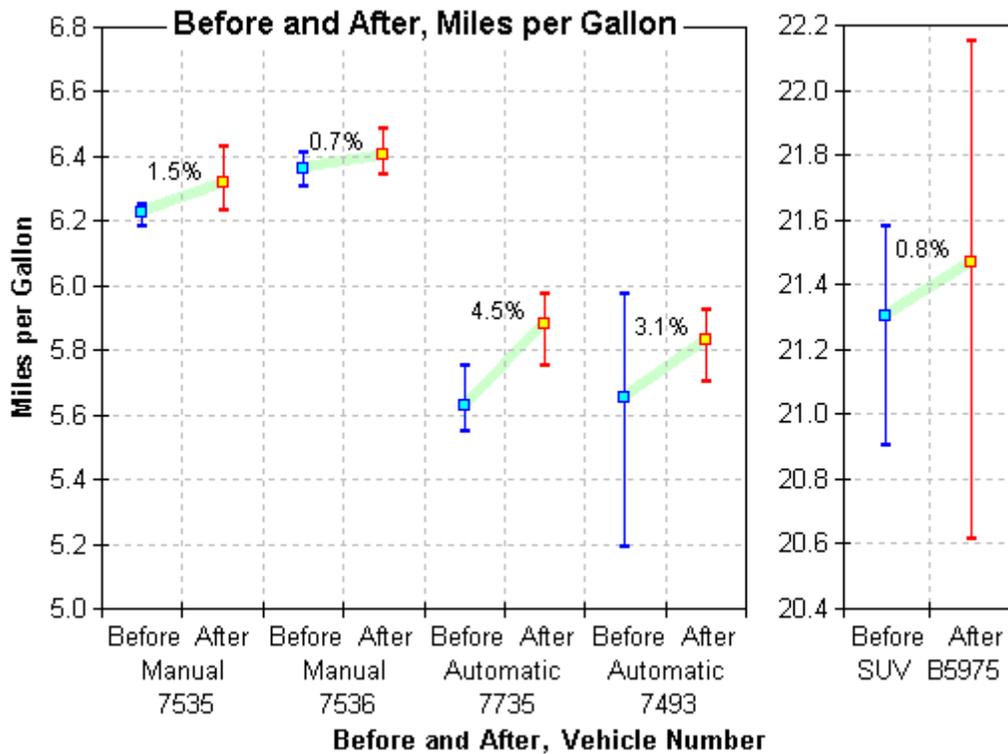


Figure 2, Graph of Minimum, Maximum, and Average Miles per Gallon Changes.

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Introduction

MoDOT, like other state DOTs, is facing pressure to do more with less, yet deliver more value for every tax dollar spent. With the completion of Missouri's Smooth Road Initiative (SRI), it is beneficial to know that not only is the traveling public driving on smoother pavement, but the smoother pavement is saving them money. These savings come from fuel savings, less frequent vehicle maintenance and fewer vehicle repairs.

A section of Interstate 70 scheduled for an SRI overlay was selected for this fuel economy study. The resurfacing project was located east of the Johnson Drive Interchange near Odessa to west of the Rt. 13 Interchange, for a total of 22 miles round-trip. This section of I-70 was considered to be moderately rough. Both the eastbound and the westbound lanes and shoulders were scheduled for resurfacing. This area of I-70 consisted of 2-12' lanes with a 10' driving lane shoulder and a 4' passing lane shoulder.

Resurfacing of started with pavement repair and joint replacement taking place in early spring. Milling 3" from the surface of each lane in both the eastbound and westbound direction followed this. A 3" Superpave 190 was used to fill the milled area followed by a 1 3/4" Stone Mastic Asphalt (SMA) using South Dakota quartzite aggregate for the riding surface. Once all lanes were covered, the shoulders were brought up to the same level. Overlay of the driving lanes was completed by September 18.



Figure 3, Before and After Pavement Surface. I-70-Lafayette Co.

Objectives

The measurable differences in pavement smoothness immediately before and immediately after an overlay placement offered a chance to investigate the effects of pavement smoothness on fuel consumption. The objective of this study is to determine the difference in vehicle fuel consumption on an existing rough pavement compared to a new, smoother pavement that was placed during the summer of 2006.



Figure 4, The Ultimate Objective, Smoother Pavement.

Present Conditions

Missouri recently completed a statewide Smooth Roads Initiative, a plan to provide 2,200 miles of smoother pavement, brighter road markings and other safety improvements in three years. The initiative is the first part of a three-part plan to use recently allocated Amendment 3 funds to improve the state's highway system. The SRI program is considered a great success and was completed on year early. Amendment 3 is a state constitutional amendment that redirected some existing highway user fees to MoDOT. Most of the funding comes from the state's vehicle sales tax.

There has been a historic perspective that a smoother road leads to an increase in fuel economy. The rougher a pavement, the more power a vehicle has to generate to overcome the rolling resistance the rough pavement creates.



Figure 5, Westbound I-70, Section of Minimum Problems, Before Resurfacing.

Over the years, several reports have been published examining fuel savings on smoother roads versus rougher pavement. A large variance in the fuel efficiency in these reports has led the public and researchers alike to question how much fuel savings a vehicle could achieve when being driven on a smooth road compared to a rough road.

