Test and Evaluation of Rear-Wheel Steering for Aircraft Rescue and Firefighting Vehicles—Part 2

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16. Abstract

The Federal Aviation Administration (FAA) has an ongoing research program that evaluates new technologies for increasing postcrash fire survivability on aircraft and determines methods to increase the performance capabilities of aircraft rescue and firefighting (ARFF) vehicles. Excessive tire wear on hard surfaces is a concern on ARFF vehicles with more than four wheels. The FAA ARFF research program evaluated a six-wheeled ARFF vehicle with rear-wheel steering (RWS).

The objectives were to evaluate an ARFF vehicle for turning diameter, tire tread wear, and estimated tire life. A six-wheeled ARFF vehicle was used with a prototype RWS system that allowed comparisons with the RWS function disabled and enabled. Tests were conducted according to FAA Advisory Circular 150/5220-10C, which specifies turning diameter procedures. Tire tread wear was achieved by driving the test vehicle on a figure-eight course for 60 miles, which generated a faster and more aggressive tire tread wear than normal driving patterns. Tire tread depth was measured according to the tire manufacturer. The data from the tread wear results were used to calculate estimated tire life.

The results showed the ARFF vehicle with RWS decreased the turning diameter by 18.7% in the clockwise direction from 116.0 feet to 94.3 feet and 18.2% in the counter clockwise direction from 108.2 feet to 88.5 feet compared to vehicle operations without RWS. Without RWS, the rear tires wore the fastest by approximately 0.406 (13/32) inch over the 60 miles. With RWS, the middle tires wore the fastest by approximately 0.121 (4/32) inch over the 60 miles. The data from the tire tread wear tests were used to calculate the estimated tire life using linear regression calculations. RWS extended the estimated tire life by 1.9 to 2.6 times on the front tires and 7.9 to 9.0 times on the rear tires compared to vehicle operations without RWS enabled. However, the middle tires showed better tire life without RWS, 5.3 to 7.3 times that of tire life with RWS.

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LIST OF ACRONYMS

AC	Advisory Circular
AFB	Air Force Base
AFRL	Air Force Research Laboratory
ARFF	Aircraft rescue and firefighting
ASTM	American Society of Testing Materials
CFR	Code of Federal Regulations
FAA	Federal Aviation Administration
NFPA	National Fire Protection Association
RWS	Rear-wheel steering
R^2	Regression coefficient of determination

EXECUTIVE SUMMARY

The Federal Aviation Administration (FAA) has an ongoing aircraft rescue and firefighting (ARFF) research program that evaluates new technologies for increasing postcrash fire survivability on aircraft and improving the performance capabilities of ARFF vehicles. New designs in ARFF vehicles have enabled manufacturers to provide larger, faster vehicles that offer large extinguishing agent capacities to airport fire departments. While enhancements to suspension systems have been developed, having to replace worn tires due to vehicle control, tire scrub, and tire tread wear continues to be an issue at some airport fire departments. ARFF vehicles with two rear axles tend to pivot on the forward rear tires while the aftmost tires drag during a turn.

The objectives were to evaluate an ARFF vehicle for turning diameter, tire tread wear, and estimated tire life. A six-wheeled ARFF vehicle was used with a prototype rear-wheel steering (RWS) system that allowed comparisons with the RWS function disabled and enabled. Tests were conducted according to FAA Advisory Circular (AC) 150/5220-10C, which specifies turning diameter procedures. Tire tread wear was achieved by driving the test vehicle on a figure-eight course for 60 miles, which generated faster and more aggressive tire tread wear than normal driving patterns. Tire tread depth was measured according to recommendations from the tire manufacturer, Michelin Corporation, using a depth micrometer. The data from the tread wear results were used to calculate estimated tire life.

The turning diameter results showed the ARFF vehicle satisfied the FAA AC requirements by turning in less than three times the vehicle's length of 117.6 feet, without and with the RWS. RWS decreased the turning diameter by 18.7% in the clockwise direction from 116.0 feet to 94.3 feet and 18.2% in the counter clockwise direction from 108.2 feet to 88.5 feet compared to vehicle operations without RWS.

The front and rear tires on both sides showed significantly less tire tread wear over an equivalent 60-mile distance compared to the wear measured without RWS. Without RWS, the rear tires wore the fastest by approximately 0.406 (13/32) inch over the 60 miles. With RWS, the middle tires wore the fastest by approximately 0.121 (4/32) inch over the 60 miles.

The data from the tire tread wear tests were used to calculate the estimated tire life using linear regression calculations. RWS extended the estimated tire life by 1.9 to 2.6 times on the front tires and 7.9 to 9.0 times on the rear tires compared to vehicle operations without RWS enabled. However, the middle tires showed better tire life without RWS, 5.3 to 7.3 times that of tire life with RWS. This was likely due to the geometry of the steering system and the close proximity of the middle and rear axles. With front- and rear-wheel steering, the middle tires are forced to slip sideways during a turn and, therefore, experience greater wear. With only front-wheel steering, the body pivots on the middle tires and forces the rear tires to slip sideways during a turn. The results were similar to the previous FAA RWS evaluation described in DOT/FAA/AR-TN08/43, "Test and Evaluation of Rear-Wheel Steering for Aircraft Rescue and Firefighting Vehicles."

INTRODUCTION

PURPOSE.

The Federal Aviation Administration (FAA) Office of Airport Safety and Standards tasked the FAA Airport Technology Research and Development Branch at the William J. Hughes Technical Center to evaluate rear-wheel steering (RWS) on an aircraft rescue and firefighting (ARFF) vehicle.

OBJECTIVES.

The objectives were to evaluate the following performance characteristics of an ARFF vehicle:

- Wall-to-wall turning diameter
- Tire tread wear
- Estimated tire life

BACKGROUND.

The FAA has an ongoing ARFF research program that evaluates new technologies for increasing postcrash fire survivability on aircraft and improving the performance capabilities of ARFF vehicles. New designs in ARFF vehicles have enabled manufacturers to provide larger, faster vehicles that offer large extinguishing agent capacities to airport fire departments. While enhancements to suspension systems have also been developed, having to replace worn tires due to vehicle control, tire scrub, and tire tread wear continues to be an issue at some airport fire departments.

The FAA previously evaluated the performance of an FAA 6x6 ARFF research vehicle with and without RWS [1]. The results from that evaluation showed an improved turning diameter and reduced tire wear using RWS. In the ARFF industry, tire tread wear is a concern on ARFF vehicles with two rear axles, such as 6x6s and 8x8s. The ARFF vehicles tend to pivot on the forward rear tires while the aftmost tires drag during a turn, causing excessive wear or scrub on hard surfaces.

According to vehicle manufacturers and airport fire departments, ARFF vehicle tires cost approximately $2500 to $4000 each and can take up to several weeks for delivery. Some fire departments are changing the tires on their ARFF vehicles after only 5000 miles of use due to excessive wear. Michelin, Inc., states that its XZL™ On/Off road commercial truck tires (table 1 and figure 1) should provide up to 50,000 miles of use, depending on the operational environment of the vehicle.

Table 1. Michelin Truck Tire Specifications

Size	Tread	Load Rating	Loaded Radius (in.)	Overall Diameter (in.)	Overall Width (in.)	Approved Rims	RPM	Tread Depth	Maximum Speed (mph)	Maximum Load Per Tire		Tire Weight (lb)
										lb	psi	
24R21	XZL	H	24.8	54.6	23.9	18.00	383	31/32	55	15,700	85	421

Figure 1. Michelin XZL Tire

The Air Force Research Laboratory (AFRL performed the evaluation on an ARFF vehicle. This task was performed under the existing Interagency Agreement between the FAA and the United States Air Force at the AFRL Fire Research facility at Tyndall Air Force Base (AFB), Florida.

RELATED DOCUMENTATION.