Based on a review of previous work in this area, there is substantial evidence that a significant difference in road smoothness, as measured by the International Roughness Index (IRI) of a pavement, results in a difference in the volume of fuel used by the traveling public. While there are a variety of research methods used in this area, the most reputable and scientific work indicates that a smooth road surface provides a 4.5% increase in fuel economy for every 10% increase in smoothness of the roadway. Previous research that examines pavement smoothness and fuel efficiency includes:

The preliminary Florida study, Performed by International Cybernetics Corporation, reports a 16% increase in fuel economy when the IRI smoothness increases by 200%.

The North Florida Manual Testing, performed by Jackson Research Engineers Incorporated, reports a 5.2% increase in fuel economy when the IRI smoothness increases by 400%.

The National Center for Asphalt Research, Opelika, Georgia, reports that rough roads adds 10% to a trucking company's fuel bill.

A report from the FHWA at the WesTrack facility in Nevada concludes that a 10% decrease in IRI roughness led to a 4.5% increase in fuel savings. The testing at the WesTrack facility is the most comprehensive and the most controlled of all the testing to date. Driverless trucks were used for 8 weeks prior to and 7 weeks after pavement rehabilitation. Ambient conditions were not factored into the fuel runs, or the fuel savings could have possibly been higher.

The study performed at the WesTrack facility provides the most rigorous research design to date. The use of driverless trucks on a closed course overcame variables that other studies could not.

Technical Approach

The study performed at the WesTrack facility was on a closed course, using driverless trucks. Because this study was being performed in real world conditions, efforts were directed to foresee, measure, and control for all the different anticipated variables. As a real world analysis, study personnel drove MoDOT vehicles in near normal nighttime traffic on I-70. Traffic levels during the day made the test unfeasible and more likely to reflect traffic volumes than pavement performance.



Figure 6, Fleet of Test Vehicles.

During this study, MoDOT personnel used the same vehicles in both the before and after fuel runs. The four trucks used during this study were MoDOT diesel powered, tandem axle dump trucks. Two of the trucks had standard transmissions, while two had automatic transmissions. The trucks were parked at the Odessa maintenance building and were not driven during the three-month down time between the before and after fuel runs. The trucks were started periodically to charge the electrical system and to circulate fluids. The same drivers drove the four loaded tandem axle dump trucks every night of the study period. The trucks were loaded with two concrete barriers and scaled at the beginning of the fuel mileage runs. The four dump trucks each weighed an average of 29,400 lbs, when loaded. These barriers were assigned to each truck until after the last test runs were completed to ensure a constant load weight from the beginning until the end.

A 2006 Ford Explorer was also used during the fuel runs. The driver of the SUV also recorded the pavement temperature, ambient air temperature, relative humidity, wind speed, and wind direction every hour from the beginning to the end of each night's run. The Explorer was driven in the same manner as the dump trucks.

The four diesel powered dump trucks used in this study were equipped with the Navistar "AWARE" system. The International "AWARE" system is an electronic in-vehicle device that provides total integration of wireless communications, a vehicle's monitoring system, and GPS location devices. The system builds upon the vehicle's electrical system in which the engine, transmission, brakes, instrument panel, and other vehicle components communicate with each other electronically. The system communicates wirelessly to deliver information to a website, which can be viewed on any PC with an internet connection, or performance updates can be delivered immediately to a pager, email, or cellular phone via text messaging.

With the "AWARE" system, telematic technology links the vehicle's electrical system to a fleet manager's PC, allowing that manager to wirelessly monitor that vehicle's routes, performance, maintenance, security, and fuel level, whether the vehicle is parked or moving. With the GPS location tracking, the vehicle's exact

location can be monitored and pinpointed 24 hours a day, 365 days a year. The system can record route history and the date and time of each stop made. If a vehicle travels outside of its geographical boundaries, “Geofencing” (an electronic fence) will alert a field manager within minutes.

The system provides an in-depth vehicle report to measure performance, preventative maintenance schedules, and vehicle malfunction information. It keeps track of idle time, odometer readings, fuel level, battery charge, fuel efficiency, and engine hours, which helps in pinpointing the cause of a malfunction of the vehicle. The “AWARE” system tracks each vehicle’s actual performance and informs when intervals will be reached for necessary maintenance. When a sensor reports an out-of-range condition, the system will automatically alert the website or mobile device to help prevent a vehicle breakdown. The system has a button mounted on the dash to alert the supervisor if the truck has been disabled or if there is a security issue. Again, the alert can be sent to a secure website and/or a cell phone or pager.

The fuel economy runs were performed on I-70, from Johnson Drive on the east end of Odessa, west to the Rt.13 Interchange, for a total of 22 miles round trip. On a typical night, each vehicle would make 16 round trips. The test runs during the before overlay period began on May 1 and were completed on the morning of May 18. The after overlay runs started on September 18 and finished on the morning of November 17. The vehicles were driven 7 hours a night, 3 nights a week, for 3 weeks, for each cycle.

As a control for a consistent fuel supply, a fuel storage tank was dedicated for this study and only the trucks used in this study were

allowed to use this fuel. The tank was never allowed to become more than half empty before it was filled. At the end of each day’s fuel run, the trucks were parked in a premarked area for refueling. The trucks were fueled to a premarked level on the truck’s fuel tank filler neck. The fuel quantity used was logged as a backup to the electronic fuel-metering device.

Every night, the trucks were started 15 minutes prior to the beginning of the fuel runs. This allowed the truck to “warm up” before they were taken out into traffic. The fuel runs normally started at 10:00 p.m. and continued to approximately 6:00 a.m. This allowed the traffic to thin out on I-70, reducing traffic impact on fuel use. The trucks were normally spaced ¼ mile apart so there was a minimal drafting effect on the trucks used in this study. The drivers usually took a 20-minute break at midnight, 2:00 a.m., and 4:00 a.m.. These

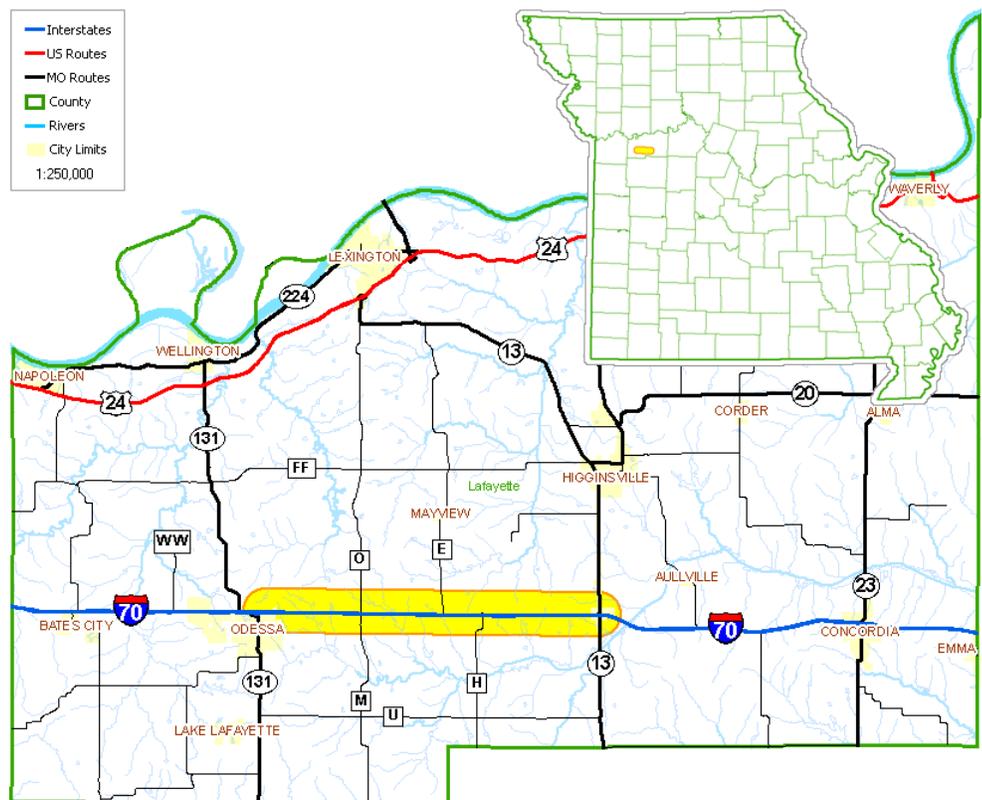


Figure 7, County and State Location Map.

break times were closely monitored to keep vehicle idle times at a minimum. It became apparent on the first night that the drivers could not keep coffee in their cups while driving.

The trucks were to be driven at 65 mph during the fuel runs, but the speed had to be lowered to 60 mph because of the severe roughness of some of the pavement at the start of the springtime runs. The cruise control was employed to remove the driver variability of a driver trying to maintain a constant 60 mph. Each driver used “tie points” from the very beginning so that he knew when and where to engage the cruise control.



Figure 8, Passenger’s View of the Test Section Before Resurfacing.

During the fuel runs, each driver was instructed not to use the air-conditioning or to roll a window down, thus eliminating more variables. The runs were conducted during periods of cool weather in the spring and fall to minimize variables due to weather. Fuel runs were not performed during a rain and were cancelled on one night because of 30-mph winds.

During the first week of the “before” fuel economy runs and the second week of the “after” fuel economy runs, MoDOT’s Automated Road Analyzer (ARAN) collected road surface smoothness data in both directions and in both lanes of the project. This data was used to illustrate the increase in smoothness after the overlay was placed.

Results and Discussion (Evaluation)

The before overlay tests were started on May 1 and were completed on May 18. The trucks averaged 2,623.26 miles for the 9 nights driven on the rougher pavement surface. The four dump trucks each used a total average of 440.70 gallons of fuel and averaged 5.97 miles per gallon.

After the overlay was placed, the after tests were run beginning on September 18. The trucks were driven an average of 3,014.2 miles during 10 nights of driving on the new, smoother overlay surface. The trucks were driven an extra night to make up for rainouts that occurred during the second week of the test runs. The four dump trucks each used a total average of 495.86 gallons of fuel and averaged 6.11 miles per gallon.

Based on the before and after overlay fuel runs, there was an increase of 0.14 mpg or a 2.46% increase in fuel efficiency. According to the “AWARE” data, the brakes on the trucks were used an average of 58 fewer times a night after the overlay was placed. Weekly totals from the AWARE system are shown in Table 1.

Table 1, Weekly Data Totals.