The following documents relate directly to the issues addressed herein and define the test protocols used during this evaluation.

- FAA Technical Note DOT/FAA/AR-TN08/43 [1], "Test and Evaluation of Rear-Wheel Steering for Aircraft Rescue and Firefighting Vehicles." This technical note describes a previous test and evaluation project conducted on the FAA 6x6 ARFF research vehicle.

- FAA Advisory Circular (AC) 150/5220-10C [2], "Guide Specification for Water/Foam Aircraft Rescue and Fire Fighting Vehicles." This AC contains information, references, and guidelines for ARFF vehicles that meet the requirements for airport response to aircraft firefighting.

- FAA AC 150/5220-10D [3], “Guide Specification for Aircraft Rescue and Fire Fighting Vehicles.” This AC contains updated information from its previous version, which includes information, references, and guidelines for a family of ARFF vehicles that meet the requirements for airport response to aircraft firefighting.

- National Fire Protection Association (NFPA) 414 Standard for Aircraft Rescue and Fire-Fighting Vehicles [4], 2007 edition. This standard specifies the minimum design, performance, and acceptance criteria for ARFF vehicles.

- American Society for Testing and Materials (ASTM) F 1016-93 (Reapproved 2001) [5], “Standard Practice for Linear Tire Treadwear Data Analysis.” This standard describes the elementary linear regression analysis of basic tread wear data.

- ASTM F 421-00, “Standard Test Method for Measuring Groove and Void Depth in Passenger Car Tires.” This standard describes procedures for reporting tread wear data.

METHODS AND PROCEDURES

TEST VEHICLE.

A Rosenbauer Panther 6x6 ARFF vehicle was used as the test vehicle for the evaluation, as shown in figure 2. It was used because it met the purpose and objectives of the evaluation and was already located at Tyndall AFB. This particular ARFF vehicle is similar to the FAA ARFF research vehicle in size, weight, water capacity, firefighting systems, and high-reach extendible turret. The difference between the two vehicles is that the test vehicle has a high-performance coil spring suspension system instead of an independent suspension system. More information on the coil spring suspension system can be found by contacting the manufacturer[1]. The test vehicle also had the manufacturer’s prototype RWS system installed, which could be enabled and disabled for testing. The RWS system was evaluated and compared to the standard suspension configuration without RWS. The prototype RWS system is an electric-over-hydraulic system that steers the rear wheels a maximum of 10 degrees in a turn, which is dependent on driver steering input and vehicle speed. The angle of the rear wheel decreases as it accelerates, and the rear wheel has a built-in safety interlock system that locks the rear axle at 0 degrees at speeds greater than 35 mph for stability at high speeds. Figure 3 shows the test vehicle with RWS enabled.

[1] http://www.rosenbaueramerica.com

Figure 2. The 6x6 Test Vehicle

Figure 3. Test Vehicle With RWS Enabled

TEST METHOD.

To evaluate and compare the test vehicle's performance with and without RWS, a switch was mounted inside the cab that allowed the driver to enable and disable the RWS function. Tests of the wall-to-wall turning diameter and tire tread wear were conducted in the same manner as described in reference 1. The tire tread wear data were used to calculate the estimated tire life. All tests were conducted with and without the RWS function. Tape measures, plumb bobs, depth gauges, etc. were used to collect numerical data; cameras were used for visual observation and documentation. The data were then used to determine the operational performance of the test vehicle with and without RWS.

WALL-TO-WALL TURNING DIAMETER.

The wall-to-wall turning diameter of the test vehicle was measured in both the right (clockwise) and left (counter clockwise) directions. Tests were conducted according to AC 150/5220-10C [2]. The AC requirement is for the vehicle to turn in a complete circle in less than three times its vehicle length in both directions. AC 150/5220-10C was used instead of AC 150/5220-10D [3] (the current version at the time of this project) since it was used during the previous FAA ARFF vehicle evaluation [1]. AC 150/5220-10D references NFPA 414 Standard (2007 edition) [4], which provides the same methodology for determining turning diameter.

The wall-to-wall turning diameter test steps are as follows.

1. The test vehicle was driven slowly in a full cramp circle (right or left) to establish a steady state in the steering linkage.

2. At approximately three equidistant points (identified as A, B, and C) around the circle, the vehicle was slowly stopped using the service brakes.

3. At each stop, a plumb bob was placed against the outermost point of the vehicle (the side mirrors) and the spot was marked on the ground directly below the plumb bob.

4. The straight line distances between each pair of points (AB, BC, and CA) were measured.

5. The wall-to-wall turning diameter (D) was calculated as follows:

$$S = \frac{AB + BC + CA}{2}$$

$$D = 2R = \frac{AB \times BC \times CA}{2\sqrt{S(S - AB)(S - BC)(S - CA)}}$$

6. Steps 1 through 5 were repeated with the vehicle moving in the opposite direction.

TIRE TREAD WEAR.

To accelerate tire tread wear above normal routine driving, the test vehicle was driven in an aggressive figure-eight pattern on a dry, nongrooved concrete surface (figure 4). The figure-eight course, shown in figure 5, was comprised of two 120-ft-diameter circles (877 ft of travel per figure-eight circuit)[2]. The test vehicle was driven at 15 mph for a total distance of 60 miles (approximately 361 complete circuits). For a more accurate tread wear analysis, 60 miles was used instead of the 40 miles used in the previous FAA evaluation [1].

Figure 4. Concrete Surface of Figure-Eight Course

The tire tread wear test was conducted in two phases. In phase 1, the test vehicle was driven without the RWS enabled. In phase 2, new Michelin XZL tires were installed on all the test vehicle's wheels, and the RWS was enabled.

[2] In reference 1, the figure-eight course is described as two 150-ft-diameter circles measuring from the outside wheel track of the FAA research vehicle. The two 120-ft-diameter circles described in this report were measured from the inside track of test vehicle. Although the course is described differently, both vehicles traveled the same distance on the same exact figure-eight course.

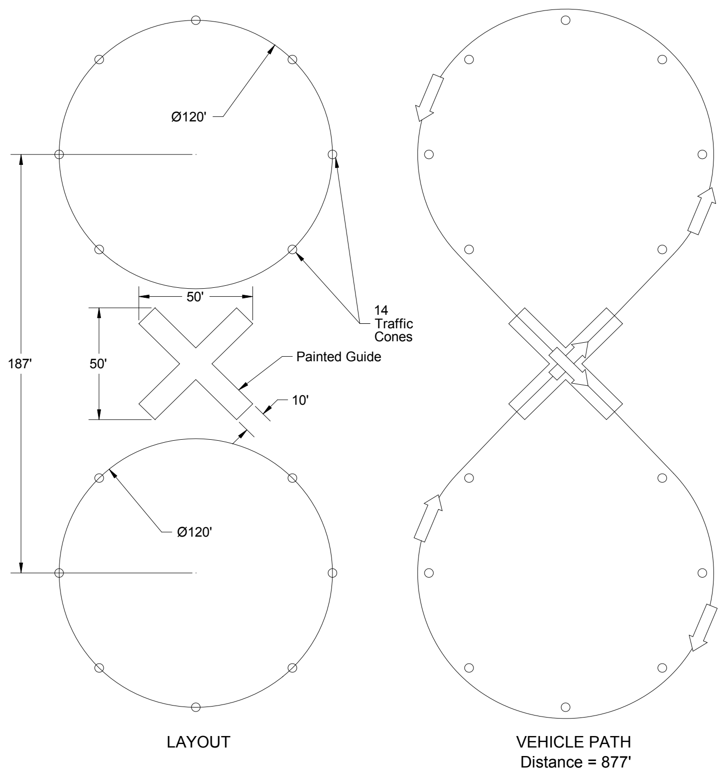

Figure 5. Figure-Eight Course

Prior to each phase, all six tires were inflated to 85 psi, as recommended by the manufacturer. Each tire was labeled at the 12, 3, 6, and 9 o'clock positions, creating four equidistant measurement locations around the circumference of each tire. At each position, six tread sections across each tire groove were marked, starting with block 1 on the outside edge of the tire and ending with block 6 on the inside edge of the tire, as shown in figure 6. The tread blocks were marked in the groove of the tire at the base of the tread so the markings were not worn off while driving the vehicle. Each marked groove was measured using a 0- to 1-inch Fowler X-Tread® digital tire tread depth gauge (figure 7) that had a spring-loaded stem, a digital readout, and an accuracy of 0.001 inch. Repeated measurements in the same position demonstrated that readings within ±0.004 inch were consistently accomplished. Tread depth was measured as recommended from the Michelin, Inc. [6].