Truck	Week	Miles	Gallons	MPG	Week	Miles	Gallons	MPG
Manual 7535	Before 1	858.03	138.73	6.18	After 1	724.06	116.16	6.23
	Before 2	879.09	140.58	6.25	After 2	564.28	87.78	6.43
	Before 3	1,013.07	162.49	6.23	After 3	1,012.45	160.91	6.29
					After 4	659.81	104.54	6.31
Manual 7536	Before 1	858.27	136.10	6.31	After 1	723.82	114.05	6.35
	Before 2	541.91	84.48	6.41	After 2	697.57	107.58	6.48
	Before 3	1,038.86	163.28	6.36	After 3	851.74	134.11	6.35
					After 4	436.90	67.72	6.45
Automatic 7735	Before 1	903.24	162.75	5.55	After 1	723.75	125.79	5.75
	Before 2	859.20	149.43	5.75	After 2	697.80	116.82	5.97
	Before 3	1,039.79	186.25	5.58	After 3	1,034.50	174.90	5.91
					After 4	736.48	125.14	5.89
Automatic 7493	Before 1	595.12	114.58	5.19	After 1	724.52	126.98	5.71
	Before 2	892.91	149.42	5.98	After 2	698.11	118.67	5.88
	Before 3	1,013.22	174.77	5.80	After 3	1,034.81	178.07	5.81
					After 4	736.02	124.21	5.93
SUV B5975	Before 1	872.0	40.7	21.4	After 1	672.0	32.6	20.6
	Before 2	830.0	39.7	20.9	After 2	672.0	31.0	21.7
	Before 3	984.0	45.6	21.6	After 3	1,008.0	47.0	21.4
					After 4	536.0	24.2	22.1

As Table 1 also shows, the 2 trucks with the standard transmissions demonstrated better fuel economy than the trucks using the automatic transmissions. Over all, the trucks using the standard transmission had a 0.5775 better mpg average than the trucks with the automatic transmission.

The use of the International Navistar “AWARE” system proved to be a very important tool during this study. Most of the data used in this study was collected on and downloaded from the Navistar website. The data from each truck was downloaded daily and presented to the drivers for comparison. By doing this, the drivers could compare their performance from one day to the next, helping each driver to perform in a more consistent manner.

Miles per gallon were then analyzed for maximum, minimum, and average per truck before and after resurfacing, as shown in Table 2 below. The changes in average miles per gallon of each truck before and after paving were calculated in miles per gallon and as a percent improvement. Finally, the average changes in the trucks were calculated.

Table 2, Summary of Weekly Data.

Vehicle Number		Miles per Gallon, Weekly Data			Change in Average		Average Change in Averages	
		Max	Min	Average	Mpg	Percent	Mpg	Percent
Manual 7535	Before	6.25	6.18	6.22	0.092	1.48%	0.142	2.461%
	After	6.43	6.23	6.32				
Manual 7536	Before	6.41	6.31	6.36	0.047	0.74%		
	After	6.48	6.35	6.41				
Automatic 7735	Before	5.75	5.55	5.63	0.254	4.52%		
	After	5.97	5.75	5.88				
Automatic 7493	Before	5.98	5.19	5.66	0.176	3.11%		
	After	5.93	5.71	5.83				
SUV B5975	Before	21.58	20.91	21.30	0.168	0.79%	Not Applicable.	
	After	22.15	20.61	21.47				

Figure 9 below graphs Table 2's data, showing both average results, and variability of the data.

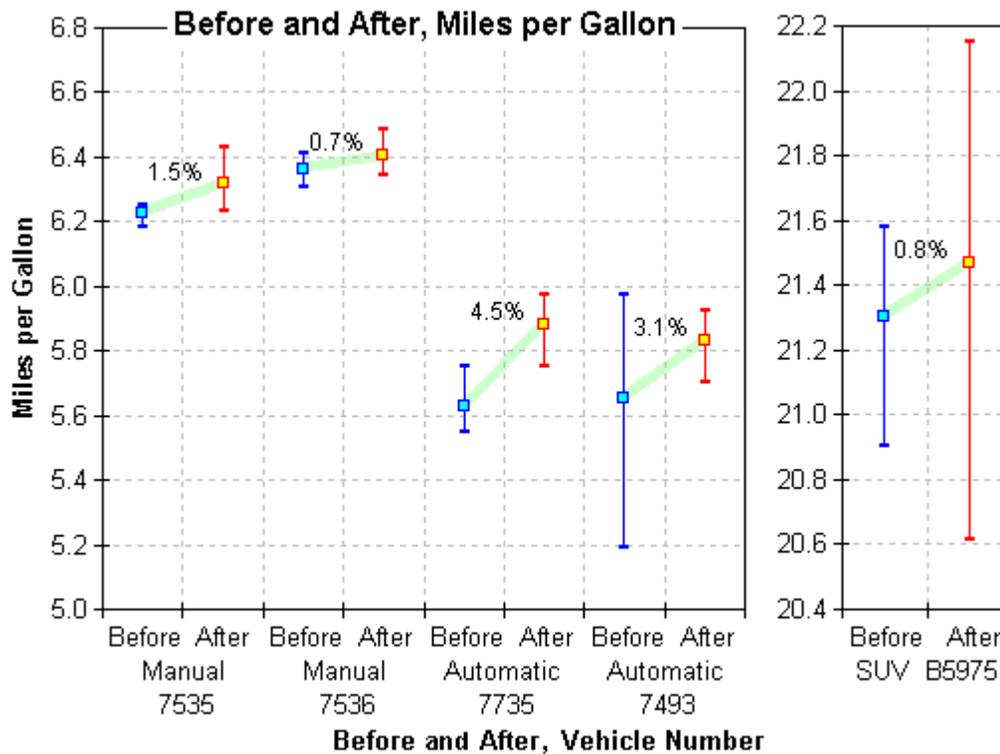


Figure 9, Graph Comparison of Before and After Miles per Gallon.