> "Tread depth measurement can be taken in several spots across the tread and around the circumference. However, to calculate the remaining amount of rubber (knowing the new tire tread depth) for a given number of miles run, the measurement should always be taken at the same spot on the tread and close to the center groove of the tire."[3]

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[3] Michelin, "Michelin Truck Tire Service Manual," http://www.michelintruck.com/michelintruck/toolbox/reference-material.jsp. September 1996.

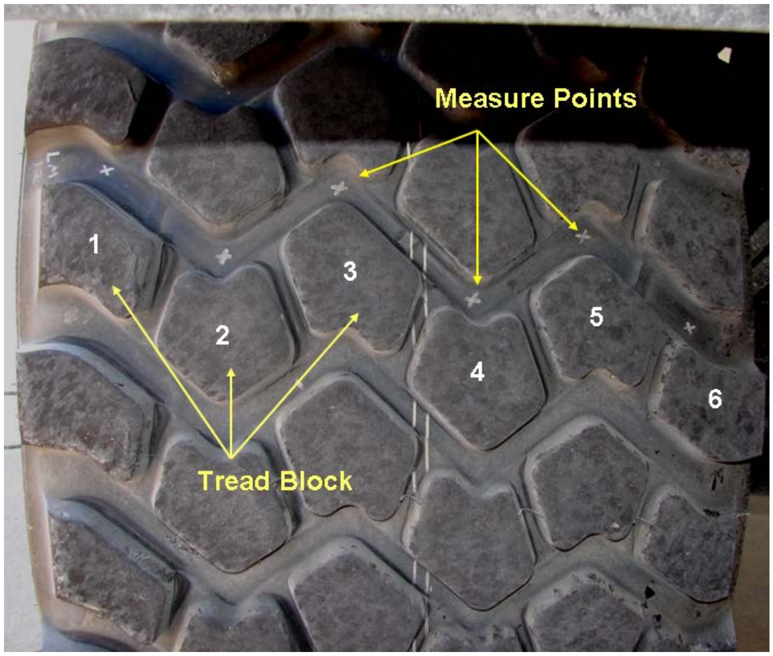

Figure 6. Markings Used to Identify Tread Measurement Points at Tread Blocks

Figure 7. Measuring Tread Depth With Fowler X-Tread Gauge

At each 20-mile interval, tire pressure was rechecked, and the tread depth was remeasured at each position. The average tread depth was determined by taking the average across each position.

TEST RESULTS

WALL-TO-WALL TURNING DIAMETER.

The wall-to-wall turning diameter tests were performed before the tire tread wear tests. The test vehicle tires had 213 miles of previous normal driving, and none of the tires had less than 0.893 (28/32) inch of tread. The overall length of the test vehicle was 39.2 ft. Results showed that the test vehicle satisfied FAA AC 150/5220-10C requirements without RWS by turning in less than three times the vehicle's length of 117.6 feet in both the clockwise and counterclockwise directions. With RWS, the wall-to-wall turning diameter improved in both the clockwise and counterclockwise directions. The wall-to-wall turning diameter decreased 21.7 feet (18.7%) in the clockwise direction and 19.7 feet (18.2%) in the counterclockwise direction, as shown in table 2.

Table 2. Wall-to-Wall Turning Diameter

Direction	Without RWS (feet)	With RWS (feet)	Difference (feet)	Difference (%)
Clockwise	116.0	94.3	21.7	18.7
Counterclockwise	108.2	88.5	19.7	18.2

TIRE TREAD WEAR.

ASTM F 1016-93 [5] defines linear tread wear as a constant rate of wear that results in a linear regression coefficient of determination (R^2) equal to or greater than 0.95 when obtained from a data set with at least three measurements. Three tread depth measurements at 20-mile intervals were used to determine uniform linear tread wear. At each interval, an analysis of the rate of wear was performed to determine for the estimated tire life. According to ASTM F 1016-93 [5], the depth loss at the fastest wearing location may be used if the tire does not show uniform wear between grooves, and the fastest wearing groove should be used to project tire life. During the tire tread wear tests, blocks 3 and 4 (middle blocks) usually showed the greatest degree of wear. The fastest wearing block on each tire was used to determine the R^2 values and calculate estimated tire life.

PHASE 1—TIRE TREAD WEAR WITHOUT RWS. Prior to phase 1, the test vehicle was driven 213 miles. According to the specifications listed by Michelin [6], the XZL tire has a manufactured tread depth of 0.969 (31/32) inch. Michelin truck tires contain wear bars in the grooves of the tire tread that indicate when 0.0625 (2⁄32) inch or less of tread is remaining. At this stage, the tires must be replaced, according to Title 49 Code of Federal Regulations (CFR) 393.75 [7], which also requires the front axle tires to have at least 0.125 (4⁄32) inch of tread depth.

At the beginning of phase 1, tire tread depths on all six tires measured between 0.878 (28/32) and 0.940 (30/32) inch. Several distinct wear patterns, based on axle location (front, middle, or rear) were observed on the 6x6 test vehicle without RWS (figure 8).

Figure 8. The 6x6 Test Vehicle Axle Positions

Average Tire Tread Wear Without RWS. Figure 9 shows a graph of the average tread wear of all six blocks from each tire. The tires on the front axle showed moderate tread wear, while the tires on the middle axle showed very little wear. However, the rear axle tires showed the most wear in the shortest amount of time from turning without RWS. The tread depth on the right-rear tire decreased from an average of 0.911 (29/32) inch to 0.598 (19/32) inch after 60 miles of driving on the figure-eight course.

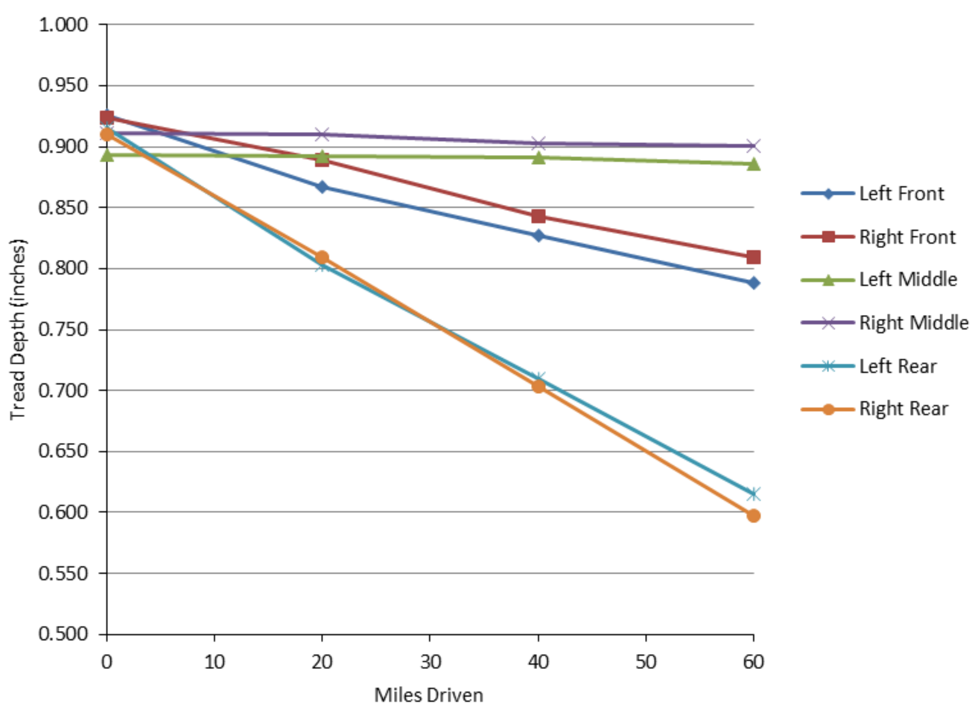

Figure 9. Average Tire Tread Wear Without RWS

<u>Front Tire Tread Wear Without RWS</u>. Figures 10 and 11 show that block 4 on the left-front tire showed the most tread wear for the front tires, decreasing from 0.925 (29/32) to 0.723 (23/32) inch. Block 6 on the right-front tire showed the least tread wear, decreasing from 0.914 (29/32) to 0.833 (26/32) inch. The R^2 value for block 4 on the left-front tire and block 4 on the right-front tire were 0.9894 (31/32) and 0.9994 (31/32), respectively, indicating linear tread wear on both sides for the fastest wearing blocks.

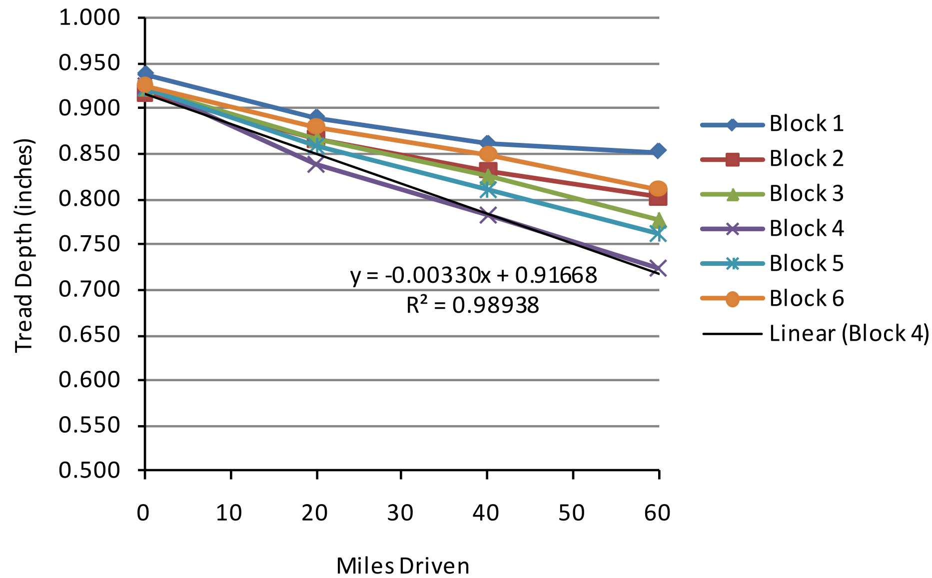

Figure 10. Left-Front Tire Tread Wear Without RWS

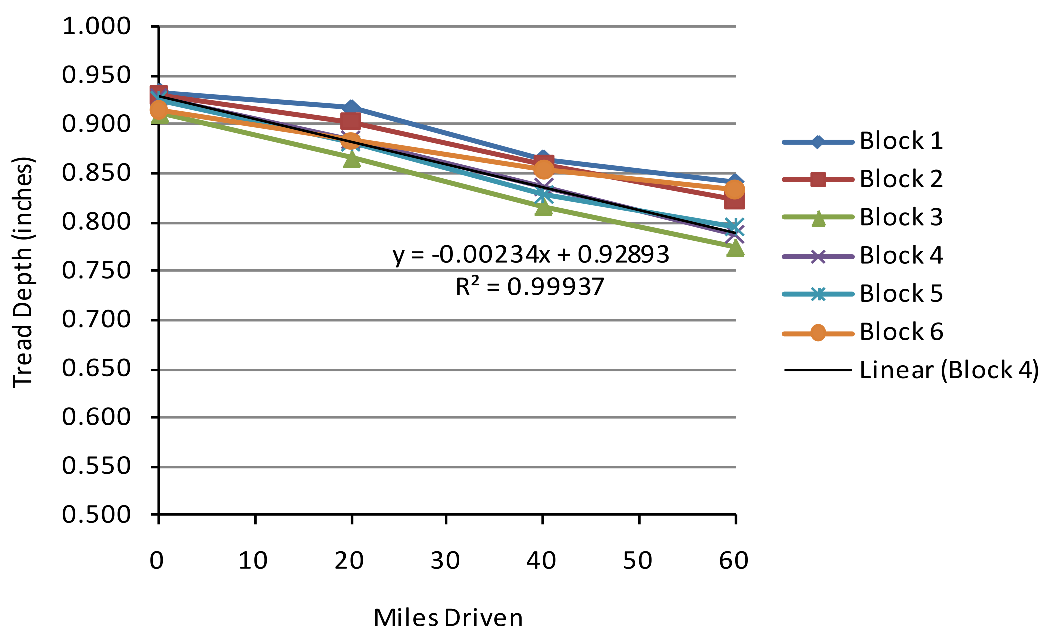

Figure 11. Right-Front Tire Tread Wear Without RWS

Middle Tire Tread Wear Without RWS. The right- and left-middle tires showed almost no tread wear during the 60-mile evaluation (figures 12 and 13). The fastest wearing block on both sides was block 6 (the innermost block). The left tire tread changed from 0.940 (30/32) to 0.917 (29/32) inch, while the right changed from 0.930 (30/32nds) to 0.915 (29/32nds) inch. Although the left-middle tire had an R^2 value greater than 0.95, indicating linear tread wear, the R^2 value for the right side block 6 was below 0.95, indicating the tread wear was not linear.