The average percent change in fuel efficiency for all dump trucks was 2.46%. The efficiency gains ranged from 0.74% to 4.52%. According to the “AWARE” data and observations, truck #7735, posted a 4.5% change and had the most consistent data week to week as well as before and after. The consistency provided by truck #7735 likely provides the best evidence that pavement conditions are directly related to fuel consumption. With reduced consistency, the average change is less likely to reflect the actual impact related to pavement condition.

The graph below shows the similarities in the weather conditions during the before and after testing. The air temperature, pavement temperature, wind speed, and the humidity were recorded every hour during each night that the test loops were being driven.

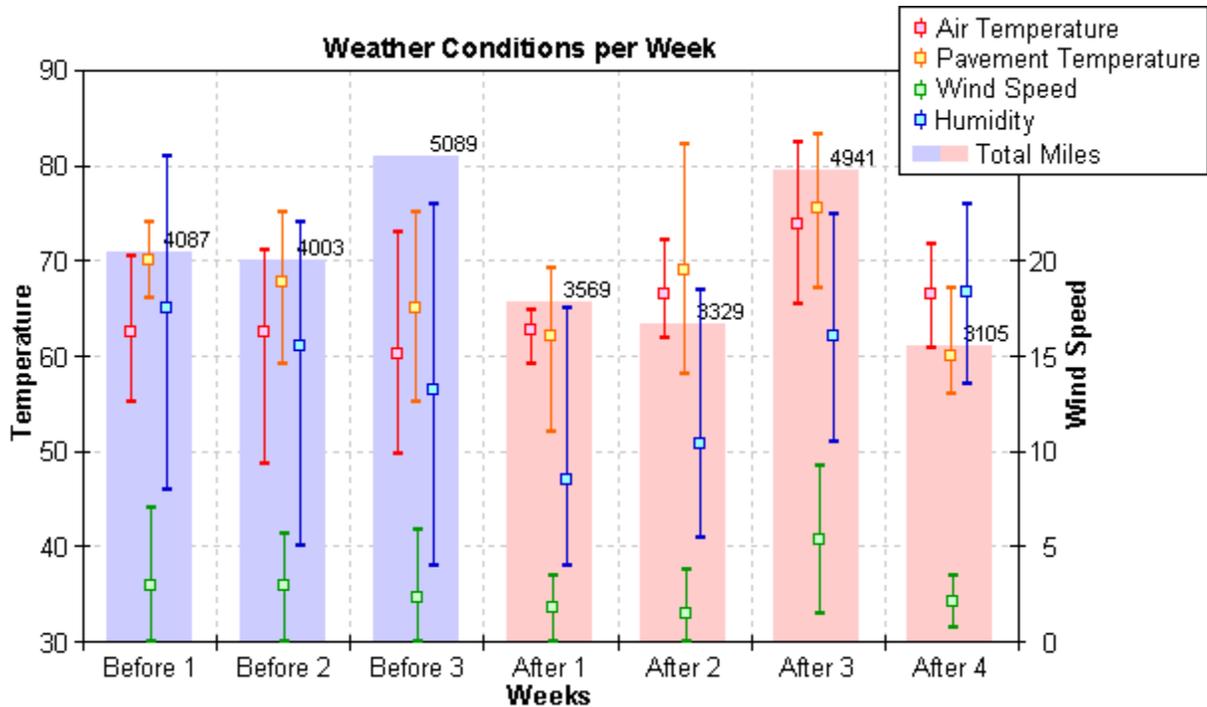


Figure 10, Graphical Comparison of Before and After Weather Conditions.

The Automated Road Analyzer (ARAN) was used to collect data for the surface and ride condition of the pavement. Data from the ARAN was used to calculate the pavement’s International Roughness Index (IRI).

The ARAN condition survey was initially run over the entire 22-mile project, in both the passing and driving lanes, on May 1, before the pavement repair. On September 25, the follow-up condition survey was performed after the new overlay had been placed.

The IRI is a measure of vertical inches that the surface changes, per mile, measured in 50-foot sections. It is not a direct measure of ride quality. Lower values are better than higher values with zero being a theoretical ideal. Extreme values, as shown in the figures below at points 41, 44, 45, 206, and 210, represent anomalies similar to railroad crossings, pavement transitions, or severe potholes. The average IRI for the 22-mile round trip before the overlay was placed was 130.25 with a low of 33.03. After repairs and overlay placement, the average IRI was 60.99 with a low of 22.69. Thus, the pavement’s IRI was improved by 53.2%.

Table 3, IRI Classifications.

Approximate IRI, inches/mile	Roughness classification
0-95	Smooth
95-133	Moderately rough
>133	Rough

The two graphs in Figure 11 below show continuous and average IRI measurements for the eastbound and then the westbound driving lanes of the test loop. Persistent peaks, such as at log mile 44, eastbound, indicate a change in pavement such as at bridges and overpasses. Removed peaks, such as at log mile 43, indicate repairs of potholes or uneven slabs. Between log mile 47 and 48, is a section of ideal improvement, which was not feasible at every location, without completely rebuilding the highway. Thus, these graphs illustrate both the improvement made, and the potential for more extensive projects to produce even better fuel savings.