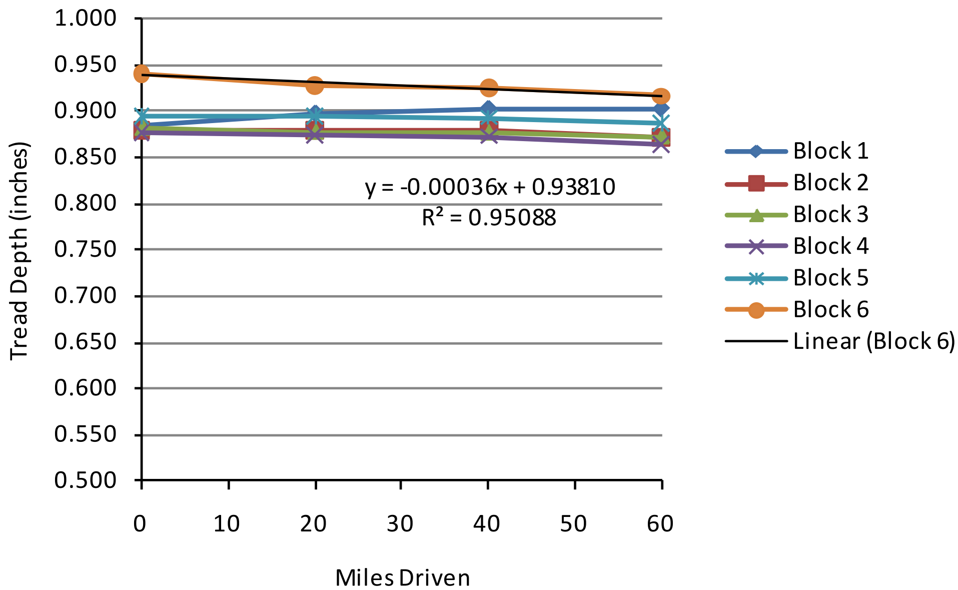

Figure 12. Left-Middle Tire Tread Wear Without RWS

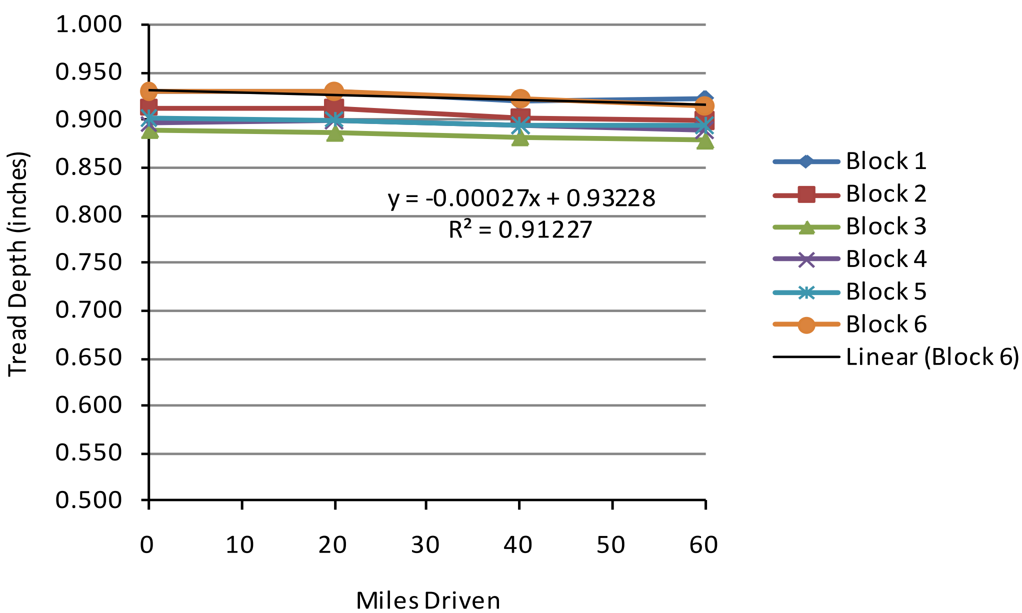

Figure 13. Right-Middle Tire Tread Wear Without RWS

Rear Tire Tread Wear Without RWS. The greatest degree of wear was observed on the two rear tires (figures 14 and 15). Block 4 of the left-rear tire decreased from 0.899 (29/32) to 0.496 (16/32) inch. This was the greatest amount of wear on any tire measured during the evaluation. The R^2 value was 0.9982, indicating linear tread wear. Block 3 wore the fastest on the right-rear tire and decreased from 0.896 (29/32) to 0.530 (17/32) inch. The R^2 value for block 3 was 0.9980, again indicating linear tread wear. Block 6 showed the least amount of wear on the rear tires at 0.199 inch.

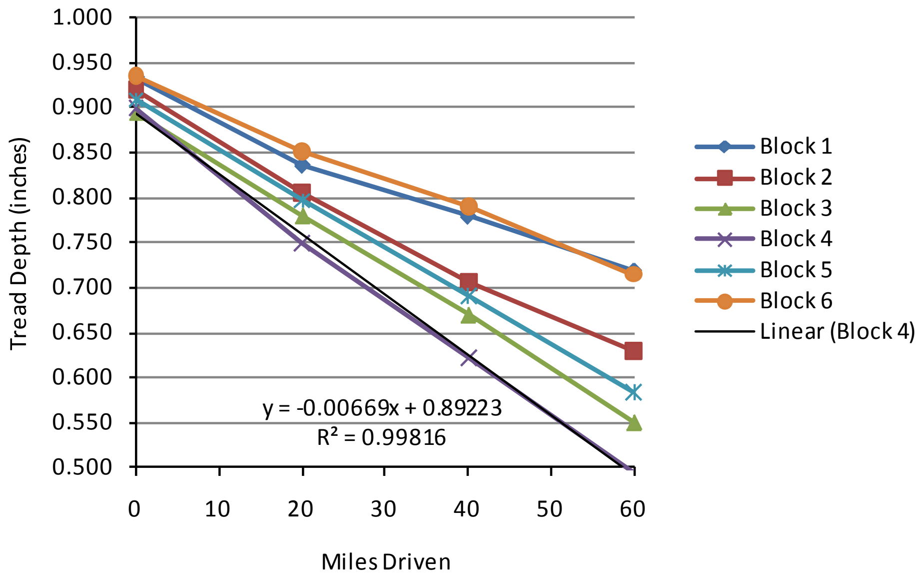

Figure 14. Left-Rear Tire Tread Wear Without RWS

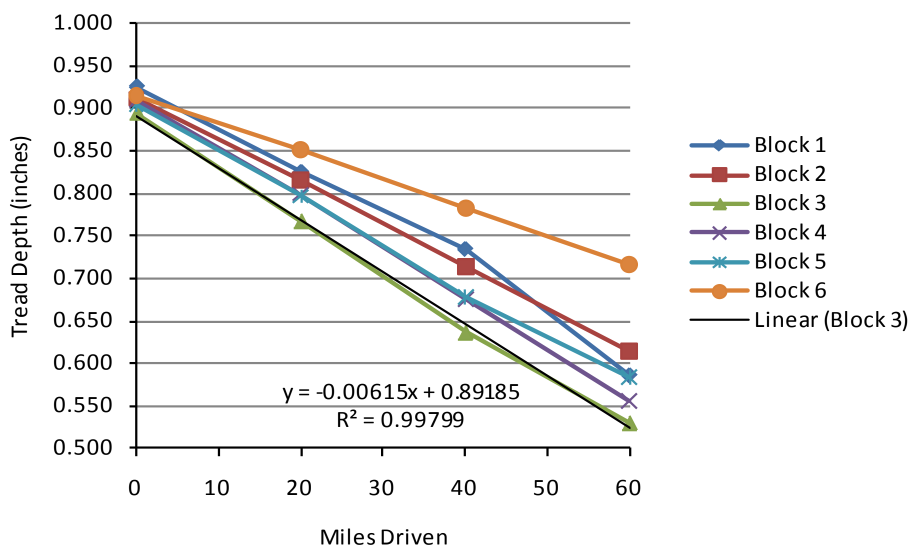

Figure 15. Right-Rear Tire Tread Wear Without RWS

PHASE 2—TIRE TREAD WEAR WITH RWS. Six new Michelin XZL tires were installed on the test vehicle prior to the start of tread wear tests with RWS. All tires had a minimum initial tread depth of 0.947 inch (30/32).

Average Tire Tread Wear With RWS. As shown in figure 16, and compared to figure 9, a different pattern was observed with RWS, although the overall tread wear was reduced for all six tires. Without RWS, the test vehicle showed the most wear on the rear tires, followed by the front, then the middle. With RWS, the middle tires showed the most wear, followed by the front, then the rear. The rear tires on both sides showed significantly less tread wear (0.035 inch) over an equivalent 60-mile distance compared to the wear measured with the RWS disabled (0.307 inch). Similarly, the front tires also showed less tread wear but to a lesser degree. However, the middle tires showed very little tread wear without RWS (0.009 inch), but showed more tread wear (0.096 inch) with RWS. The tread wear on the middle tires was less than the wear on the front and back tires without RWS. This phenomenon was likely due to the geometry of the steering system and the close proximity of the middle and rear axles. With front- and rear-wheel steering, the middle tires are forced to slip sideways during a turn and, therefore, experience greater wear. With only front-wheel steering, the body more or less pivots on the middle tires and forces the rear tires to slip sideways during a turn.

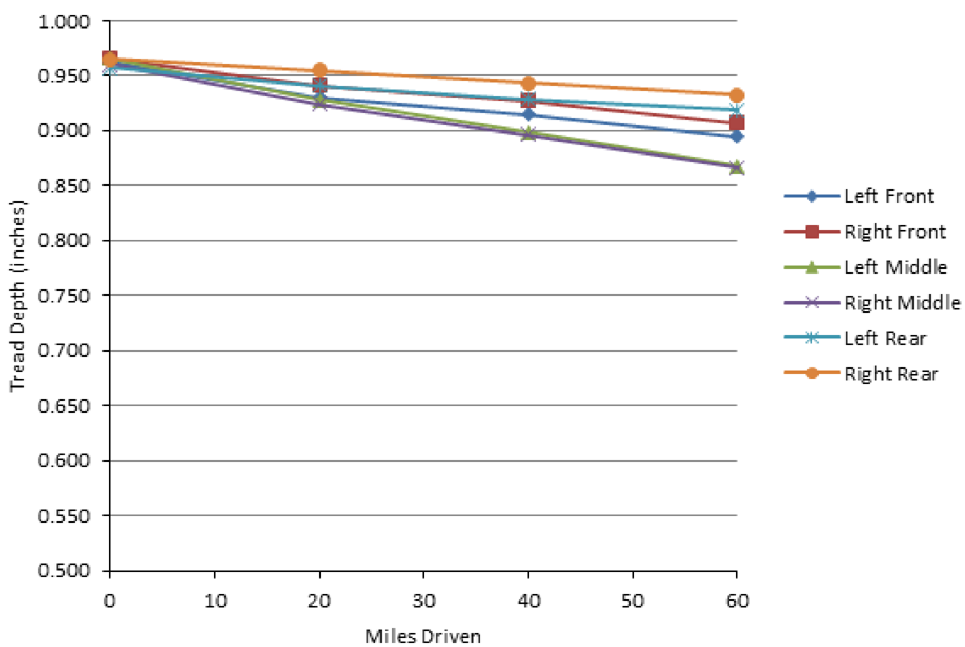

Figure 16. Average Tire Wear With RWS

Front, Middle, and Rear Tire Wear With RWS. Specific tire wear data is shown in figures 17 through 22. Linear regression showed R^2 values greater than 0.95 for the fastest wearing blocks on all six tires, indicating linear tire wear. The fastest tread wear was observed in blocks 3 and 4 (the middle blocks) for all tires, except in the right-rear tire in which block 5 showed the fastest wear. The middle tires wore the fastest by approximately 0.121 (4/32) inch over the 60 miles.