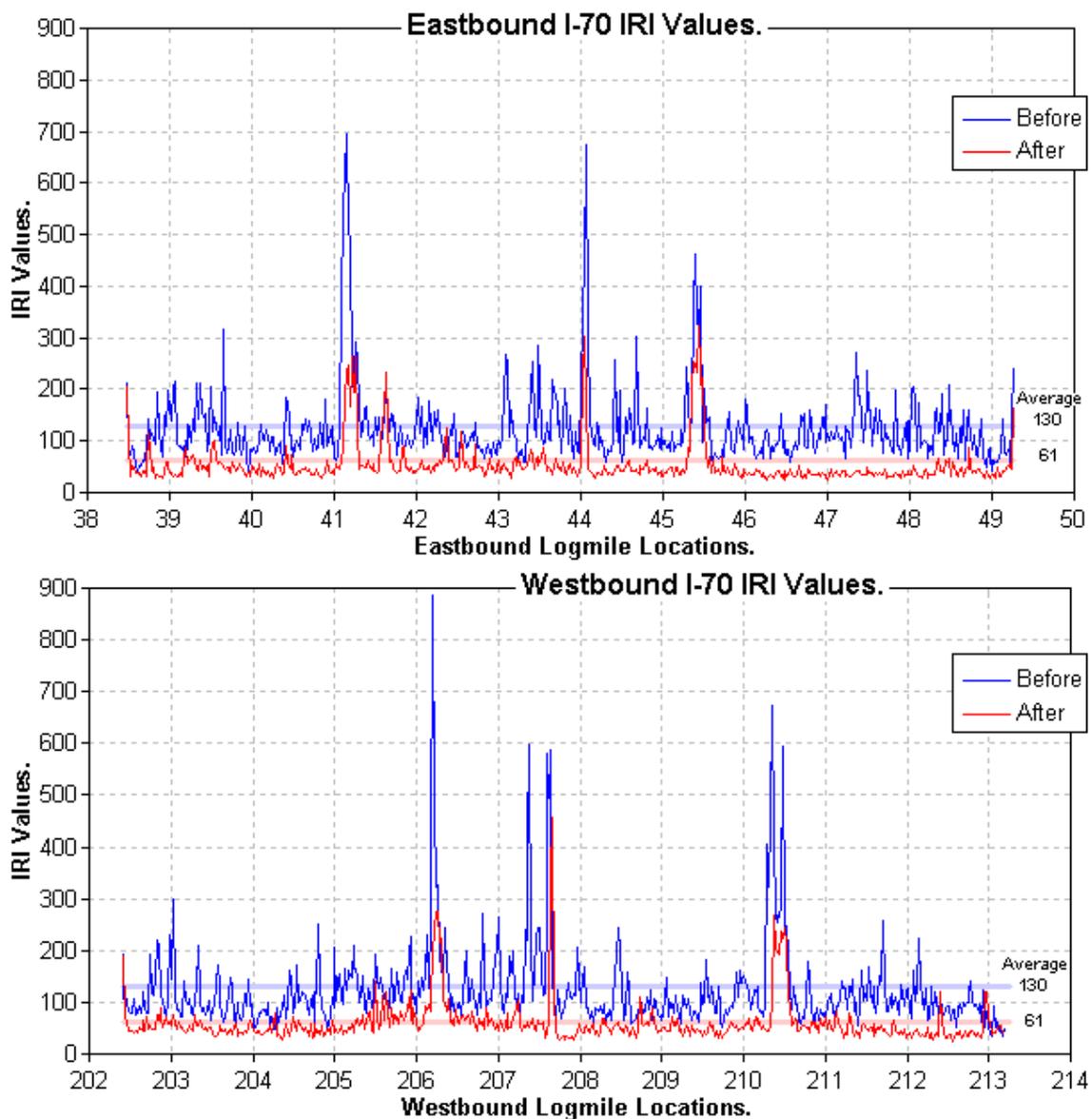


Figure 11, Graphs of Before and After IRI Values.

The following pictures illustrate the difference in pavement condition before and after resurfacing.



Figure 12, Previous Patches.

Figure 12 shows a concrete patch in the foreground, and overlapping asphalt patches in the middle ground. The asphalt patch is shoving. Chalky, pale material on the shoulder and right wheel path is base material pumped up through cracks in the pavement and patches. Repairs before resurfacing can fix the roughness of the asphalt patches, eliminate the heaving bump, and improve the base. The transition from concrete patch to asphalt pavement will remain or redevelop a bump after resurfacing, and it cannot be fixed without completely rebuilding the roadway.



Figure 13, Transition at an Underpass.

Several locations had pavement transitions due to bridges or underpasses. Figure 13 shows a transition approaching an underpass. All such transitions were improved in the project, but they could not be eliminated without rebuilding the roadway.

Conclusions

1. Based on the data collected, the diesel trucks used in this study showed an increase of 0.142 mpg or a 2.461% increase in fuel efficiency when driven on a new, smoother overlay as compared to the rough driving surface. Our study supports previous work performed in this area.
2. The driver comfort and the ability to control the vehicles improved dramatically from driving on the rougher pavement to driving on the new, smoother pavement.
3. The use of the vehicle's brakes declined an average of 58 times per night when driving on the new overlay compared to the old, rougher surface.
4. The trucks using the standard transmission averaged 0.5775 miles per gallon higher than the trucks using the automatic transmission.
5. The use of the Navistar "AWARE" system proved to be a valuable tool when collecting data and monitoring vehicle performance.
6. In summary, fuel economy, driving comfort, and reduced vehicle maintenance cost result from quality, smooth riding pavements.



Figure 14, Before and After Surface Details.