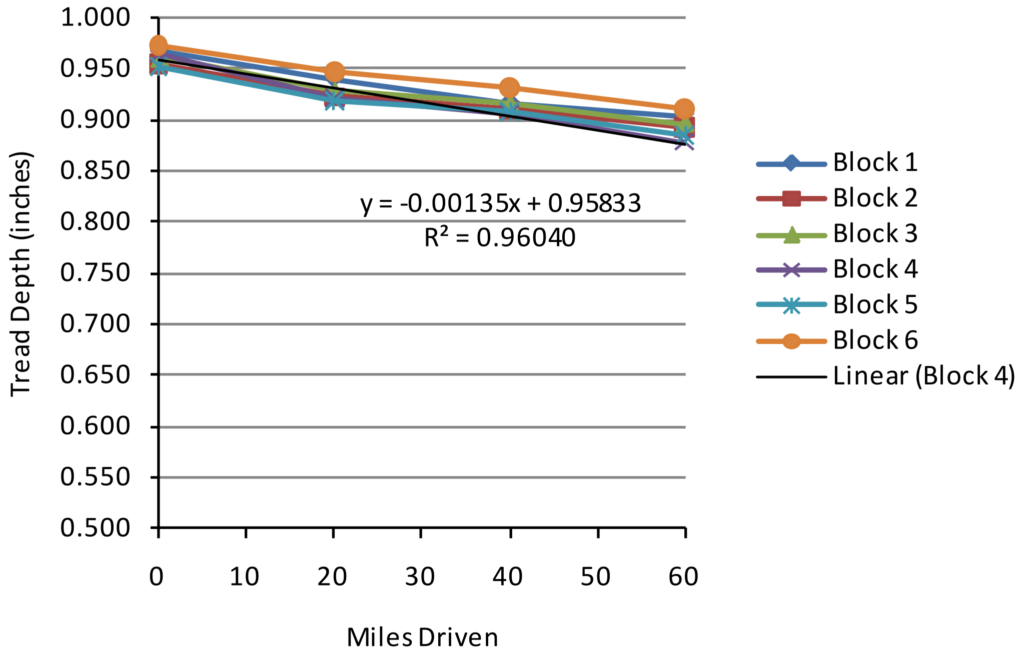

Figure 17. Left-Front Tire Tread Wear With RWS

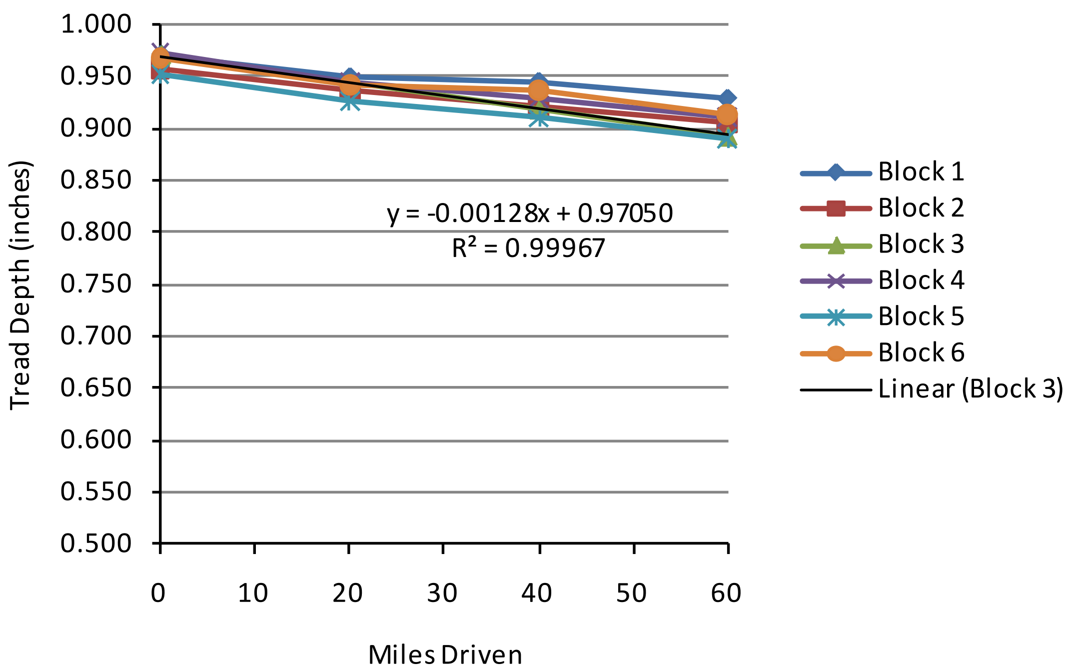

Figure 18. Right-Front Tire Tread Wear With RWS

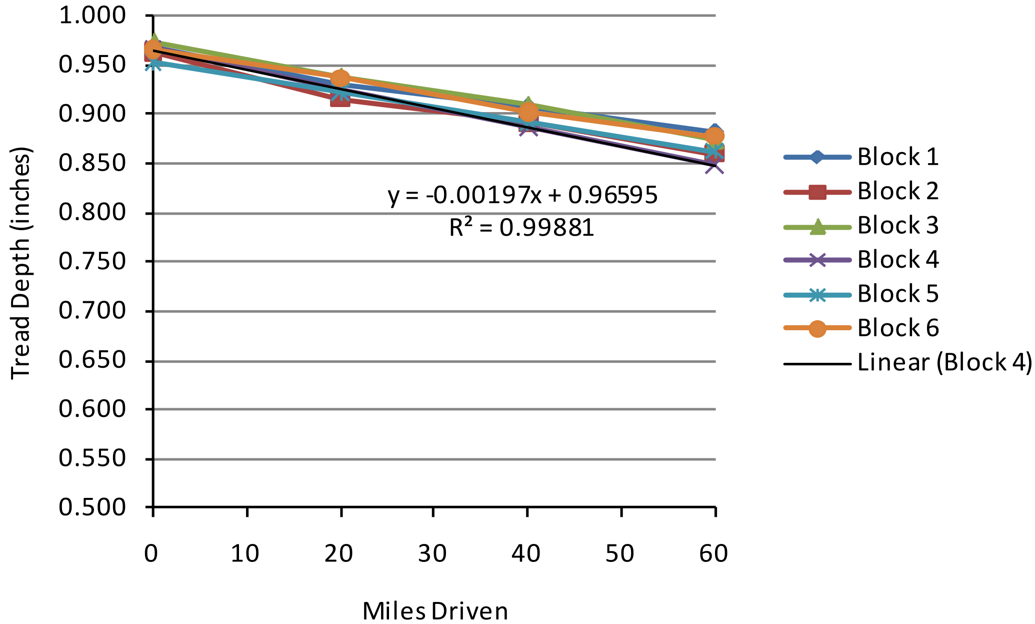

Figure 19. Left-Middle Tire Tread Wear With RWS

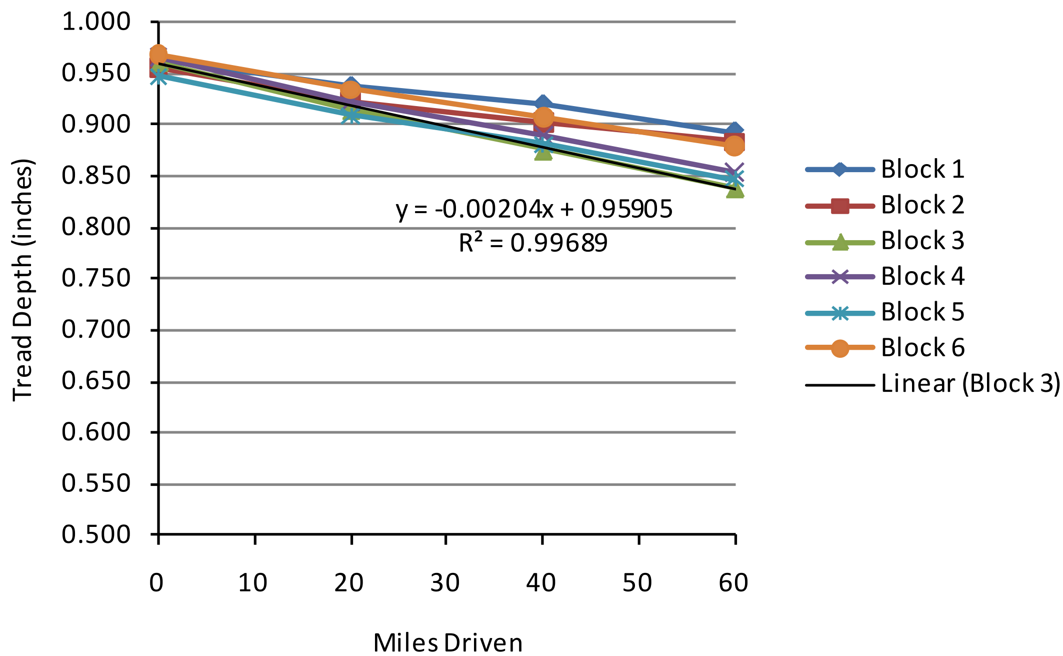

Figure 20. Right-Middle Tire Tread Wear With RWS

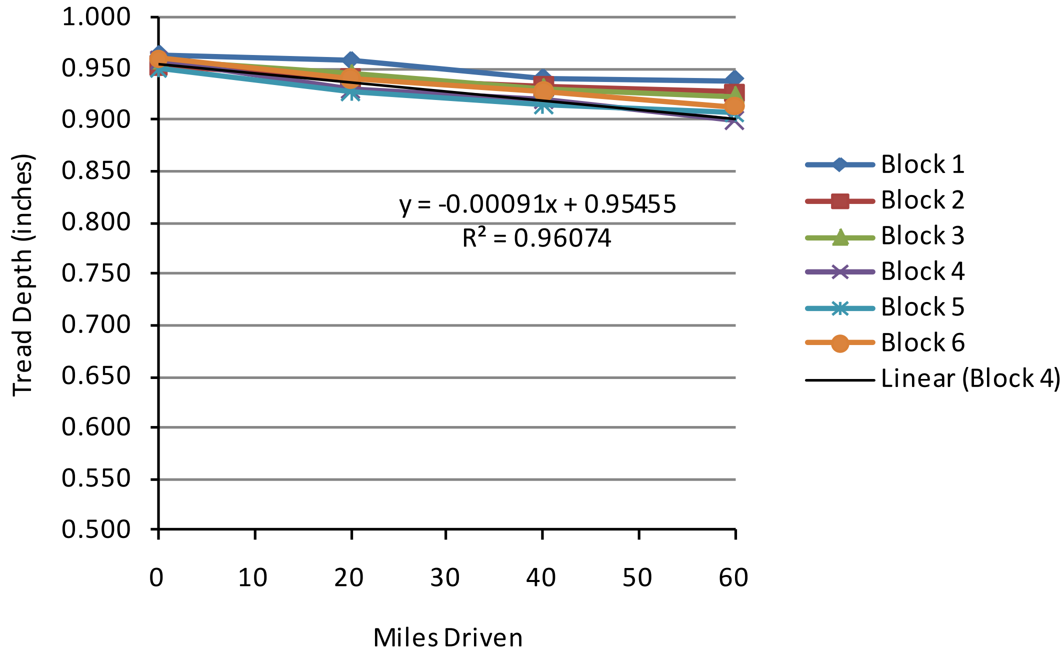

Figure 21. Left-Rear Tire Tread Wear With RWS

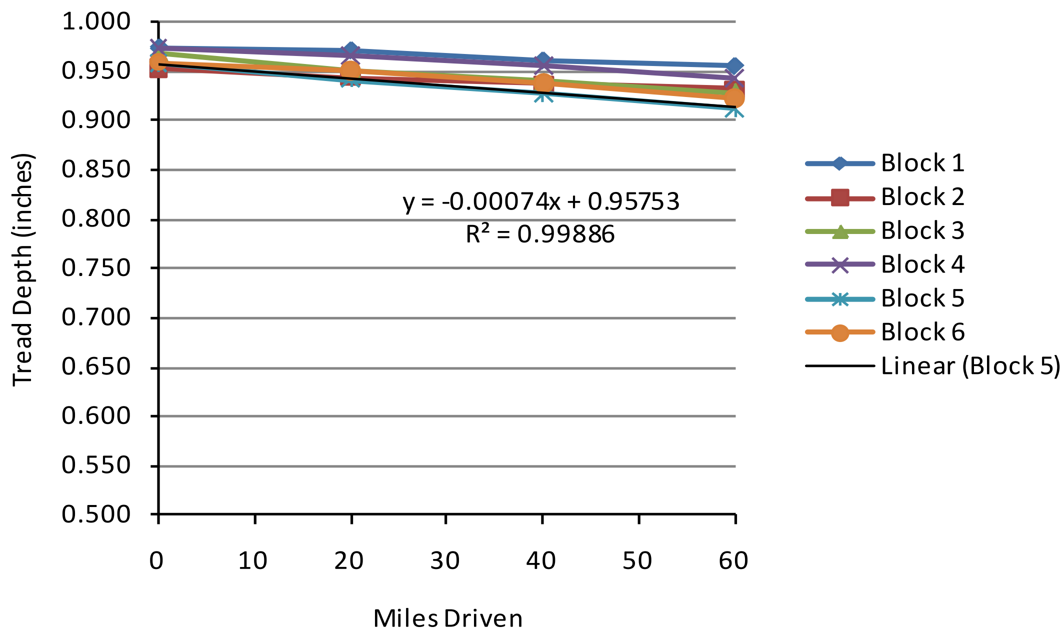

Figure 22. Right-Rear Tire Tread Wear With RWS

ESTIMATED TIRE LIFE.

The equation generated by the linear regression was used to determine the estimated tire life based on measurements taken for the fastest wearing block specific to the individual tire. The estimated tire life was based on replacing the middle and rear axle tires at 0.0625 inch (2/32) of tread depth and replacing the front axle tires at 0.125 inch (4/32) tread depth, as required by federal regulations [7]. Figure 23 shows the differences in estimated tire life using linear regression equations based on axle location and use of RWS. Note that the estimated tire life is based on continuous driving on the figure-eight course. This test method was used in reference 1, which generated faster and more aggressive tire tread wear than normal driving patterns. For rear axle tires, RWS extended tire life by 7.9 to 9.0 times compared to tire life without RWS. For front axle tires, RWS extended tire life by 1.9 to 2.6 times that of tire life without RWS. However, the middle axle tires showed more tire tread life without RWS, 5.3 to 7.3 times compared to tire life with RWS. The trends shown in figure 23 were also similar to the previous FAA RWS evaluation [1].

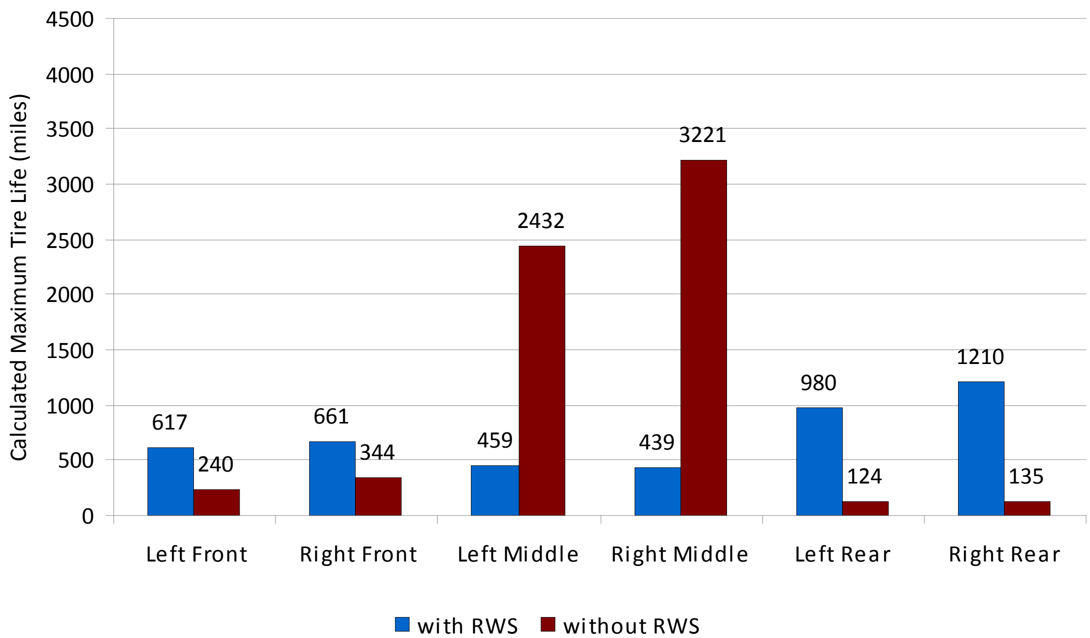

Figure 23. Estimated Tire Life Based on Linear Regression Equations

Figures 24 and 25 show the outside block (block 1) of the left-rear tire, both without and with RWS, respectively, after 60 miles of accelerated wear driving. Noticeable tread wear is shown in figure 24 along with a feathering effect on the leading edge of the block. With RWS, wear is unnoticeable (figure 25).

Figure 24. Left-Rear Tire After 60 Miles Without RWS

Figure 25. Left-Rear Tire After 60 Miles With RWS

Figures 26 and 27 show the right-middle tire after the same 60-mile conditions. However, it is more difficult to observe the decrease in tire life on the middle tires. The differences in tread wear on the front tires, with and without RWS, were impossible to observe visually.

Figure 26. Right-Middle Tire After 60 Miles Without RWS

Figure 27. Right Middle Tire After 60 Miles With RWS

It is difficult to judge the overall effect of RWS on all tires because the estimated tire life of both the front and rear tires benefit from RWS, while the estimated tire life of the middle tires does not. It should again be noted that the test conditions and methods are worst-case wear conditions, generating much more tire tread wear, and decreased tire life, than normal, routine driving.

CONCLUSIONS

Results showed that the 6x6 test vehicle satisfied the Federal Aviation Administration (FAA) requirements for wall-to-wall turning diameter by turning in less than three times the vehicle's length of 117.6 feet in both the clockwise and counterclockwise directions with rear-wheel steering (RWS) enabled and without. With RWS, the turning diameter decreased 21.7 feet (18.7%) in the clockwise direction from 116.0 feet to 94.3 feet and 19.7 feet (18.2%) in the counter clockwise direction from 108.2 feet to 88.5 feet.

The tire tread wear test methods used for this evaluation generated faster and more aggressive tire tread wear than normal driving patterns. The front and rear tires on both sides showed significantly less tire tread wear over an equivalent 60-mile distance compared to the wear measured without RWS. Without RWS, the rear tires wore the fastest by approximately 0.406 (13/32) inch over the 60 miles. With RWS, the middle tires wore the fastest by approximately 0.121 (4/32) inch over the 60 miles.

The data from the tire tread wear tests were used to calculate the estimated tire life. For the rear axle tires, enabling the RWS extended the estimated tire life by 7.9 to 9.0 times compared to tire life without RWS. For the front axle tires, enabling RWS extended tire life by 1.9 to 2.6 times compared to tire life without RWS. However, the middle axle tires showed better tire life without RWS, 5.3 to 7.3 times compared to tire life with RWS. The results were similar to the previous FAA RWS evaluation. This was likely due to the geometry of the steering system and the close proximity of the middle and rear axles. With the front- and rear-wheel steering, the middle tires are forced to slip sideways during a turn and, therefore, experience greater wear. With only front-wheel steering, the body pivots on the middle tires and forces the rear tires to slip sideways during a turn.

REFERENCES

1. Bagot, K., "Test and Evaluation of Rear-Wheel Steering for Aircraft Rescue and Firefighting Vehicles," FAA Technical Note DOT/FAA/AR-TN08/43, September 2008.

2. Federal Aviation Administration, "Guide Specification for Water/Foam Aircraft Rescue and Fire Fighting Vehicles," Advisory Circular (AC) 150/5220-10C, February 2, 2002.

3. Federal Aviation Administration, "Guide Specification for Water/Foam Aircraft Rescue and Fire Fighting Vehicles," AC 150/5220-10D, September 24, 2007.

4. National Fire Protection Association (NFPA), *NFPA 414 Standard for Aircraft Rescue and Fire-Fighting Vehicles*, 2007 edition, NFPA, Quincy, Massachusetts, August 17, 2006.

5. American Society for Testing and Materials (ASTM) F 1016-93, "Standard Practice for Linear Tire Treadwear Data Analysis," Reapproved 2001.

6. Michelin, Inc., “Michelin Truck Tire Service Manual,” http://www.michelintruck.com /michelintruck/toolbox/reference-material.jsp (Last visited September 1996).

7. U.S. Federal Register, Title 49 Code of Federal Regulations, Part 393.75, “Parts and Accessories Necessary for Safe Operation, Subpart G—Miscellaneous Parts and Accessories: Tires,” Government Printing Office, Washington, DC.