Recommendations

- Smooth roads make sense in Missouri. Previous research studies show rough highways cost more money in increased vehicle maintenance costs. The non-profit organization TRIP, estimates that driving on roads in need of repair costs the average urban driver \$383 annually in extra vehicle operation costs. The Missouri MAP planning process and statewide customer satisfaction surveys have told us that MoDOT customers want a smooth ride. In MoDOT's 2005 customer survey, "smoothing" interstates and state highways was listed as one of the top 5 improvements needed in Missouri. Nearly 804 of 3100 respondents replied that "smoothing" interstates and highways was very important.
- And now, our research backs up what others have been saying all along, - - smooth roads save money, smooth roads save fuel, when compared to moderately rough and rough pavements.
- MoDOT's new programs, "85 & 5" and the "Safe and Sound Bridge Program", compliment the results of Missouri's SRI. These efforts, along with a continued effort and investment, will ensure Missouri's investments in the transportation system result in a benefit to the state as well as to interstate travelers.



Figure 15, Before and After Surface Conditions.

Project Members

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Figure 16, Safety Barriers Used as Cargo in the Test Trucks.

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Figure 17, Surface Conditions Before and After.

Appendix A, Work Plan

Study Proposal

Date: 09/06/05

Project Number: RI05-040

Title: Vehicle Fuel Efficiency Before and After Resurfacing I-70

Research Agency: Organizational Results

Principal Investigator: Dave Amos

Objective: The objective of this study is to determine the difference in vehicle fuel consumption on an existing, rough pavement compared to a new, smoother pavement that will be placed in the spring of 2006.

Background and Significance of Work: Missouri is in the early stages of a statewide smooth road initiative. Some believe that a smoother driving surface leads to an increase in fuel economy.

Over the years, several reports have been published relating to fuel savings on smoother versus rougher pavement. A large variance in the fuel consumption in these reports has lead the public and researcher alike to wonder how much fuel could a vehicle save when being driven on a smooth road compared to a rough road. This project is designed to examine actual pavement and driving conditions in relation to potential fuel efficiency gains with smoother road surfaces.

Action Plan: Organizational Results will use 4 MoDOT diesel powered dump trucks and a MoDOT gas powered SUV to collect fuel mileage data prior to and after a resurfacing project on Interstate 70. The resurfacing project is located on I-70, east of the Johnson Drive Interchange near Odessa to west of the Route 13 Interchange, for a total of 22 miles round-trip. Before these vehicles are used to collect the fuel mileage data, the Automated Road Analyzer (ARAN) van will collect International Roughness Index (IRI) information before and after the placement of the new roadway surface. The current pavement is very rough.

Data Collection and Methodology Procedures: The vehicles, used to make the fuel mileage runs on I-70, will have the appropriate maintenance performed prior to the before and after overlay test runs. Maintenance will consist of new filters, fresh engine oil, proper fluid levels, and tire. A dedicated fuel supply will be used during the tests. This way, the same fuel would be used throughout the complete test period. Trucks will be scaled on site at a MSHP scale station. The Odessa maintenance shed will load portable concrete barriers on the dump truck to simulate a load.

The same personnel will drive the trucks used to collect the fuel mileage data both before and after the resurfacing operation. The vehicles will be driven at 65 mph between the hours of 10:00 pm and 6:00 am three days a week for three weeks. It is estimated, each vehicle will be driven between 250-280 miles each night. Running the tests during these hours should help eliminate some of the variables encountered during day time hours, including higher volumes of traffic, queuing, and higher pavement /ambient temperatures. The trucks will be driven predominately in the driving lane. Vehicles will be fueled the first morning at the Odessa maintenance building. At the end of each days test runs, the vehicles will be refueled and the fuel used will be recorded. Mileage and fuel consumption will be calculated for each day.

Ambient conditions will be recorded during each pass made, and include air temperature, wind speed, relative humidity, and pavement temperature. The vehicle's tire pressure will be closely monitored. The decision to drive with the vehicle's window in the up or down position, or the use of the air-conditioner will be made on site, but will remain the same for the entire test procedure. The decision to drive using the cruise control will be made at a later date. The trucks must be driven in a consistent manner from one pass to the next; any variation could lead to data issues and will be recorded by the driver for each test pass. Tests will not be performed during a rain.

Summary of Control Variables:

Variable:	Issue:
Ambient temperature.	Measure ambient temperature during each round-trip pass.
Pavement temperature.	Measure pavement temperature during each round-trip pass.
Tire air pressure.	Tire pressure will be monitored prior to each days run.
Tires.	The same type and manufacturer of tire will be used.
Relative humidity.	Relative humidity will be recorded during each round-trip pass.
Wind speed and direction.	Wind speed will be recorded during each round-trip pass.
Trucks drafting.	Trucks will be separated by ¼ mile.
Truck speed.	Truck speed will be 65 mph. (Reduced to 60 mph during tests)
Vehicle maintenance.	Vehicles will have new filters, fresh engine oil, and proper fluid levels before the pre overlay and post overlay test runs.
Vehicle weight.	The dump truck will have the same load as the previous set of test runs.
Driver variability.	The same drivers will drive the same vehicle during all test passes before and after the overlay has been placed. Drivers will record any anomalies encountered with the test runs.
Driver fatigue.	A driver schedule containing breaks will be devised.
Cruise control.	The decision to drive with or without cruise control will be made before tests begin.
Traffic volume.	Test runs will be performed between the hours of 10:00 pm and 6:00 am when traffic will be at a minimum.
Fuel type.	The same fuel will be used for all test runs, taken from the tank that will be dedicated to the tests being performed.
Test run on smooth overlay.	The test will be performed as soon as possible after the overlay has been placed.
Air conditioner vs. windows up or down.	The use of the air conditioner or driving with the windows down will be decided on the first set of test runs and maintained throughout the entire test procedure.

Prior to pavement repair and overlay:

1. Operation of the ARAN van to collect IRI (International Roughness Index) data.
2. Perform maintenance on all vehicles to be used in fuel mileage data collection.
3. Perform fuel mileage runs on I-70 project from 10:00 pm to 6:00 am three days a week for three weeks.
4. Record ambient conditions and fuel consumption, document conditions for all control variables.
5. Install and test the Navistar “AWARE” system.

After overlay operations have been completed:

1. Operation of the ARAN van to collect IRI (International Roughness Index) data.
2. Perform maintenance on all vehicles to be used in fuel mileage data collection.
3. Perform fuel mileage runs on I-70 project from 10:00 pm to 6:00 am three days a week for three weeks.
4. Record ambient conditions and fuel consumption, document conditions for all control variables.
5. Compare data for test periods and complete report.

Literature Search: A literature search provided the following literature:

1. Rough Roads Found To Add 10% To Truck Fuel Costs, Jim Starling.

Preliminary results indicate that smooth roads save 10% on truck fuel costs. Four trucks, weighing 152,000 lbs. Each are being run on the National Center for Asphalt Research test track. With a 10% increase in smoothness, researchers found that heavy-duty truck fuel consumption improved 4.5%.

2. Fuel Consumption vs. Pavement Smoothness, Mike Jackson and James Fletcher.

Findings include fuel savings from as low as 2% to as high as 10-12%. Some questions about the procedures, variables, and equipment used. Study was completed by driving on rumble strips and on the regular pavement surface for comparison.

3. A Review of Pavement Roughness Effects on the Road User, T. Papagiannkis, J. Carson, J. Mahoney, F. Garcia De Quevedo, M. Delwar .

Uses empirical observations and regression analysis to estimate fuel consumption in relation to pavement roughness. Found no agreement between empirical studies on the effect of pavement roughness on fuel consumption.

Appendix B, Navistar AWARE Data

Table 4, Example Table of One Day's Data from the Navistar "AWARE" System.

Report Date Range Between: 10/16/2006 and 10/17/2006

Vehicle		Average	Total	Minimum	Maximum
7535	TotalEngineHours	6.0 Hours	11.9 Hours	150.5 Hours	162.4 Hours
7535	OdometerTotal	270.3 Miles	540.6 Miles	6,167.9 Miles	6,708.5 Miles
7535	IdleTime	1.0 Hours	2.0 Hours	25.4 Hours	27.4 Hours
7535	TotalFuelConsumed	42.6 gallons	85.1 gallons	1,058.4 gallons	1,143.5 gallons
7535	BatteryVoltage	12.9 Volts	n/a	12.9 Volts	12.9 Volts
7535	BrakeDuration	743.5 Seconds	1,487.0 Seconds	677.0 Seconds	810.0 Seconds
7535	BrakeCount	143.5	287	107	180
7535	FuelEconomy	6.3 Miles/gallon	n/a	6.3 Miles/gallon	6.5 Miles/gallon
7536	TotalEngineHours	3.4 Hours	6.9 Hours	128.2 Hours	135.1 Hours
7536	OdometerTotal	158.9 Miles	317.8 Miles	5,189.1 Miles	5,506.9 Miles
7536	IdleTime	0.5 Hours	1.0 Hours	22.6 Hours	23.6 Hours
7536	TotalFuelConsumed	24.6 gallons	49.1 gallons	826.5 gallons	875.6 gallons
7536	BatteryVoltage	12.8 Volts	n/a	12.7 Volts	12.9 Volts
7536	BrakeDuration	374.0 Seconds	748.0 Seconds	136.0 Seconds	612.0 Seconds
7536	BrakeCount	79.5	159	48	111
7536	FuelEconomy	6.5 Miles/gallon	n/a	6.1 Miles/gallon	6.6 Miles/gallon
7735	TotalEngineHours	6.0 Hours	12.1 Hours	142.2 Hours	154.3 Hours
7735	OdometerTotal	271.3 Miles	542.6 Miles	5,966.9 Miles	6,509.5 Miles
7735	IdleTime	1.0 Hours	2.0 Hours	26.6 Hours	28.6 Hours
7735	TotalFuelConsumed	45.5 gallons	90.9 gallons	1,053.5 gallons	1,144.4 gallons
7735	BatteryVoltage	12.9 Volts	n/a	12.8 Volts	12.9 Volts
7735	BrakeDuration	408.0 Seconds	816.0 Seconds	360.0 Seconds	456.0 Seconds
7735	BrakeCount	86.5	173	80	93
7735	FuelEconomy	6.0 Miles/gallon	n/a	5.8 Miles/gallon	6.1 Miles/gallon
7493	TotalEngineHours	6.1 Hours	12.2 Hours	139.1 Hours	151.3 Hours
7493	OdometerTotal	271.1 Miles	542.2 Miles	5,756.7 Miles	6,298.9 Miles
7493	IdleTime	1.1 Hours	2.1 Hours	25.4 Hours	27.5 Hours
7493	TotalFuelConsumed	45.6 gallons	91.2 gallons	1,015.5 gallons	1,106.7 gallons
7493	BatteryVoltage	13.6 Volts	n/a	13.1 Volts	14.2 Volts
7493	BrakeDuration	822.0 Seconds	1,644.0 Seconds	805.0 Seconds	839.0 Seconds
7493	BrakeCount	122.5	245	119	126
7493	FuelEconomy	5.9 Miles/gallon	n/a	5.8 Miles/gallon	6.1 Miles/gallon



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